



Research article

UDC 691.3

DOI: 10.34910/MCE.139.4



## Use of fluorohydride as a binder for stabilization of weak soils in road construction

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**Keywords:** soil stabilization, strengthening, fluoroanhydrite, IR spectroscopy, differential thermal analysis, microstructure

**Abstract.** In the conditions of growing attention to resource saving and environmental safety in road construction, the search for new binding materials for soil stabilisation is topical. This work is devoted to the study of the possibility of using fluoranhydride, a waste product of hydrofluoric acid production, as a binder for road base stabilisation. The object of the study is a composite material based on fluoranhydride, clay, and activator – sodium phosphate solution. The influence of fluorohydride activation on the physical and mechanical characteristics of the composite, including compressive strength, water absorption, and softening coefficient, has been studied. Fluoroanhydrite is activated by 3 % sodium phosphate solution, which increases the strength of the obtained material. The physical and mechanical properties of composites consisting of fluoranhydrite, loam, and sodium phosphate have been investigated. X-ray phase and IR spectral analyses were carried out, as well as scanning electron microscopy and energy dispersive X-ray spectroscopy. The results show that the optimum ratio of loam to fluorohydrite is 40/60 as it provides the highest economic efficiency. The compressive strength of this composition at the age of 28 days is also favourable: 8.9 MPa in the dry state and 7.3 MPa in the wet state, while the water absorption is 6.82 % and the softening coefficient is 0.82. The study confirms that fluorohydrite can be used as a binder to stabilize weak soils, which helps to reduce the cost of works and reuse waste materials, reducing the environmental load.

**Citation:** Alexandrov, A.M., Yakovlev, G.I., Buryanov, A.F., Bekmansurov, M.R., Martyshev, N.V., Vatin, N.I., Karlina, A.I. Use of fluorohydride as a binder for stabilization of weak soils in road construction. Magazine of Civil Engineering. 2025. 18(7). Article no. 13904. DOI: 10.34910/MCE.139.4

### 1. Introduction

A road is a complex structure, and its strength depends directly on the quality of the base on which it is built. The durability and reliability of the entire road depends on the stability of the soil, its strength, and ability to withstand loads. However, the soils is not always suitable for road construction 'as is'. Often, it is too weak, unstable, easily subsides under the weight of vehicles [1–3]. Soil stabilization (a process of

improving the mechanical and physical properties of soil to increase its strength and durability) is a crucial step for creating reliable roads. This leads to serious problems: the road surface can deform, cracks and potholes can appear, and the whole road surface can subside and lose its shape [4, 5].

Another problem is that the soil is susceptible to various factors that can aggravate the situation, namely, high moisture that makes the soil soft and unable to bear loads or low humidity, which, on the contrary, can cause the soil to shrink, causing cracks and deformations in the road. Besides, the roads are always subjected to variable traffic loads, which can create 'fatigue' in the soil, leading to its gradual deterioration [6].

In the conditions of growing attention to resource saving and environmental safety in road construction, the search for new binding materials for stabilisation of weak soils is relevant. This paper is devoted to the study of the possibility of using fluorohydride, a waste product of hydrofluoric acid production, as a binder for stabilising (rather than strengthening) weak soils in the base of road pavements. The use of fluorohydride will reduce the cost of road construction by utilising industrial waste and reducing the need for traditional, more expensive materials, as well as reducing the environmental burden. It is important to note that materials used in road construction must meet the requirements of the Technical Regulations of the Customs Union TR TS 014/2011 'Safety of Motorways'. In particular, Section 5 'Requirements for earth bed and road pavements' establishes requirements for physical and mechanical characteristics of soils reinforced or stabilised with binding materials.

Thus, before building a road, it is necessary to improve the properties of the soil – this is called 'soil stabilization'. Soil stabilization is an important step to make the road base strong, stable, and less sensitive to various external factors. Soil stabilization is not just a desirable step but a mandatory element in road construction and repair [7, 8]. Imagine a road as a huge 'pie' where each layer fulfils its role, and the base, i.e. soil, plays the role of foundation, which provides the strength and durability of the whole structure. The problem is that the characteristics of the soil can vary dramatically [9]. Sometimes the soil is too weak, unable to withstand traffic loads, easily subsides, or has an uneven structure [10, 11]. Such soil can cause many troubles: the road surface will deform, cracks and potholes will appear, and the whole road may subside and lose its shape [12].

Soil stabilization solves this problem by making the soil stronger, more stable, and able to withstand loads. This increases the durability of the road surface and reduces the number and frequency of repairs needed. The benefits of soil stabilization are not just limited to strength. It also saves money and time in construction as the amount of excavation work is reduced by eliminating the need to replace weak soil with stronger material. Therefore, it allows existing soil to be used with minimal changes, reducing the cost of delivery and purchasing additional materials.

In summary, soil stabilization is not just a technological process but a necessary investment in road quality, durability, and safety. There are many methods of soil stabilization, each suitable for specific conditions. One of the most common methods is mixing soil with various binding materials. The binders help to 'glue' the soil particles together, making the soil stronger and more stable. Portland cement, lime, non-metallic materials (crushed stone, gravel), high calcium ash [13], and other substances are often used as binders. Apart from mixing with binders, other methods are also used to stabilise the soil:

- Mechanical compaction: Compacting the soil with rollers or other mechanisms can remove air from the soil and make it more dense.
- Wetting and drying cycles: The use of wetting and drying cycles can improve the soil structure and make it more resistant to moisture [14].
- Application of geosynthetics: Special geosynthetics can be used to reinforce the soil, which improves its strength and resistance to deformation [15].
- Electrical stabilization: This method can strengthen the soil using electric current.
- Biopolymer treatment: Biopolymers are organic substances that can bind soil particles and improve soil properties.

