Properties of phosphogypsum as technogenic soil

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Abstract. Phosphogypsum (CaSO4·2H2O) is heavy tonnage waste generated by binding calcium in the process of sulfuric acid decomposition of phosphate raw materials when obtaining wet-process phosphoric acid in the production of phosphate fertilizers. In appearance, it is solid fine-crystalline substance of white or gray color with inclusions of large aggregates. The paper presents the results of laboratory studies of more than 390 samples of phosphogypsum neutralized with construction lime. The deformation and strength properties as well as the water permeability were determined on specially prepared samples with the relative compaction of 0.95, 0.90 and 0.80 by methods used in engineering and geological surveys. While the angle of internal friction, the cohesion and the coefficient of permeability of the phosphogypsum have the values typical for fine or silty sands, the compressibility characteristics are significantly worse due to the solubility of the particles. Phosphogypsum is characterized by subsidence and suffusion settling, which are proper for carbonate rocks (dolomite, limestone). The use of the phosphogypsum as ground is possible for subbase of roads with low traffic intensity with a gravel pavement, for dams at industrial solid waste storage facilities, as well as for engineering reclamation of those storage facilities, but only if implementing water protection measures.

1. Introduction
Phosphogypsum is dehydrate of calcium sulfate (CaSO4·2H2O) generated by binding calcium in the process of sulfuric acid decomposition of phosphate raw materials when obtaining wet-process phosphoric acid in the production of phosphate fertilizers. Its annual output in the Russian enterprises exceeds 14 million tons and most of this by-product goes to dumps or gypsum storage [1].

There is certain experience of using phosphogypsum as ground material in road construction [2-4] and hydroengineering construction [5-8] as well as in the construction of dams at industrial solid waste storage facilities, but the deformation and strength characteristics of this material have not been sufficiently studied.

This paper presents the results of laboratory studies of phosphogypsum generated by the company LLC “Industrial group “Phosphorit” in the city of Kingisepp. We have tested the phosphogypsum neutralized with construction lime.
2. Materials and methods
The properties of the phosphogypsum were determined by methods used in engineering and geological surveys (GOST 5180, 12248, 22733, 25584). The samples were taken from the dump a month after it was released from the processing line.

The degree of solubility of the phosphogypsum in water under normal conditions was 3.8 g/l, the total content of easily soluble salts was 2.4% and the content of impurities insoluble in hydrochloric acid was 2.0%. The average value of pH is 6.4. The corrosion activity against carbon and low alloy steel, to the aluminum cable sheath, to the concrete of all water resistance grades is high and against steel reinforcing rods in reinforced concrete structures is low.

The grain–size analysis performed by rubbing the samples on sieves and washing with a solution of gypsum with a concentration of 3-4 g/l. They showed that the composition of the examined phosphogypsum contains 47.8 – 82.4% of particles smaller than 0.1 mm, 6.8 – 21.2% of particles with size from 0.1 to 0.25 mm and 10.8 – 31.0% of particles larger than 0.25 mm.

The free water content of the samples determined by drying at the temperature of (60±2) °C was 19.8-29.5%. The content of hydrated water determined by calcination at the temperature of 400°C of pre-dried samples was 25.2%.

The density of the soil solids was 2.35 g/cm³.

The deformation and strength properties were determined on specially prepared samples in modern automated devices manufactured by Geocomp Corporation, USA. Three types of samples were prepared – with the relative compaction (RC) of 0.95; 0.90 and 0.80, or with the average dry density of 1.31; 1.24 and 1.10 g/cm³. Their initial water content was close to the optimal one that is from 21 to 24%. Approximately half of the total number of the samples were tested at the specified water content value and the remaining samples were saturated with water after loading into the devices.

The compressibility of the phosphogypsum was tested in the oedometer (GOST 12248). The load to the samples was increased by steps: 12.5, 50, 100, 200 kPa. 36 samples were tested – 6 for each value of RC and water content.

The consolidation tests were performed in oedometer too. The load to the samples was applied in one step and was equal 25, 50, 100, 200 and 300 kPa. All samples were saturated with water before testing. 90 samples were tested – 6 for each value of RC and load factor.

