Soil strengthening using fine composite binder based on carbide slurry

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Abstract. It is shown that increasing the strength and impervious properties of strengthened soil massifs, keeping at the same time the low cost, is possible by use of injecting compositions based on the fine composite mineral binder – bio-silicon oxide together with the carbide slurry. The carbide slurry has fine particles size less than 10 µm. Aqueous suspensions based on bio-silicon oxide with the carbide slurry have required workability due to low viscosity and sedimentation of not more than 1.2%. Such suspensions had a sufficiently good penetrating ability and allowed transforming of the sandy soil into ground concrete in 28 days. Strength values of 12.5 MPa and 11 MPa were achieved using lime and carbide slurry, respectively. A distinctive feature of the carbide slurry application is that it is a waste product. It also solves the environmental problem.

1. Introduction

At present, the soil strengthening problem which is raising both in new construction and in reconstruction and repair of existing buildings and structures, including subway facilities, is very relevant. Due to high density of urban development, a distinctive feature of modern urban construction is the desire to use limited underground space, where violation of the strengthened array structure soil integrity in the course of works is unacceptable. Injection technology fully meets this requirement. However, it should be noted that a uniform spatial impregnation of the soil mass is possible only when particle size of mineral binder used as an aqueous suspension does not exceed 10-16 µm. Such binders production technology is characterized by increased wear of the equipment used and is very energy-intensive, which, ultimately, effects the cost of the product [1, 2, 3, 4, 5].

Over the last 15-20 years, both in the leading countries of the world and in Russia, underground construction technologies applying diluted aqueous suspensions of micro-cements for injecting to loose or low-strength porous soils have been developing very actively. Currently, several types of micro-cements are produced in the world [6, 7, 8, 9, 10, 11].

In Russia, industrial production of micro-cements is not widespread, however at present, due to arose problem of foreign micro-cements substitution by domestic ones, enterprises producing fine cements in individual batches are gradually emerging. The cost of domestic materials, as a rule, is lower than cost of imported materials, but is still more than an order of magnitude higher than the Portland cement of ordinary grade [1, 2, 5, 7, 8].
Micro-cement is produced by means of remilling with adding of organic modifier in mill units for Portland cement. It is difficult to reach desired fractional composition of the micro-cement using this technology, and what is more important - it is difficult to exclude presence of larger size grains. In the process of slurry injection into soil, this part of grains performs the role of "plugs" which close capillaries and pores and slow (or stop) the injection process. Therefore, in Russia, to solve this problem, micro cement made by foreign producers is bought and used, which is produced using technology of the initial cement remilling with subsequent separation and sieving into fractions \([1, 5]\). During the subsequent mixing, the micro-cement of the required fractional composition is produced, which does not contain particles larger than required. This is an expensive material and its use greatly increases the cost of the final product – strengthening soil (ground concrete).

Soil consolidation is artificial transformation of soil properties at the soil place by a variety of physical and chemical methods. This allows increasing strength and reducing deformation of the soil by providing adhesion between its particles. It should be noted that the most intensive strengthening is provided for soils which are water-permeable and filter water well. The main consolidation methods are: cementation, silification, electrochemical binding, heat roasting, tarring, claying and bituminous grouting \([6, 12, 13, 14, 15]\).

The most common soil bases consolidation method is injection which is not accompanied by a violation of the soil structure.

In the course of buildings reconstruction, injection of suspensions based on fine mineral binders used both for bases strengthening (figure 1a) and enhancing of "foundation bottom - soil" contact, and also for strengthening of partially demolished brick masonry (figure 1b) or rubble concrete \([13, 16, 17]\).

![Figure 1. Using of the fine mineral binders: a - for bases strengthening; b - for strengthening of brick masonry](image)

In addition, in coarse-grained and sandy soils, cementation is used to create anti-filtration barriers that prevent small particles removal from the foundations of existing buildings when water is pumped out from the adjacent pit \([6, 16, 17, 18, 19, 20]\).

Solution of the problem on enhancing of strength and impervious properties of strengthened massifs, their resistance to various aggressive media, keeping at the same time the low cost, is possible by use of injecting compositions based on the fine composite mineral binder – bio-silicon oxide - together with the carbide slurry \([21, 22, 23, 24, 25]\).