The choice of soil stabilisation method and materials used should be made taking into account the requirements of regulatory documentation. According to GOST R 58406.1-2020 'Public roads. Crushed stone and gravel-sand mixtures, crushed stone and gravel mixtures treated with inorganic binding materials. Technical requirements', mixtures used for road base construction must meet certain requirements for strength, frost resistance, and water resistance. The use of fluorohydride meets these requirements [16].

In addition, special additives are used to strengthen weak soils, which also improve other soil properties such as environmental resistance and drainage quality. In recent years, resource- and energy-saving technologies have been increasingly emphasised in road construction. Therefore, scientists are looking for new ways of soil stabilization that would be not only effective but also environmentally friendly

and economically viable. One of such promising directions is the use of anhydrite as a binding material [17–19].

Anhydrite binder is an air binder consisting mainly of anhydrous calcium sulfate  $\text{CaSO}_4$ , which is a natural material that usually accompanies gypsum deposits. The technology for producing anhydrite binder is quite simple and, unlike cement, does not require heat treatment. Therefore, its production includes the extraction of anhydrite itself, its crushing and drying. Another method to obtain anhydrite is from natural gypsum by firing it at a temperature of 600–700 °C with subsequent grinding. The advantages of anhydrite include its environmental friendliness, non-flammability, the possibility of reprocessing products from it into a binder with the preservation of properties.

A cheap substitute for natural gypsum and anhydrite are wastes from various industries such as phosphogypsum, formed during the sulfuric acid decomposition of phosphate raw materials in the production of mineral fertilizers; red gypsum, formed during the desulfurization of flue gases; fluorogypsum or fluoroanhydrite, formed during the production of hydrofluoric acid; citrogypsum – a waste from the biochemical production of citric acid; hydrolysis gypsum – a waste from the technological processing of cellulose in the production of ethyl alcohol, a waste from the chemical polishing of glass, etc.

The most widely used multi-ton chemical industry waste in the production of building materials, phosphogypsum, requires preliminary preparation – neutralization with lime, and further dehydration at a temperature of 150–170 °C. Sulfogypsum, obtained during gas purification in the non-ferrous metallurgy industry, contains virtually no harmful impurities, being one of the purest gypsum-containing wastes, however, it requires heat treatment to obtain gypsum grade G2–G4.

Fluoroanhydrite, a by-product of hydrofluoric acid production after leaving the reactor, does not require additional processing and can be used in construction material industry in its original form. It is also possible to obtain an anhydrite binder from uncooled acidic waste from the production of hydrogen fluoride, including mixing and neutralizing the acidic fluoroanhydrite waste with a lime-containing agent while simultaneously grinding the mixture. In this case, Ilyinsky [20] suggests to add self-disintegrating ferrochrome slags a neutralizing lime-containing agent, and during mixing introduce a setting accelerator and superplasticizer in an amount of 0.7 and 0.5 wt.%, respectively, of the mass of the waste. The compressive strength of the composition after 28 days of hardening reached 27 MPa.

Anikanova et al. [21] developed compositions based on fluoroanhydrite, including structural, thermal insulation, and finishing materials, which can be used in the construction of enclosing and load-bearing structures of low-rise residential buildings.

Another composition [22] for the production of facing slabs, finishing layers of building products, load-bearing structures of buildings, wall stones based on fluoroanhydrite with the addition of slag and fillers – anhydrite crushed stone and carbonate sand has been developed. The characteristics of the binder on the 3<sup>rd</sup> day of hardening are as follows: strength 48.6 MPa, softening coefficient 0.89–0.91.

A fluoroanhydrite binder can also be used for road base construction. Fedorchuk describes a method for the use of joint soil fluoroanhydrite and substandard ferroalloy slag as a binder [23]. During grinding, acid (sulfuric, orthophosphoric, or their mixtures) is additionally introduced until the mixture pH reaches 1.0–6.5, followed by mixing the grinding product with an alkaline additive (lime, liquid glass, alkali – NaOH or KOH, soda) until pH reaches 7.0–12.0. Processing the mixture with this method promotes the decomposition of CaO, MgO and the formation of insoluble compounds that increase the water resistance of the finished product. The declared strength of the samples on the 28<sup>th</sup> day reaches 40 MPa.

The use of fluoroanhydrite as a binder would provide an opportunity to reduce the cost of road construction. Also this solution allows to reduce the environmental load due to the utilisation of industrial waste. The aim of this work was to evaluate the possibility of using fluoroanhydrite as a binding material for stabilising weak soils in road construction.

To achieve this goal, the following tasks were solved:

- Optimisation of the mixture composition: Determination of the optimal ratio of fluoroanhydrite, loam, and activator (sodium phosphate) to achieve the required mechanical characteristics of the material.
- Study of physical and mechanical properties: Study of compressive strength, water absorption, softening coefficient, and other important characteristics of the obtained composite material.

It is important to note that the research presented aims not only to investigate the feasibility of using fluoroanhydrite but also to find a way to reduce the cost of construction, and to have a positive impact on the environment by utilising the industrial waste product.

## 2. Methods and Methods

In the course of this work, an attempt is made to use fluorohydrate, a waste product of hydrofluoric acid production, in the construction industry. This material, obtained at the enterprise 'HaloPolymer' in Perm, meets all the necessary technical requirements (TU 5744-132-05807960-98), which makes it potentially suitable for use in construction.

The chemical composition of fluorangidrite is as follows – CaO – 35.0–36.5 %; SO<sub>3</sub> – more than 45 %; Fe<sub>2</sub>O<sub>3</sub> – 0.2–0.95 %; SiO<sub>2</sub> – 2.6–3.4 %; CaF<sub>2</sub> – 2.2–5 %; Al<sub>2</sub>O<sub>3</sub> – 0.5–0.7 %.

