Man-made soils and mining wastes as raw materials for building composites

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Abstract. The crucial task up to date is to find effective solutions to expand the raw material base of the construction industry by involving local natural and man-made raw materials instead of traditional expensive energy-intensive materials. An inexhaustible source of raw materials can be mining waste, such as dolomite and lime. Currently, they are large-tonnage industrial deposits that limit the area of development. The problems of strengthening man-made cohesive soils for the manufacture of wall materials, and their use as natural bases is also front and center. The optimal compositions of soil-concrete mixtures based on waste carbonate deposits are selected. The goal of this work was to design a composition of a complex binder for strengthening clay soil. The second goal of the work was to obtain masonry soil-concrete products. For this purpose, waste from the dolomite production of the Melekhovsky deposit was used. To solve the problems, authors carried out such tests as chemical analysis, mineralogical analysis, X-ray phase analysis, raster electron microscopy, compressive strength test, frost resistance test, and water resistance test. Comparing the obtained results, it is now becoming apparent that the compositions of GD-4 and GD-5 at close density values have high strength characteristics at design age. The content of dolomite waste above 30\% leads to an increase in strength, the best results are achieved with a dolomite content of 34.6-45.3\%, in this range also with increasing binder content, water absorption and density increase, and therefore porosity decreases. The phosphates that make up the composite increase its water resistance.

1. Introduction

The traditional methods of soil research include sounding and test boring with sampling. Regulatory documents indicate the required number and distance between borehole and the depth of the survey depending on the object being built. The situation is similar with test borings. In the conditions of a new construction site, these methods are justified, but if it is necessary to study the foundations of existing objects, considerable difficulties arise due to cramped conditions, the need to damage previously constructed structures (during sounding reinforcement are damaged in densely reinforced structures of foundation slabs). These works are labour-consuming and have limitations on the number of points, due to maintaining the operation capacity of the foundations. In this regard, researchers get a discrete picture of the state of the base. To create a general situation at the facility, one has to apply personal experience and the experience of other researchers in similar conditions, but this assessment will be probabilistic. The radar sounding is deprived of these disadvantages [1-3].
Surface radar sounding (Ground Penetrating Radar (GPR)) is often used to study the structure, identify bearing capacity and detect defects of the base. This method is often used to determine the properties of the soil and to monitor changes in these properties near and under construction. This method not only allows not to break the structure of the soil but also to repeatedly study the same area for a long time to control the dynamics of the changes. This allows to receive a huge amount of digital data that is processed in real time, as a result significantly increasing the accuracy of research and minimizing the probability of error [4-7].

This method does not require significant labor costs and has a low cost, so the method is optimal for many tasks on the study of soil bases. Modern GPR systems are able to accurately determine the location of the "defects" of the base. Moreover, there is a continuous improving of data processing, what leads to an increase in accuracy of the method.

The finite-difference time-domain (FDTD) method is the base for most of existing approaches. The ease of implementation in a computer program and good scalability when compared with other popular electromagnetic modelling methods are the reasons of popularity of this method [7]. The FDTD method has a disadvantage, which is necessity to discretize the volume of the problem space which could lead to excessive computer memory requirements and the staircase representation of curved interfaces. In-depth description of the FDTD method is outlined in [8]. Examples of the application of GPR studies are in the following sources [9-13].

This study analyses the results of a survey of an object in emergency state of a building, identifies the causes of damage, proposes a method for eliminating the consequences, and draws conclusions about the possibility of preventing such situations and solutions at all stages of identifying defects.

The construction site has complex hydrogeological conditions. Landing of the building was performed incorrectly, some of the foundations are located at the groundwater level. Execution of construction works led to the creation of pressure movement of groundwater. As a result of groundwater movement, the soil was washed out from under the foundations. As a result, transversal crack associated with its flexure appeared on the foundation plate of the constructed object. Figure 1 shows the layout of cracks in the foundation plate.

To use man-made cohesive soils as raw materials for the synthesis of building composite materials, it is necessary to achieve a stable connection of soils, which allows to get high long-term strength of soils in various climatic conditions.

Additives change the colloid-chemical nature of finely dispersed soil, which is the clay component of the man-made soils base.

In accordance with the statements of the authors [1-6], hydrated calcium silicates are formed during the interaction of Ca(OH)\(_2\) with clay.