The strength characteristics (cohesion c and internal friction angle φ) were determined in the direct shear test according to the types of consolidated-drained (CD) and unconsolidated–undrained (UU) tests under four values of normal stresses – 50, 100, 200 and 300 kPa. The unconfined compression strength cu was determined in triaxial consolidometers under three values of the puc reconsolidation pressure – 100, 200 and 300 kPa. A total of 126 samples were tested.

The water conductivity, which is characterized by the coefficient of permeability k, was tested in falling head permeameter (GOST 25587). The load of 25, 50, 100, 200 and 300 kPa was applied to the samples. A total of 108 samples were tested.

The shrinkage was determined by drying of water-saturated samples in three steps: in a box at room temperature 20-24 °C, in the open air at 20–24°C and in a drying chamber at 60°C. 6 samples were tested for each value of RC.

The swelling was determined in special devices without vertical pressure. 6 samples were tested for each value of RC.

The experiments to determine the subsidence were performed in special oedometers in accordance with the “two curves” diagram and under the load on samples of 25, 50, 100, 200 and 300 kPa. The water-soaked subsidence values: relative subsidence εcs, initial pressure psd subsidence and relative suffusion compression εc due to dissolution and removal of components of the test material under water filtration were obtained for 6 samples for each pressure value.

3. Results
The tests with the Proctor device showed that under dynamic compaction, it is possible to achieve the maximum dry density of 1.37 g/cm³ at the optimum water content of 23%, where the water content
was found by drying the samples at the temperature of (60±2)°C (Fig. 1).

![Compaction curve of phosphogypsum](image)

**Figure 1.** Compaction curve of phosphogypsum.

The average values of the oedometric modulus of phosphogypsum in the stress range from 100 to 200 kPa are shown in Table 1. As you can see, the tested material can be attributed to medium-deformable soils (GOST 25100) at RC of 0.95 and to highly and extremely deformable at RC from 0.90 to 0.80. Moreover, the water saturation of the samples with RC of 0.95 practically did not affect the modulus of deformation, but it decreased by 1.2 and 2 times for the samples with a lower initial density.

**Table 1.** Oedometric modulus.

| Water content of samples       | $E_{oed}$, MPa, at RC of samples: |
|--------------------------------|-----------------------------------|
| Optimal                       | 10.9 8.6 4.3                      |
| Full water saturation         | 11.3 4.2 3.6                      |

The average values of primary and secondary consolidation coefficients – $c_v$ and $c_α$ are shown in Table 2. The Table shows the overall values of the secondary consolidation coefficient for the three sample types due to its insignificant variation. The obtained values of the consolidation coefficients are typical for highly deformable (weak) soils and it is most likely due to the dissolution of the particles and not to the slow removal of water from the pores nor to the creep of the particles as in the specified types of soils.

**Table 2.** Consolidation coefficients.

| Load, kPa | $c_v$, m²/year, at RC of samples: | $c_α$ $10^3$ |
|-----------|----------------------------------|--------------|
|           | 0.95 0.90 0.80                   |              |
| 25        | 5.0 4.9 2.5                      | 1.3          |
| 50        | 6.3 5.6 3.3                      | 1.6          |
| 100       | 9.0 7.8 4.6                      | 2.3          |
| 200       | 12.9 8.3 5.9                     | 2.9          |
| 300       | 11.2 7.4 7.2                     | 2.9          |

The average values of strength characteristics are shown in Table 3. As it turned out, the phosphogypsum has values of cohesion and internal friction angle, which are typical for sands. According to the value of unconfined compression strength, the phosphogypsum with RC of 0.95, 0.90 and 0.80 refers to very dense, dense and loose soils, respectively [9].
Due to the solubility of carbonate rocks (dolomite, limestone), when the pressure of the phosphogypsum acting on the samples, the coefficient of permeability decreases from 0.80 to 0.95, the coefficient of permeability decreases from 2.5 to 4.5 times depending on the vertical load acting on the samples.

The average values of the coefficient of permeability shown in Table 4, as well as its strength characteristics, are typical for fine or silty sands. When the relative compaction increases from 0.80 to 0.95, the coefficient of permeability decreases from 2.5 to 4.5 times depending on the vertical load acting on the samples.