The analysis of the X-ray diffraction of fluorohydrate showed the presence of reflections corresponding to soluble anhydrite – CaSO<sub>4</sub> ( $d_a = 3.50; 2.85; 2.33; 2.21; 1.87 \text{ \AA}$ ). In addition to these reflections, reflections of gypsum dihydrate CaSO<sub>4</sub> · 2H<sub>2</sub>O ( $d_a = 7.55; 4.26; 2.85 \text{ \AA}$ ) are visible in the X-ray spectrum. Reflections of silicon oxide SiO<sub>2</sub> ( $d_a = 3.35 \text{ \AA}$ ) and calcite CaCO<sub>3</sub> ( $d_a = 3.03 \text{ \AA}$ ) are also present. However, the reflections of gypsum dihydrate, silicon oxide, and calcite are weak, and the intensity of the peaks is not high.

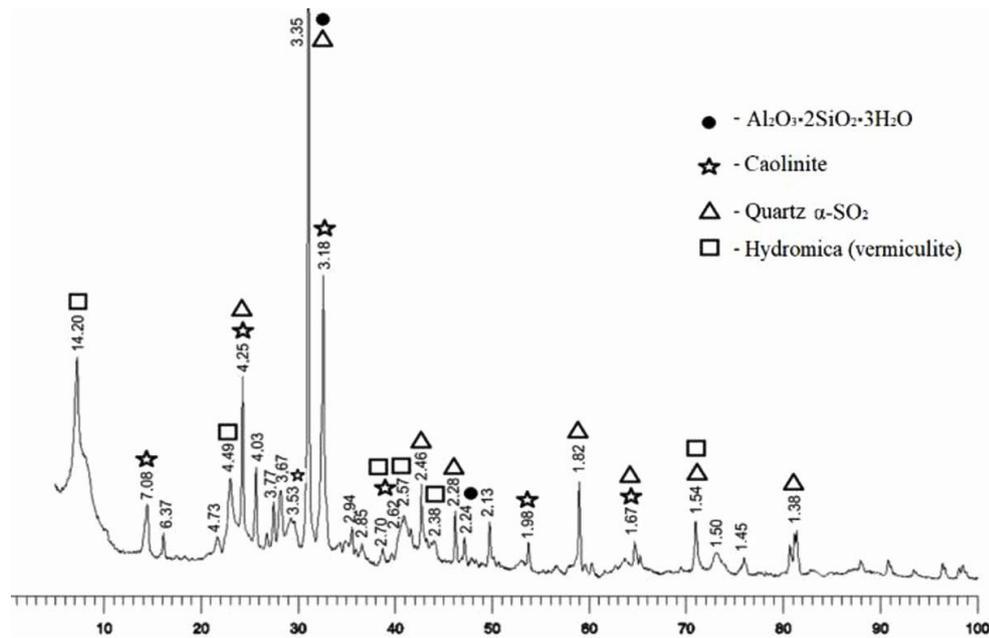


Figure 1. Diffractogram of loam.

The X-ray diffraction pattern of the loam (Fig. 1) shows strong reflections of quartz ( $d_a = 4.25; 3.35; 2.46; 1.82 \text{ \AA}$ ), which suggests its predominance in the soil. Reflection lines in the range of  $d_a = 7.08; 4.25; 3.18; 2.55; 1.98 \text{ \AA}$  correspond to the presence of kaolinite. Strong reflection line  $d_a = 14.20 \text{ \AA}$ , corresponding to hydromica (vermiculite), was also noted.

Fluorohydrate, like many other materials, does not simply mix with water and solidify. In order for it to acquire the desired properties and become a strong building material, it is necessary to activate its solidification process. In this study, the authors used sodium phosphate (Na<sub>3</sub>PO<sub>4</sub>) to activate fluorohydrate. Sodium phosphate 'triggers' the hydration process, that is, the interaction of fluorohydrate with water. The water reacts with anhydrous calcium sulphate, which is the main component of fluorohydrate, to form calcium sulphate hydrate [24–27]. This process leads to an increase in volume and the formation of a solid structure.

To verify the effectiveness of this method, experimental studies were conducted. The samples of fluorohydrate-based composition were prepared by mixing it with water without the added activator (reference group). These samples were aged for 28 days and then, their compressive strength was measured. As a result, the control samples were found to have a compressive strength of up to 20 MPa. Then, another group of samples was prepared, with a 3 % sodium phosphate solution added to the mixture. After 28 days, it turned out that the compressive strength of these samples reached 40 MPa. Thus, the study confirmed that activation of fluorohydrate with sodium phosphate significantly increases its strength. This makes fluorohydrate a more promising material for use in construction.

In this study, the soil at the experimental site is represented by loams with a moisture content of 15.5 %. The site area is 5 hectares, which is planned to be used for storage of gravel and crushed stone. It was suggested to use fluorohydrate as a binder to stabilize the soil. Sodium phosphate was used as an

activator for fluoroanhydrite hardening. The mixing water complied with the requirements of GOST 23732 – 2011 ‘Water for concrete and mortars’. The water-to-binder ratio was  $W/B=0.2$ .

In order to study in detail the properties of the obtained composites based on fluorohydrate and soil, several modern analysis methods were used.

One of such methods is differential scanning calorimetry (DSC). DSC measures the thermal effects that occur in a material when it is heated or cooled. In this study, DSC was used to study the phase transformations occurring in the composite when it was heated. For this purpose, composite samples were placed in a special device, a MettlerToledo TGA/DSC1 Starsystem derivatograph. The samples were heated from 60 to 1100 °C at a rate of 30 °C per minute, which allowed the thermal effects to be recorded and the changes in the material to be analysed.