As is known, the strength properties of clay rocks increase when they interact with slaked lime.

The more swellable components, the more effective the addition of Ca(OH)\(_2\) in the equations 1,2.

\[
\begin{align*}
Ca(OH)_2 + SiO_2 &\rightarrow CaSi O_3*n H_2O \\
Ca(OH)_2 + CO_2 &\rightarrow CaCO_3 + H_2O
\end{align*}
\]

According [2], the maximum amount of lime, which leads to an increase of soil strength in the case of kaolinite, is from 4 to 6\%, with illite and montmorelian clay - 8\%.

The crucial task is to find effective solutions to expand the raw material base of the construction industry by involving local natural and anthropogenic raw materials instead of traditional expensive power-consuming materials [7].

An inexhaustible source of raw materials can be mining waste, such as dolomite and lime. Currently, they are large-tonnage industrial deposits that limit the build-up area [8-11].

The development of technology of soil concrete based on dolomite and lime binder can help solve the issues facing the construction industry both in terms of strengthening weak soils and creating composite materials of low cost with the necessary structural properties [12].
2. Methods
To solve the problem at the first stage of research, the composition, properties, microstructure of waste dolomite, lime and clay of various deposits were studied.
- developed a complex binder to strengthen clay soil;
- developed a composition of soil concrete for masonry material based on dolomite and lime production.

Table 1 and Figure 1a and 1b show the mineralogical composition of the waste of dolomite from the Melekhovsky field.

Table 1. The mineralogical composition of dolomite waste according to the X-Ray Diffraction.

| Mineral  | Mass content of mineral, % |
|----------|----------------------------|
| Dolomite | 95.22                      |
| Quartz   | 0.62                       |
| Calcite  | 4.16                       |

The chemical composition of dolomite waste is presented in table 2.

Table 2. The chemical composition of dolomite waste.

| Oxides Content, % mass | CaO     | MgO     | Al₂O₃+Fe₂O₃ | SiO₂ | Loss on ignition |
|------------------------|---------|---------|-------------|------|------------------|
| 29.4-30.6              | 19.8-   | 0.3-1.8 | 0.5-        | 44.9-45.9 |
| 30.6                   | 20.2    |         | 4.2         |       |

Figure 1 a, b. X-ray Diffraction of waste dolomite.

The figure and table 3 show the chemical and mineralogical composition of lime waste.

Table 3. The chemical composition of lime waste.

| Mineral | Formula, mass % |
|---------|-----------------|
|         | Ca(OH)₂ SiO₂ MgO Calcite |
| Portlandite | 68.35 - - - |
| Quartz | - 2.29 - - |
| Periclase | - - 4.12 - |
| Calcite | - - - 25.23 |
The investigated soil, which is a combination of mineral particles, liquid and gas enclosed in its pores, has the following chemical and mineralogical composition [13], presented in table 4.

| Mineral | Weight, % | Oxide | Weight, % |
|---------|-----------|-------|-----------|
| SiO₂    | 77.8      | SiO₂  | 70-80     |
| CaO*Al₂O₃*₂SiO₂ | 5.3 | Al₂O₃ | 12-18 |
| Al₂O₃*₂SiO₂*H₂O | 7.0 | Fe₂O₃ | 5-8 |
| K₂O*Al₂O₃*6SiO₂ | 5.9 | MgO   | 1.5-3.0 |
| Na₂O*Al₂O₃*SiO₂ | 4.0 | CaO   | 0.5-1.6 |
|         | Na₂O     |       | 0.5-0.65 |
|         | K₂O      |       | 5-6     |

Figure 2 shows the x-ray diffraction of the test sample.

![Figure 2](image-url)

**Figure 2.** Radiograph of the test sample.

Wastes of dolomite and lime are characterized by different microstructure according to REM (Fig. 3 a, b).

![Figure 3 a, b](image-url)

**Figure 3 a, b.** REM data on the structure of waste dolomite (a) and lime (b).
An analysis of the physicomechanical properties and phase composition of man-made soil and dolomite mining waste allowed us to determine the maximum concentration of Ca ++ and Mg ++ compounds in order to achieve optimal soil strengthening and use properties for the synthesis of masonry (wall) materials.

