Soil stabilization with modern TM MAPEI materials in reconstruction of buildings and structures

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Abstract. The article deals with the findings of experimental and theoretic research into the efficiency of applying prepared substances TM MAPEI for chemical soil stabilization for foundations of buildings in reconstruction. The objects of the study were soils of rapid, average and slow permeability. Determination of physical and mechanical characteristics of soils before and after stabilization was conducted in laboratory environment. The results were obtained on the basic of the project into stabilization of foundations under complex reconstruction of a four-storied building. The chemical stabilization technology for foundations purported uniform mixing of soil with a special mixing screw, supplying needed components, and further consolidation. A design diagram for the building was made in software package Lira-SAPR 2018. Calculations of carrying capacity of the foundation were made for six design patterns which differed in characteristics of the stabilized soil according to the materials applied. The first design pattern considered the application of non-stabilized soil. Results of the calculations are presented as isofields, soil reaction coefficients C₁ and C₂, loads (pressure) on the foundation P₀, and vertical deformations. On the basis of the research the authors state that application of TM MAPEI for chemical stabilization of collapsible soils under reconstruction allows increasing the foundation rigidity by three times and more, the carrying capacity by 10 times and more, depending on the formulations accepted.

1. Introduction
Soil stabilization is an urgent problem in reconstruction of buildings in cities. A need for such work is conditioned by commercial attractiveness of purchasing structures located in the city center for heightening the building or internal re-planning. Each case implies greater loads on the foundation. Besides, in cities and rapidly growing towns there is a liability to soil watering with anthropogenic and ground water, which leads to foundation weakening.

Advantages of soil chemical stabilization are relative production simplicity, possibility to stabilize soil at any depth without foundation opening, short production terms, and continuous use of the building during reconstruction [1-4]. Occasionally, chemical stabilization is the only technical possibility to improve stability and rigidity characteristics of the foundation.
2. Determination of physical and mechanical characteristics of soils

Physical and mechanical characteristics of soils before and after stabilization were defined in laboratory environment [5] with application of sets of soil samples under study and formulations. Sand of average fineness and density was taken as soil of rapid and average permeability. And loamy plastic sand was taken as soil of slow permeability in the research. The stabilized soil samples were manufactured with modern materials TM MAPE of a wide range of application, including one for soil stabilization. The composition formulation, and also the name and description of additives are given in Table 1.

| #  | Composition name | Description of the additive | Composition formulation |
|----|------------------|-----------------------------|-------------------------|
| 1  | Expanjet Ground  | Single-component cementing mixture based on high content of fine additive of expansion property of over 70% relative to the injected amount | Expanjet – 1 kg Sand – 0.01 m$^3$ Water – 0.00055 m$^3$ |
| 2  | Expanfluid Ground | Powder additive of expansion property, added to cement for preparation of non-shrinking and plastic mixtures for injecting | Expanfluid – 43 gr. Sand – 0.01 m$^3$ PC I-500 – 1.43 kg Water – 0.00051 m$^3$ Dynamon Easy 11 – 10 gr. |
| 3  | Dynamon Easy Ground | Modified superplasticizing agent based on acrylic for prepared concrete, mixtures or soils | Sand – 0.01 m$^3$ PC I-500 – 1 kg Water – 0.0008 m$^3$ |
| 4  | Microcem Ground | Microthin hydraulic cementing (with a particle size of up to 25 mkm) with pozzolanic activity for consolidation and hydro-isolation of soil under injecting cement mixtures | Microcem 8000 – 0.75 kg Loamy sand – 0.01 m$^3$ Water – 0.00075 m$^3$ Dynamon Easy 11 – 7.5 gr. Viscofluid Jet 5000 – 10gr. |
| 5  | Viscofluid Jet Ground | Cementing modifier of injecting formulations as flimsy natural cellulosic polymer. | Loamy sand – 0.01 m$^3$ PC I-500 – 1 kg Water – 0.0008 m$^3$ |

Resistance of soil cut ($\tau$), angle of internal friction ($\phi$) and specific cohesion ($C$) were determined on the basis of the findings of the study on the samples with the method direct shear in cutting devices of fixed cutting plane. The method is based on a shift of one part of a sample relative to the other part by applying tangential load at simultaneous impact on the sample of the load, normal to the cut plate (Figure 1).