Another important method of analysis is thermogravimetric analysis (TGA). TGA measures the change in mass of a sample when it is heated. In this work, TGA was used to determine, which components vaporise or decompose when the sample is heated and how the sample composition changes during the heating process. The TGA was also conducted on MettlerToledo TGA/DSC1 Starsystem derivatograph.

In order to determine the mineralogical composition of the composite, X-ray phase analysis was carried out. X-ray phase analysis was carried out on a diffractometer DRON-3 using a cobalt X-ray tube.

IR spectroscopy method was used to study the chemical bonds in the composite and to determine the presence of different chemical groups. The method is based on the fact that different chemical bonds absorb infrared radiation at different frequencies. By analysing the absorption spectrum of infrared radiation, the composition and structure of the substance can be determined. IR spectroscopy was carried out on a Shimadzu IRAffinity-1 spectrometer in the frequency range of 400 to 4000  $\text{cm}^{-1}$ .

Scanning electron microscopy (SEM) was used to study the microstructure of the composite. In this study, SEM was performed on a Thermo Fisher Scientific Quattro S scanning electron microscope at the Centre for Collective Use ‘Surface and New Materials’ of the Ural Branch of the Russian Academy of Sciences (Izhevsk, Russia). Energy dispersive X-ray spectroscopy (EDS) was used to determine the chemical composition of individual regions of the sample.

### 3. Results and Discussion

To determine the optimal ratio between soil and binder, cube samples with the dimensions of 100×100×100 mm were prepared in metal molds (Fig. 2) and exposed to semi-dry pressing on a hydraulic press under a pressure of 20 MPa.



**Figure 2. 100×100×100 mm cube samples with fluoroanhydrite to loam ratio 40:60 by weight.**

The compressive strength of the samples at the age of 5 and 28 days is presented in Table 1.

**Table 1. Compressive strength of the samples.**

No.	Composition	Compressive strength, [MPa] at the age of	
		5 days	28 days
1	Fluoroanhydrite 100 %	6	30.7
2	Fluoroanhydrite + Sodium phosphate	10	40.2
3	80 % Fluoroanhydrite + 20 % Loam	13	17.3
4	60 % Fluoroanhydrite + 40 % Loam	4.3	8.9
5	50 % Fluoroanhydrite + 50 % Loam	2.4	6.3
6	40 % Fluoroanhydrite + 60 % Loam	1	4.6

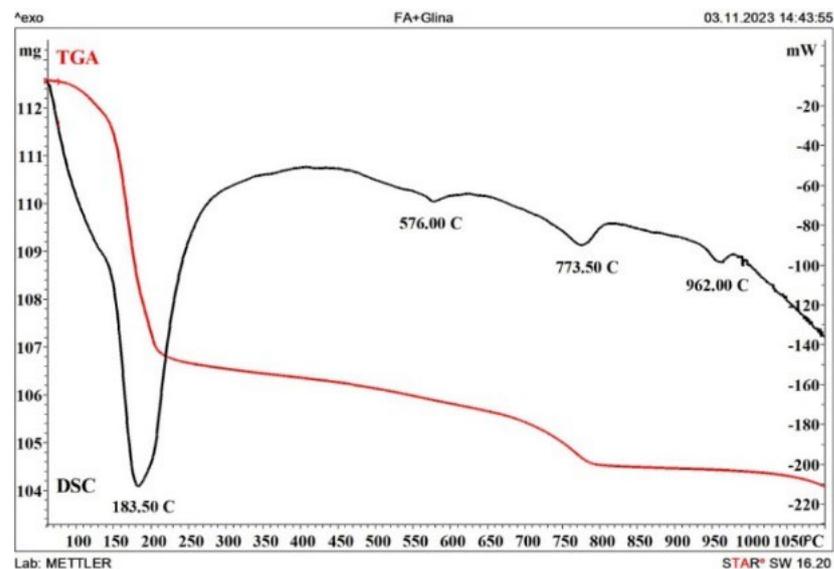
In the study, samples of pure fluorohydrate were prepared, mixed with water and kept for 28 days to fully harden. The compressive strength of these samples was then measured. The tests showed that it reached 30.7 MPa. This means that fluorohydrate itself already has a fairly good strength. Further studies allowed to reveal the possibility of further strengthening of fluorohydrate. For this purpose, an activator, sodium phosphate, was added. Sodium phosphate is a substance that can accelerate and enhance the hydration process of fluorohydrate. Hydration is the interaction of fluorohydrate with water, resulting in the formation of calcium sulphate hydrate, which makes the material stronger. New samples of fluorohydrate were mixed it with water, sodium phosphate in the form of 3 % solution was added. These samples were also aged for 28 days. Then, their compressive strength was measured. The result showed that the strength of the samples with sodium phosphate reached 40.2 MPa. Thus, the study showed that activation of fluorohydrate with sodium phosphate significantly increases its strength. This makes fluorohydrate an even more promising material for use in construction because it allows for the creation of stronger and more reliable structures.

As a result of the tests, three optimal compositions were selected (Table 2), which can be used as road bases according to the standards [10]. It is noted that with an increase in the proportion of fluoroanhydrite in the composition, the content of calcium sulfate dihydrate also increases (Fig. 7a), whereas the content of hydroaluminosilicates decreases. Due to the fact that calcium sulfate dihydrate has low water resistance, an increase in its amount in the samples (for example, Sample 3) is accompanied by a decrease in the softening coefficient.

**Table 2. Optimal compositions.**

No.	Composition	Sample weight, [g]	Sample weight after saturation with water, [g]	Compressive strength of the sample, [MPa]	Compressive strength of a water-saturated sample, [MPa]	Water absorption, W, [%]	Softening coefficient, Kp
1	80 % Fluoroanhydrite + 20 % Loam	1969	2140	17.3	12.3	8.68 %	0.71
2	60 % Fluoroanhydrite + 40 % Loam	1994	2130	8.9	7.3	6.82 %	0.82
3	50 % Fluoroanhydrite + 50 % Loam	1949	2150	6.3	4.1	10.31 %	0.65
4	40 % Fluoroanhydrite + 60 % Loam	1944	2230	4.6	2.6	14.71 %	0.56

In order to study the structure and properties of the composition, physical and chemical analyzes of the samples at the age of 4 months were carried out.