Table 5 shows the properties of soil and wastes.

| Index                      | Name title of material          | Soil  | Lime waste | Dolomite Waste |
|----------------------------|--------------------------------|-------|------------|----------------|
| True density, kg/m³        |                                | 2630  | 2540       | 2760           |
| Humidity, %                |                                | 10.27 | 6          | 5              |
| Optimal W, %               |                                | 14-18 | -          | -              |
| Plasticity index           | Solid and fluidity             | -     | -          | -              |
| Dispersion (specific       |                                | 500 m²/kg | 560 m²/kg | 800 m²/kg      |
| surface)                   |                                |       |            |                |
| Name title in accordance   |                                |       |            |                |
| “Construction Standards and Regulations” | | | | |
|                            | silty clay      | sandy silt | fine grade sand |

Guided by the Pareto principle (20/80) and [14-15], the parameter of maximum concentration of waste use to obtain the most durable soils, technologically and economically justified composite masonry materials was selected. This criterion can be achieved by complete banding of the alumino-silicates component with Ca ++ ions.

The output parameters for the selection of the optimal concentration of the additive were soil density (ρ, kg/m³), compressive strength (Rc, MPa) and water resistance (W, %) and frost resistance (F, cycles).

Table 6 presents the compositions of the synthesized strengthened soils with lime-containing waste.

| Composition name title | Components, mass % |
|------------------------|---------------------|
|                        | Clay soil | Lime waste | Water |
| GBI-5                  | 60         | 5          | 35    |
| GBI-10                 | 50         | 10         | 40    |
| GBI-20                 | 40         | 20         | 40    |
| GBI-30                 | 30         | 30         | 40    |
| GBI-40                 | 20         | 40         | 40    |
| GBI-50                 | 10         | 50         | 40    |
| GBI-60                 | 5          | 60         | 35    |

For research and creation wall masonry materials, clay soil of fluidity and solid conditions, located in the territory of Vladimir (a former quarry of a brick factory) were used. The chemical composition is shown in table 7.
For the synthesis of composite wall materials were used the components shown in table 7.

**Table 7.** The chemical composition of the components.

| Component name title | Chemical composition | Physical properties |
|----------------------|----------------------|---------------------|
|                      | MgO  | CaO  | SO₃ | PO₄ | Loss on ignition | Density, g/cm³ | Degree of dispersion, mm |
| Dolomite waste (after firing) | 30   | 40   | -   | -   | 30               | 1.1            | 0.01-0.05 |
| Grouting fluid       | MgSO₄ * 7H₂O    | 3.5  | 2.66 | -   |                   |                | -          |
| Phosphate complex additive | Ca(PO₄)₂ |       |      |      |                   |                |            |
| Clay                 | Al₂O₃·2SiO₂·2H₂O | -    | 670-1090 | Less than 0.05 mm |                 |                |            |

Table 8 presents the compositions of the masonry material based on dolomite waste.

**Table 8.** The compositions of the masonry material based on dolomite waste.

| Component              | Composition name title |
|------------------------|------------------------|
| Semi-burnt dolomite    | GD-1 GD-2 GD-3 GD-4 GD-5 |
| Clay                   | 8 17 24.6 34.6 45.3     |
| Phosphate complex additive | 4.5 4.7 4.7 5.0 5.2  |
| Magnesium sulphate     | 23.5 21.3 27.5 23.3 16.8 |

In laboratory setting, the following technology was used:
- grinding of dry components in a laboratory mill;
- dosage on a laboratory balance;
- mixing dry components;
- gauging;
- formation using press;
- dismantling after 24 hours.

The frost resistance of the samples was determined using a climatic chamber CM-60 / 75-80 TX in accordance with Russian all-Union State Standard No 10060-2012 “Concretes. Methods for determining frost resistance”.

Determination of water absorption of the samples was carried out in accordance with Russian all-Union State Standard No 12730.3-78 “Concrete. Method for the determination of water absorption”. When determining water absorption, cubic-shaped samples were used.

The surface of the samples was cleaned of dust, dirt and lubricant using an abrasive stone. Samples were placed in a drying box and dried at a temperature of (105 ± 5) °C to constant weight in accordance with Russian all-Union State Standard No 12730.2-78 “Concrete. Method for determination of humidity”, after what the samples were weighed. Samples were placed in a container filled with water at a temperature of 20 °C so that the water level in the container was approximately
50 mm higher than the upper level of the stacked samples. The samples were in water until complete water saturation, after which they were weighed.