A distinctive feature of the carbide slurry application is that it is a waste product. This solves the environmental problem as well. In addition, carbide slurry is a ready-made raw material that can be used for preparation of mineral aqueous suspension for injection into the soil, without additional processing. It can be noted that the carbide slurry has fine particles of not more than 10 µm \([26, 27]\).
2. Methods
Following materials were used as the main components:
- lime hydrate for construction made by Stroymaterialy, JSC, Belgorod;
- carbide slurry from dumps of OTZ Protvino (chemical composition is given in table 1);
- active mineral additive - bio-silicon oxide – made by DIAMIX Group (see table 2);
- plasticizing additive “Sika viscocrete 5 new”.

| Name          | Content, wt. % |
|---------------|----------------|
|              | SiO₂          |
|              | CaCO₃         |
|              | Ca(OH)₂       |
| Carbide slurry| 0.1-0.6       |
|               | 5.6           |
|               | 93.8-94.3     |

Table 1. Chemical composition of carbide slurry.

| Name          | Content, wt. % |
|---------------|----------------|
|              | Loss on ignition |
|              | SiO₂          |
|              | Al₂O₃         |
|              | Fe₂O₃         |
|              | MgO           |
|              | K₂O           |
| Bio-silicon oxide | 0.92-1.92   |
|                 | 87.0-88.0     |
|                 | 6.1           |
|                 | 2.8           |
|                 | 0.84          |
|                 | 1.34          |

Table 2. Chemical composition of bio-silicon oxide.

The material strength was defined as per GOST 30744-2001 "Cements. Methods of test using polyfraction standard sand", conditional viscosity was defined as per GOST 33762-2016 "Materials and systems for protection and repair of concrete structures. Requirements for injection products and filling of cracks, voids and interstice", sedimentation was performed as per RD 39-2-645-81. "Method of evaluation of drilling mud parameters", suspension density was defined as per GOST 5802-86 "Mortars. Test methods.”

Evaluation of aqueous suspension penetrating ability and impregnated soil sampling were carried out according to specially developed technique using unidirectional linear model (figure 2). To carry out the tests, the model soil is loaded into the transparent cylinder 1, and then it is compacted to a state close to the natural density.

![Diagram of the linear unidirectional model](image)

Figure 2. Diagram of the linear unidirectional model. 1 - model soil; 2 – substrate; 3 - grid; 4 – flange; 5 – inlet and outlet.

The unidirectional model is fixed vertically. Water is pumped through the model soil and aqueous suspension of the design composition is fed under a pressure of 0.3 – 1.0 MPa, depending on the type of soil under study. During the test process, slurry is spread through the transparent cylinder. At the end
of the impregnation, the cylinder with saturated soil is placed in the specified conditions of hardening
and, after a given time, is tested to evaluate physical and mechanical characteristics.

3. Results and Discussion

Aqueous suspensions with various bio-silicon oxide / lime component ratio were prepared in a high-
speed mixer with rotation speed of 2800 -3000 rpm. Water/binder ratio in all cases was equal to 2.0.

Mandatory criteria of the mineral binder applicability in injection technology, except for the requirement
that particle size should not exceed 10 \( \mu \text{m} \), are requirements to technological properties of the aqueous
suspension, that is, maximum allowable viscosity and sedimentation of the suspension particles for 90
minutes. It is established from the production experience that the viscosity, characterized by the rate of
suspension flow from the standard funnel with volume of one liter (conditional viscosity), should not
exceed 40 seconds. Maximum permissible sedimentation of the binder particles in the suspension during
90 minutes is 2% of the suspension volume.

As can be seen from Table 3, all studied suspensions showed sedimentation rate in the range of 0.8-
1.2% during 90 minutes. This is less than the maximum permissible value and indicates high dispersion
and water-retaining capacity of the applied composite binder.

| Table 3. Sedimentation of aqueous suspensions |
|---------------------------------------------|
| **Name of composition** | **Observation time, min** | **Sedimentation, %** |
|                            | 0    | 30   | 60   | 90   |
| Bio-silicon oxide /lime = 0.5 | 0    | 0    | 1    | 1    |
| Bio-silicon oxide /lime = 1.0 | 0    | 0    | 1    | 1    |
| Bio-silicon oxide /lime = 0.5 + Sika | 0 | 0.8 | 0.8 | 0.8 |
| Bio-silicon oxide /lime = 1.0 + Sika | 0 | 0.8 | 1.2 | 1.2 |
| Bio-silicon oxide /lime = 1.5 + Sika | 0 | 1    | 1    | 1    |
| Bio-silicon oxide /carbide slurry = 0.75 + Sika | 0 | 1    | 1    | 1    |
| Bio-silicon oxide /carbide slurry = 1.0 + Sika | 0 | 0.8 | 1    | 1    |
| Bio-silicon oxide /carbide slurry = 1.25 + Sika | 0 | 1    | 1    | 1    |

Conditional viscosity of the suspension based on the same compositions is given in Table 4. The study
results showed that the suspensions without super-plasticizer do not meet the requirements for the
conditional viscosity value which should not be more than 40 seconds. Therefore, in further studies,
suspensions were prepared with the super plasticizer addition in the amount of 1% of the composite
binder mass. At the same time, their conditional viscosity was in the range of 36-39 seconds, which is
slightly more than the conditional viscosity of water equal to 32 seconds. Such suspensions had a
sufficiently good penetrating ability and allowed transforming of the sandy soil into ground concrete in
28 days.