**Figure 3. DTC and TGA spectra of a mixture of fluoroanhydrite (40 %) and loam (60 %) mixed with 3 % sodium phosphate solution.**

In order to find out the changes occurring in the composite material during heating, two types of analyses were carried out: differential thermal calorimetry (DTC) and TGA. DTC allowed to detect thermal changes in fluorohydrate when it was heated (Fig. 3). This explains how the energy within the material changes and what processes occur within it. TGA focused on the mass change of the sample when heated. It showed which substances vaporise or decompose when heated and how the composition of the material as a whole changes. The results of these analyses revealed a number of interesting thermal effects occurring in the composite when it is heated:

At around 183.5 °C, an endothermic peak is observed. This means that at this point there is heat absorption by the material. This peak is due to dehydration of gypsum dihydrate and hydrosilicate formations such as calcium aluminosilicate hydrates. There was a release of water from the material when it was heated. In the temperature range of 100 to 350 °C, the composite lost about 5.6 % of its mass.

At about 400 °C, a weak exothermic peak was observed. This means that at this point, there is a release of heat by the material. This peak is due to the rearrangement of the calcium sulphate crystal lattice resulting in the formation of insoluble anhydrite.

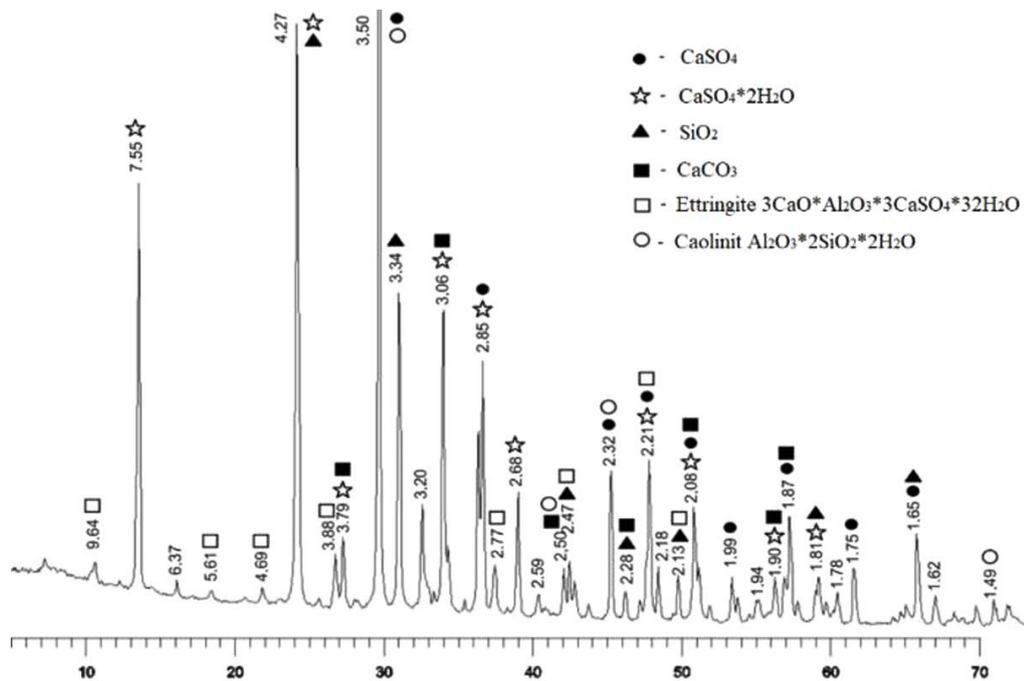
When the composite was heated to a temperature of about 400 °C, the material started to release heat, an exothermic effect was obtained. This heat release is due to the rearrangement of the internal structure of calcium sulphate. When calcium sulphate is heated, a new mineral, anhydrite, is formed. Anhydrite is a more stable form of calcium sulfate that does not dissolve in water. Thus, when the composite is heated, there is a 'transition' of calcium sulfate into anhydrite. This process is accompanied by the release of heat, as recorded in the experiment.

When the composite is heated to a temperature of 576 °C, heat absorption (an endothermic effect) occurs. This heat absorption is due to the rearrangement of the internal structure of silicon oxide. Silicon oxide is a mineral that is present in loams. The silicon oxide is heated to a specified temperature and the recrystallisation process begins. The recrystallisation of silicon oxide causes it to become more resistant to high temperatures. This is an important factor because the composite can be used in a variety of environments, including elevated temperatures.

When the composite is heated to a temperature of about 773.5 °C, it absorbs heat again, the endothermic effect starts again. And this time, the heat absorption is due to dehydration. In the composite at this temperature, there is a release of water from calcium silicate hydrates, potassium aluminosilicate hydrates, and calcium carbonate. These are substances that are part of the loam and as a result of interaction with fluorohydrate have formed hydrates, that is, compounds that contain water. When heated to 773.5 °C, these hydrates lose their water and as a result, the mass of the composite is reduced by 1.8 %. This is similar to how a wet sponge loses weight when dried.

At 962 °C, there is an endothermic peak associated with the breakdown of the crystal lattice and crystallisation of amorphous calcium aluminosilicate products.