The tests have shown that the samples with RC of 0.95 tend to swell weakly and the phosphogypsum with a smaller compaction does not swell. When dried, the samples do not shrink.

The values of subsidence in the process of soaking with water: relative subsidence $\varepsilon_{sl}$, initial pressure of the subsidence $p_{sl}$ and relative suffusion compression $\varepsilon_{sf}$ due to the dissolution and removal of the components of the test material during water filtration are shown in Table 5.

The phosphogypsum has values of relative subsidence and suffusion compression typical for carbonate rocks (dolomite, limestone). When RC increases from 0.80 to 0.95, the relative subsidence and suffusion compression decrease by 14-37 and 2.7-4.5 times, respectively, depending on the vertical load acting on the samples. Due to the solubility of the phosphogypsum, any long-term filtration of water through the phosphogypsum body will lead to its leaching followed by development of suffusion settling.

### Table 3. Strength properties.

| Type of test         | Water content | Strength properties | $\phi$ (degree) / $c$ (kPa) | RC of samples: |
|----------------------|---------------|---------------------|-----------------------------|---------------|
| Direct shear test (CD) | Optimal       | $\phi$ (degree) / $c$ (kPa) | 35.2 / 6.7                  | 0.95 | 0.90 | 0.80 |
|                      | Full water saturation | $\phi$ (degree) / $c$ (kPa) | 32.3 / 6.3                  | 34.1 / 7.2    | 32.4 / 7.6 |
| Direct shear test (UU) | Optimal       | $\phi$ (degree) / $c$ (kPa) | 32.9 / 6.0                  | 30.4 / 4.7    | 29.0 / 5.6 |
|                      | Full water saturation | $\phi$ (degree) / $c$ (kPa) | 29.6 / 5.9                  | 32.0 / 5.8    | 29.0 / 7.4 |
| Triaxial test (UU)   | Optimal       | $c_{uw}$ at $p_{uw}$: | 100 kPa                     | 110.8          | 53.0   |
|                      |               |                     | 200 kPa                     | 147.4          | 74.0   |
|                      |               |                     | 300 kPa                     | 185.6          | 88.1   |

### Table 4. Coefficient of permeability.

| Load, kPa | $k$, m/day, at RC of samples: |
|-----------|-------------------------------|
|           | 0.95 | 0.90 | 0.80 |
| no        | 0.091 | 0.165 | 0.431 |
| 25        | 0.063 | 0.119 | 0.182 |
| 50        | 0.056 | 0.096 | 0.146 |
| 100       | 0.056 | 0.089 | 0.138 |
| 200       | 0.056 | 0.074 | 0.112 |
| 300       | 0.039 | 0.055 | 0.104 |

### Table 5. Indicators of subsidence and suffusion compression.

| RC of samples | $\varepsilon_{sl}$ under load, kPa | $p_{sl}$, kPa | $\varepsilon_{sf}$ under load, kPa |
|---------------|------------------------------------|----------------|------------------------------------|
| 0.95          | 0.001, 0.001, 0.003, 0.003, 0.003 | $>300$         | 0.004, 0.007, 0.013, 0.016, 0.017 |
| 0.90          | 0.002, 0.003, 0.007, 0.020, 0.027 | 30             | 0.006, 0.011, 0.018, 0.020, 0.021 |
| 0.80          | 0.035, 0.037, 0.043, 0.044, 0.049 | $<25$          | 0.022, 0.028, 0.035, 0.046, 0.058 |
4. Summary
The studied phosphogypsum can be used as ground for subbase of roads with low traffic intensity with a gravel pavement, for dams at industrial solid waste storage facilities, as well as for engineering reclamation of those storage facilities, but only if the following conditions are met:

– filling with compaction up to relative compaction 0.95 at least;
– applying a layer of soil that is not subject to water erosion on top of the phosphogypsum;
– surface levelling, installation of impervious blanket and lateral drainage to prevent infiltration of rain and meltwater, infiltration of ground water through the phosphogypsum layer;
– arrangement of geotechnical monitoring for timely detection of deformations and for eliminating defects.

Compliance with these conditions will reduce the risk of structures shifting into a limited operational or emergency state due to its inherent properties because of its particle solubility, subsidence and exposure to chemical suffusion.

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