Figure 1. Tests on soil samples with the method of direct shear.
Resistance of the soil cut was defined as the boundary average tangential stress at which the soil sample was cut off along a fixed plane at a set normal stress. For defining the specific cohesion and angle of internal friction more than three tests were conducted at various values of the normal stress. And a sample ring with the soil was fixed in the cutting box. Then, a solid stamp was established, loading mechanism was regulated, a gap of 0.5-1 mm between the movable and unmovable parts of the cutting box was fixed, a device for measuring deformation of the cut was fixed, and the initial indicators were recorded. As soon as the normal load was transferred, the mechanism for tangential loading was activated and the sample was cut. The tests were considered finished when during a regular stage of tangential load a part of a sample was immediately cut (torn) off one part of the sample relative to another or the total deformation of the cut exceeded 5 mm.

For defining the compressibility factor \((m_0)\) and the deformation modulus \(E\) tests on the samples with the method of compression pressure were conducted. These characteristics were defined by results of the research on the samples of soil in compression devices – odometers (Figure 2), which exclude a possibility for a soil sample to be expanded at vertical loading.

![Figure 2. Tests on the soil samples with the method of virgin compression.](image)

After the tests the results were processed and the average values of soil characteristics obtained were compared (Figures 3, 4, 5).

![Figure 3. Results of defining the deformation modulus.](image)
Figure 4. Values of the angle of internal friction in the test sets of soil.

Figure 5. Values of the specific cohesion in the test sets of soil.

3. Soil stabilization of the foundation in reconstruction of a building

The results of laboratory tests before and after soil stabilization were on the basis of the project on soil stabilization under complex reconstruction of a four-storied building. The structural layout of the building before reconstruction was a wall-bearing (external and internal) brick structure. The structural layout of the building after reconstruction was a non-complete framed structure with external and internal self-bearing walls and an internal monolithic reinforced concrete frame. The total rigidity and stability of the frame was provided by united work of diaphragm plates, stairs, columns, slabs and floor beams, and also slab foundation, united in a spatial system. A need for reconstruction was conditioned by emergency technical state and spatial rigidity damages due to cracks in both the bearing walls, and external and internal walls, which divided the building into parts.

Combined foundations in the form of natural slab (for the columns and stairs in the input section) and slab-type pole foundations (for two other sections), with column support of the frame in the centers of the sections (columns’ central location) were added during reconstruction. The foundation under additional bases, chemically stabilized, was composed of collapsible loamy soils with an initial collapsing pressure of 0.12 MPa.

The chemical soil stabilization technology implied formation of an artificial substructure by the uniform mixing of the soils with special mixing screws [6] with a simultaneous supply of needed components, blending and further consolidation before building additional foundations (Figure 5).
Figure 6. Diagram of chemical soil stabilization.

The major objective of blending is a uniform dissemination of soil cementing components for rapid and effective triggering chemical hydration reaction. The deep mixing technology for soils was firstly proposed in Japan at the beginning of 1950s [7]. Due to its universal nature and possibility to be applied for different soils, most popular is the moist mixing technique [8], which allows erecting on the site conditional soil-cement columns (poles) of the diameter 400-1200 mm and the maximum length 26 m. For obtaining the best results in soil-cement column stabilization, mixing process was repeated several times.

The structural calculation was made with the finite element method (FEM) in software package Lira-CAD SYSTEM 2018 [9], earlier used successfully in calculation of steel reinforced concrete structures [10] and reinforced concrete span bridge structures [11]. The design model was made with shell elements for walls, beams and covers, and universal cane finite elements for the frame (trimmer beams, columns). Universal finite elements of the cover with consideration of elastic foundation parameters, calculated on a 3D soil model, were applied for foundations. The 3D soil model was built on the basis of the results obtained in the engineering-geologic survey of the construction site. According to the model, along the whole foundations area, the authors defined the coefficients of soil reaction $C_1$, $C_2$ which depended on the proper loads on the foundations and loads from the adjacent buildings, and also calculated the compressed layer depth and sediment. Parameters of the elastic foundation were determined by the modified Pasternak’s model.

Figure 7. Design model of the building.