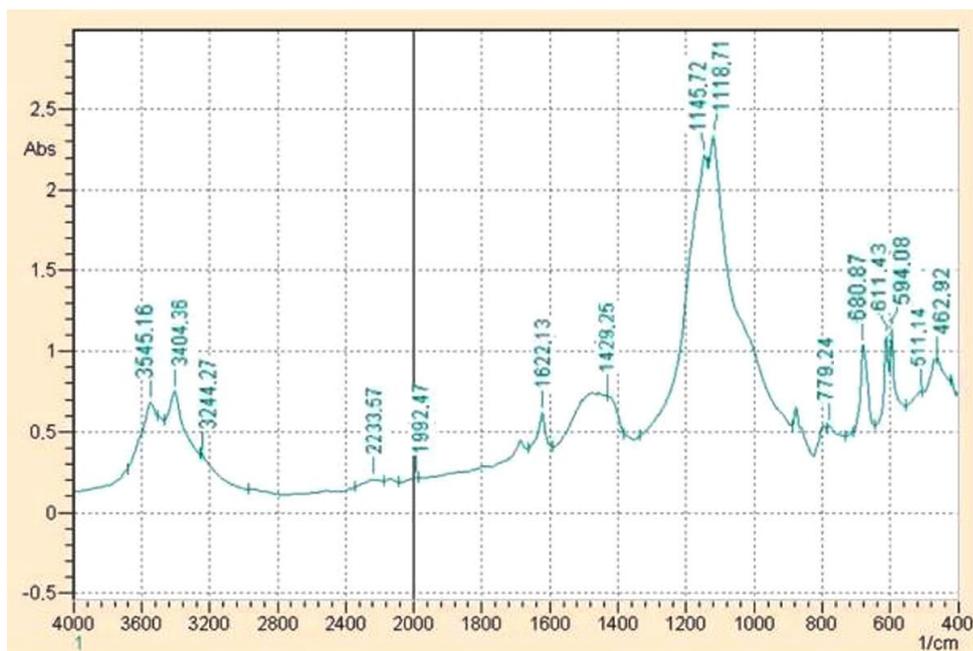
These data help scientists better understand the properties of the composite and the processes that happen to it when heated. This is important in order to prevent the material from degrading during application and to ensure its reliability and durability.



**Figure 4. X-ray phase analysis of a mixture of fluoroanhydrite (40 %) and loam (60 %) mixed with a 3 % sodium phosphate solution.**

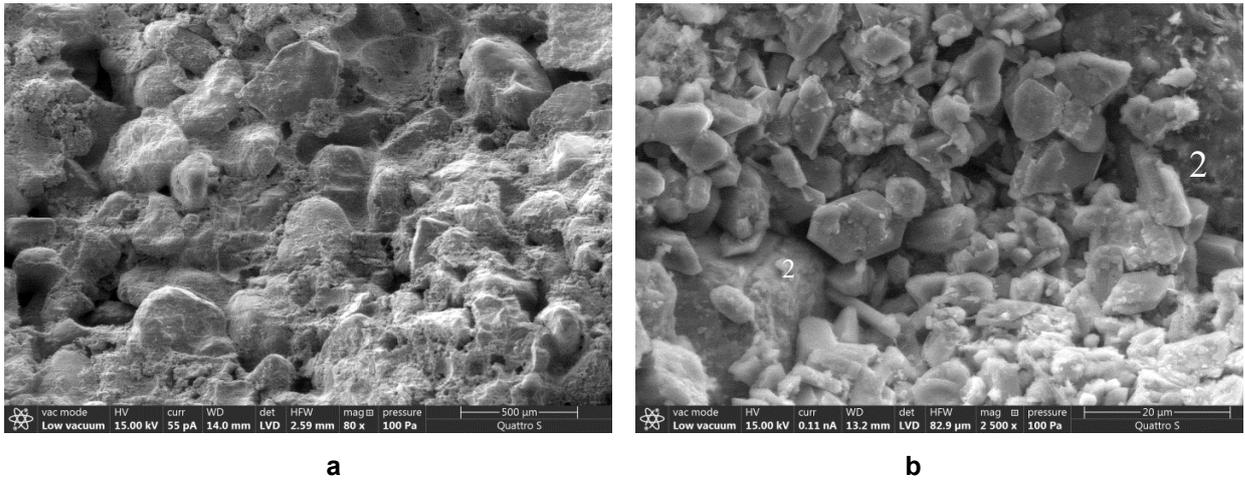
X-ray phase analysis (Fig. 4) of the composition showed the presence of calcium sulfate dihydrate ( $d_{\alpha} = 7.55; 4.27; 3.79; 2.68; 2.11; 2.08 \text{ \AA}$ ), which is formed in the process of anhydrite ( $d_{\alpha} = 3.50; 2.85; 2.08 \text{ \AA}$ ) activation with sodium phosphate. Reflection lines corresponding to quartz ( $d_{\alpha} = 3.34 \text{ \AA}$ ) and calcium carbonate  $\text{CaCO}_3$  ( $d_{\alpha} = 3.88; 3.06; 2.08; 1.87 \text{ \AA}$ ) were also noted. The formation of aluminosilicate (kaolinite) and ettringite  $3\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot 3\text{CaSO}_4\cdot 32\text{H}_2\text{O}$  is suggested by the presence of reflection lines  $d_{\alpha} = 3.50; 2.50; 2.32; 1.49 \text{ \AA}$  and  $d_{\alpha} = 9.64; 5.61; 4.69; 3.88; 2.77; 2.21 \text{ \AA}$ , respectively.

IR spectral analysis (Fig. 5) of the composition confirmed the presence of gypsum dihydrate (absorption lines  $580.87; 1145.72; 1118.71; 1622.13; 3404.36$  and  $3545.18 \text{ cm}^{-1}$ ), anhydrite ( $1145.72; 611.43; 1400 \text{ cm}^{-1}$ ) and ettringite ( $1118.71 \text{ cm}^{-1}$ , in the region of  $1675 \text{ cm}^{-1}, 3404.36 \text{ cm}^{-1}$ ). Absorption lines at  $1429.25 \text{ cm}^{-1}$  and in the region of  $874 \text{ cm}^{-1}$  corresponding to calcium carbonate were also noted. The presence of ettringite is associated with the interaction of aluminosilicates in the composition of loam and calcium sulfate in the composition of fluoroanhydrite. The formation of ettringite was later confirmed by the results of energy dispersive analysis (Fig. 10).