Durability (7 days, 28 days). Determination of compressive strength was carried out in accordance with Russian all-Union State Standard № 10180-2012 “Concretes. Methods for determining the strength of control samples” at the age of 7 and 28 days.

In determining the compressive strength, cubic samples with a rib length of 100 mm were used.

3. Results and Discussion
Table 9 presents the physical and mechanical characteristics of soil concrete on 28, 60 and 90 days of hardening.

| Composition name | Compressive strength, MPa | Frost resistance, cycles | Water resistance, % |
|------------------|---------------------------|--------------------------|---------------------|
|                  | 28 | 60 | 90 | 28 | 60 | 90 | 28 | 60 | 90 |
| GBI-5            | 1.2 | 1.8 | 2.12 | - | - | F5 | W2 | W2 | W4 |
| GBI-10           | 1.5 | 1.9 | 2.4 | F5 | F5 | F10 | W2 | W2 | W4 |
| GBI-20           | 2.1 | 2.9 | 3.35 | F5 | F10 | F10 | W2 | W2 | W4 |
| GBI-30           | 3.05 | 3.7 | 4.2 | F10 | F15 | F15 | W2 | W2 | W4 |
| GBI-40           | 3.01 | 3.8 | 4.0 | F10 | F15 | F25 | W2 | W2 | W4 |
| GBI-50           | 3.0 | 3.5 | 4.0 | F15 | F15 | F25 | W2 | W4 | W4 |
| GBI-60           | 2.8 | 3.0 | 3.9 | F15 | F25 | F25 | W2 | W4 | W4 |

Figure 4 shows the correlation of strength and frost resistance on the concentration of strengthening lime additives in clay soils at the age of 90 days.

Figure 4. Correlation of strength and frost resistance on the concentration of strengthening lime additives in clay soils at the age of 90 days.

Table 7 and figure 4 shows that the maximum amount of lime waste, which leads to an improvement in the physicomechanical characteristics of strengthening soil, is 28% of the mass.

The optimal amount of lime confirms to the origination of the maximum amount of crystalline hydrates of silicates and calcium aluminates, as evidenced by the results of microstructural analysis (REM), in Fig. 5.
The results obtained in this study give hope for a more active use of mining waste in the strengthening of industrial soils. At the same time, the achieved results made it possible to increase the amount of lime in comparison with previous studies [16–20] by more than 7% (mass), what accords well with the theory explaining the strengthening effect of additives on clay soils [4].

The interaction of hydrated lime, the main component of waste with clay soil, is due to aggregation of dispersed soil, pozzolanic reactions, as well as the interaction of calcium hydroxide with carbon dioxide of air and water in the soil with the formation of calcium carbonate, which ultimately leads to cementation of the soil.

The second goal of the work was to obtain masonry soil-concrete products. For this purpose, dolomite production waste of the Melekhovsky deposit was used (Table 7).

Table 10 shows the results of a study of the technical characteristics of the synthesized compounds.

**Table 10. Technical characteristics of the synthesized compounds.**

| Composition name title | Density, g/cm³ | Strength, MPa | Water resistance, % |
|------------------------|----------------|---------------|---------------------|
|                        | 7 days / 28 days | 7 days / 28 days |                     |
| GD-1                   | 1.88 / 1.71     | 3.1 / 9.4     | 12.1                |
| GD-2                   | 1.84 / 1.73     | 3.3 / 9.9     | 12.6                |
| GD-3                   | 1.86 / 1.78     | 3.7 / 6.7     | 12.9                |
| GD-4                   | 1.93 / 1.85     | 7.8 / 19.0    | 13.4                |
| GD-5                   | 1.87 / 1.80     | 7.1 / 14.4    | 13.1                |

4. Conclusions
Comparing the obtained results (Table 9), we can conclude that the compositions of GD-4 and GD-5 at close density values have high strength characteristics at design age.

The content of dolomite waste above 30% leads to an increase in strength, the best results are achieved with a dolomite content of 34.6-45.3%, in this range also with an increase in the binder content, water absorption and density increase, and therefore porosity decreases. The phosphates that enter into the composition increase its water resistance.

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