The coefficients of soil reactions $C_1$ and $C_2$ were defined by the iteration method according to the pressure law on the foundation surface and the soil foundation model. Characteristics of the soils included in the calculations are given in Table 2. The calculation also considered the pressure (approximately measured) on the soil from the buildings located in direct proximity to the building under reconstruction.
Table 2. Soil characteristics.

| EGE number | Name                        | Deformation modulus, MPa | Poisson’s ratio | Specific weight, kN/m³ | Natural moisture, fractions | Flow index | Porosity factor | Specific cohesion, kPa | Angle of internal friction, ° |
|-------------|-----------------------------|--------------------------|-----------------|------------------------|-----------------------------|------------|-----------------|-------------------------|-------------------------------|
| 1           | Collapsible loamy soil      | 4.90                     | 0.35            | 17.3                   | 0.16                        | 0.10       | 0.74            | 30.40                   | 17                            |
| 2           | Loamy soil                 | 10.8                     | 0.35            | 17.9                   | 0.21                        | 0.14       | 0.76            | 36.30                   | 14                            |
| 3           | Sand of middle density     | 35.6                     | 0.30            | 17.6                   | 0.09                        | -          | 0.57            | 0.039                   | 32                            |

The design diagram considered the following types of loading: constant loads (weight of carrying and non-carrying structures) and design temporary loads. The effective load on the underground floor (normative load without proper weight) was accepted 300 kg/m², on the 2nd and 3rd floors – 300 kg/m², on the 4th floor and attic floor – 200 kg/m².

The carrying capacity of the foundation was calculated for six design patterns which differ from each other in characteristics of stabilized soil according to the materials used. The first design pattern implied application of non-stabilized soil.

Table 3. Soil characteristics for design patterns.

| №  | Name                                      | $E$, MPa | $C$, kPa | $\phi$, ° | Design resistance, MPa |
|----|-------------------------------------------|----------|----------|-----------|------------------------|
| 1  | Collapsible loamy soil in a set condition | 4.90     | 30.400   | 17.0      | 0.120                  |
| 2  | Expanjet Ground composition               | 14.5     | 243.20   | 21.2      | 2.420                  |
| 3  | Expanfluid Ground composition             | 5.60     | 182.40   | 24.6      | 2.270                  |
| 4  | Dynamon Easy Ground composition           | 5.10     | 91.200   | 37.0      | 2.610                  |
| 5  | Microcem Ground composition               | 8.10     | 466.80   | 76.5      | 12.07                  |
| 6  | Viscofluid Jet Ground composition         | 5.30     | 4676.8   | 52.7      | 98.88                  |

The results of the calculations are presented as isopoles of the coefficients of soil reaction $C_1$ and $C_2$, loads (pressure) on the foundation $P_z$, and vertical deformations (Figure 7). For each case the carrying capacity of stabilized soil was evaluated according to the design resistance values of foundation soils (Table 4).

Figure 8. Stabilized soil Expanjet Ground composition.
Table 4. Results of the calculation.

| Name                  | Pressure on the soil (MPa) | Coefficients of soil reaction (MN/m³, MN/m, mm) | Carrying capacity reserve of the foundation |
|-----------------------|----------------------------|-----------------------------------------------|-------------------------------------------|
| Non-stabilized soil   | 0.137                      | 1.12-1.58, 17.50-24.70, 116                   | 0.89                                      |
| Expanjet Ground       | 0.125                      | 3.31-4.69, 52.10-73.40, 37.2                   | 19.6                                      |
| Expanfluid Ground     | 0.135                      | 1.27-1.80, 20.00-28.20, 101                    | 17.1                                      |
| Dynamon Easy Ground   | 0.136                      | 1.16-1.64, 18.20-25.70, 111                    | 19.5                                      |
| Microcem Ground       | 0.131                      | 1.84-2.61, 28.90-40.80, 68.3                   | 93.8                                      |
| Viscofluid Jet Ground | 0.136                      | 1.22-1.72, 19.10-26.90, 106                    | 740                                       |

4. Conclusions

Analysis of the results of physical and mechanical characteristics of soils after stabilization with TM MAPEI materials demonstrated that they considerably improve the soil properties. Soil stabilization in reconstruction makes it possible to increase the foundation rigidity by three times and more, the carrying capacity by ten times and more relative to the compositions taken. In order to obtain rational formulations providing an adequate stabilization level at minimal financial expenditures, it is reasonable to continue the research into improved production technologies and adjusted ratios of components.

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