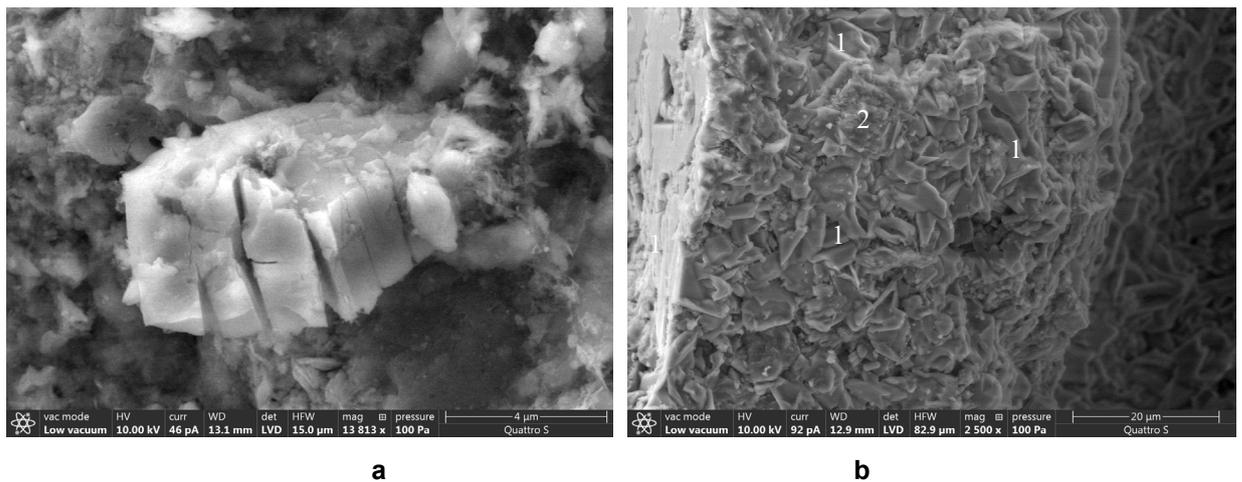


**Figure 5. IR spectrum of a composition based on fluoroanhydrite (40 %) and loam (60 %) activated with sodium phosphate.**

Microstructure analysis performed on a Thermo Fisher Scientific Quattro S scanning electron microscope showed that the hydration of fluoroanhydrite and the formation of new hydration products based on gypsum dihydrate of prismatic (Fig. 6b) and acicular structure (Fig. 7a) contributed to the compaction of the matrix (Fig. 6a, b).



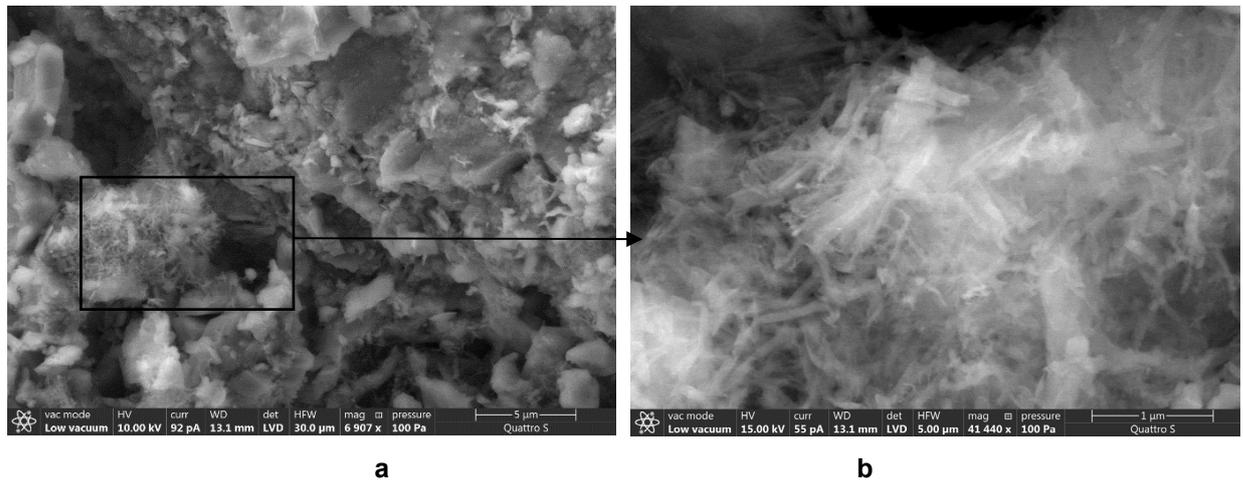
**Figure 6. Composition of a mixture of fluoroanhydrite (40 %) and loam (60 %), mixed with a 3 % sodium phosphate solution: a) general view at 80-fold magnification, b) formation of prismatic crystals based on gypsum dihydrate (1) between loam particles (2).**



**Figure 7. Crystal hydrates of gypsum dihydrate with a needle-like structure (a), compaction of gypsum crystals (1) by hydration products (2) when interacting with loam minerals in a composition of a mixture of fluoroanhydrite (40 %) and loam (60 %), mixed with a 3 % sodium phosphate solution (b).**