| Table 4. Conditional viscosity of aqueous suspensions |
|-----------------------------------------------|
| **Name of composition** | **Observation time, min** | **Conditional viscosity, sec** |
|                            | 0  | 30  | 60  | 90 |
| Bio-silicon oxide /lime = 0.5 | 52 | 50  | 48  | 48 |
| Bio-silicon oxide /lime = 1.0 | 56 | 56  | 52  | 52 |
| Bio-silicon oxide /lime = 0.5 + Sika | 38 | 38  | 38  | 39 |
| Bio-silicon oxide /lime = 1.0 + Sika | 37 | 38  | 38  | 39 |
| Bio-silicon oxide /lime = 1.5 + Sika | 38 | 38  | 38  | 38 |
| Bio-silicon oxide /carbide slurry = 0.75 + Sika | 36 | 36  | 37  | 37 |
| Bio-silicon oxide /carbide slurry = 1.0 + Sika | 36 | 36  | 36  | 37 |
| Bio-silicon oxide /carbide slurry = 1.25 + Sika | 36 | 37  | 37  | 37 |

Over the time, reaction of bio-silicon oxide with carbide slurry forms low-alkali calcium hydro-
silicates [2, 4]. Bio-silicon oxide contains active silicon oxide which is able to react with Ca(OH)\(_2\) at
room temperature: $\text{SiO}_2 + \text{Ca(OH)}_2 + n \ (\text{H}_2\text{O}) \rightarrow (\text{B})\text{CaO}_2\times\text{SiO}\times\text{H}_2\text{O}$. Calcium hydrosilicates, having binding properties, transform sandy soil into the ground concrete.

Soil strengthening purposes can be various: consolidation of non-stable soil, construction of anti-filtration barriers, enhancing the bearing capacity of the soil being the base for foundations of buildings or structures. In the first two cases the consolidated soil strength is not very important, but the foundation should have increased compressive strength. As a rule, the strengthening of the soil under the foundations has a goal to bring the soil strength to 4-6 MPa, and in the case of concentrated load, for example, base under the columns foundations - up to 9-10 MPa.

Results of compressive and bending strength tests of the samples show that the fine composite binder provides the required strength values (figures 3 and 4). Values of 12.5 MPa and 11 MPa were achieved using lime and carbide slurry, respectively. It should be noted that the highest strength of the lime and carbide slurry were achieved at different ratios with bio-silicon oxide. This is 1.5 for lime and 0.75 - for carbide slurry. This fact is interesting, first of all, from the economic point of view.

![Figure 3](image-url)

**Figure 3.** The effect of the components ratio on compressive strength of the composite binder based on bio-silicon oxide. 1) Bio-silicon oxide /lime = 0.5 + Sika; 2) Bio-silicon oxide /lime = 1 + Sika; 3) Bio-silicon oxide /lime = 1.5 + Sika; 4) Bio-silicon oxide /carbide slurry = 0.75 + Sika; 5) Bio-silicon oxide /carbide slurry = 1 + Sika; 6) Bio-silicon oxide /carbide slurry = 1.25 + Sika;
Figure 4. The effect of the components ratio on bending strength of composite binder on based on bio-silicon oxide. 1) Bio-silicon oxide /lime = 0.5 + Sika; 2) Bio-silicon oxide /lime = 1 + Sika; 3) Bio-silicon oxide /lime = 1.5 + Sika; 4) Bio-silica/carbide slurry = 0.75 + Sika; 5) Bio-silicon oxide /carbide slurry = 1 + Sika; 6) Bio-silicon oxide /carbide slurry = 1.25 + Sika.

It was mentioned above that the cost of a unit of strengthening soil is largely defined by the high cost of micro-cements currently used in injection technologies. In this case, cost of the composite binder, bio-silicon oxide + carbide slurry is not only significantly lower (7-9 times) than cost of micro-cement, but 30-40% lower than the cost of bio-silicon oxide + hydrated lime composition. This is explained by a reduction of the bio-silicon oxide consumption (at a ratio of 0.75) the cost of which is higher than the cost of lime by 2.5-3 times. Use of carbide slurry in the composite binder also reduces its cost in comparison with lime, however, in our opinion, the environmental effect of the industrial use of waste – carbide slurry - is much more important.

4. Conclusions
Application of mineral binder based on reaction of bio-silicon oxide with carbide slurry as a binder for permeable soils strengthening appears to be very effective and will solve several problems: improving the strength of sandy and coarse-grained soils in a wide range of values, environmental protection and ecological safety. Aqueous suspensions on the basis of bio-silicon oxide with the carbide slurry have required workability due to low viscosity and sedimentation of not more than 1.2%. Compared with foreign analogues, they have a competitive cost and easy logistic.

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