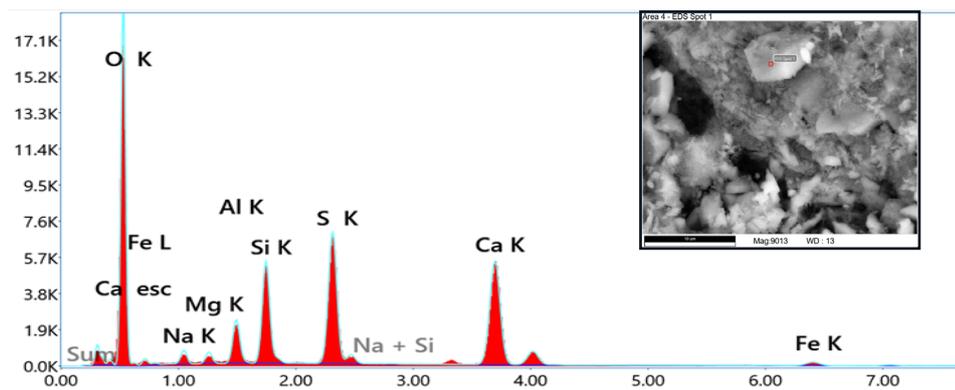
Studying the microstructure of the composite material under the microscope (Figs. 7, 8) showed interesting results. It turned out that the gypsum matrix formed from fluorohydrate was not just mixed with loam minerals, but interacted with them. This interaction led to the formation of new compounds, calcium and potassium hydrosulfoaluminates. These new compounds are located inside the composite and act as a 'fastener', additionally strengthening the structure of the material. They seem to 'bind' the particles of gypsum and minerals of loam, making the composite more dense and strong (Fig. 8a, b). The formation of hydrosulfoaluminates also gives the composite increased water resistance. This means that the material is less affected by moisture and does not swell or deteriorate when exposed to water. The formation of hydrosulfoaluminates increases the water resistance of the composite, which is an important factor for the durability of the pavement.

Thus, the interaction between fluorangydrate and loam leads to the formation of new compounds that improve the properties of the composite, making it stronger and more resistant to moisture. This means that fluorangydrate can be used as an effective and reliable material for soil stabilization in road construction.



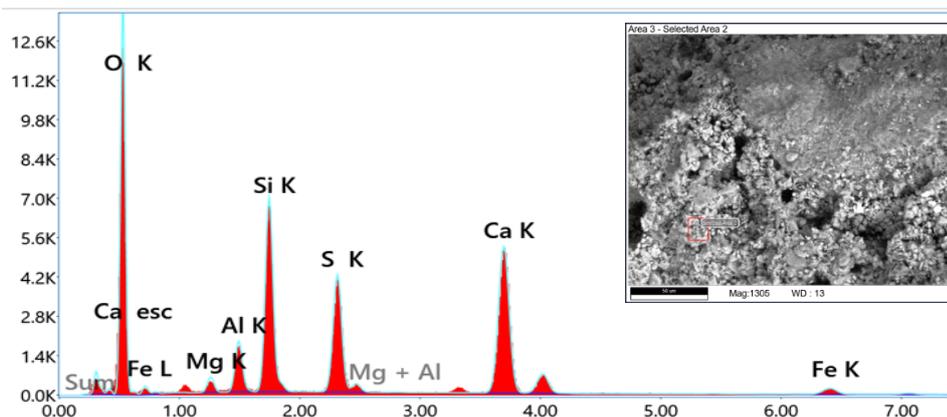
**Figure 8. Formation of calcium hydrosulfoaluminates in the contact zone between gypsum crystals and clay mineral in the composition of a mixture of fluoroanhydrite (40 %) and loam (60 %), mixed with a 3 % sodium phosphate solution: a) at 6907-fold magnification (G – gypsum crystal), b) at 13813-fold magnification (E – ettringite).**

In the process of fluoroanhydrite hydration, gypsum dihydrate  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  is formed, which is partially crystallized on the surface of loam particles in the form of large crystals (Fig. 9). Fig. 10 shows that the influence of an electron beam during microanalysis of gypsum crystals (Fig. 9) results in a partial dehydration of these crystals (Fig. 7a) even despite the presence of a 'shell' containing silicon and aluminum atoms (in the composition of hydroaluminosilicates) around them. As a result, a layered structure (Fig. 7a) is formed due to the removal of water molecules from the internal layers of gypsum dihydrate, which additionally confirms the interaction of fluoroanhydrite and loam in the composition.



**Figure 9. Energy dispersive analysis of a gypsum crystal.**

Energy dispersive analysis confirmed the formation of calcium hydrosulfoaluminates in the contact zone between loam minerals and fluoroanhydrite (Fig. 10). Calcium (Ca), sulfur (S), aluminum (Al), and oxygen (O) atoms were noted on the spectrum, which are present in calcium hydrosulfoaluminates  $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}$  (ettringite).



**Figure 10. Energy dispersive analysis of hydration products in the contact zone between fluoroanhydrite and loam particles in a composition of a mixture of fluoroanhydrite (40 %) and loam (60 %) mixed with a 3 % sodium phosphate solution.**

The study of fluorangydrate and loam composite showed that its strength is not just the result of mechanical mixing of different materials. New chemical bonds are formed between the fluorangydrate particles and the loam minerals. These new bonds bind the particles together and make the material stronger. In addition, the interaction between the fluorangydrate and the loam leads to the formation of new compounds called calcium and potassium hydrosulfoaluminates. These compounds make the composite stronger and more resistant to various influences such as moisture or temperature variations. Thus, the study showed that the strength of the composite is not only due to physical bonding but also due to chemical interactions between its components. This is an important factor that makes fluorohydrate a promising material for use in construction.

#### 4. Conclusions

In this paper, fluoranhydrite composition designed for road base reinforcement was described. This composition consists of fluorangydrate mixed with loam and 3 % sodium phosphate solution. The conducted research has shown:

- Fluorangydrate by itself has sufficient strength, reaching 30.7 MPa at the age of 28 days.
- Activation of fluorangydrate with sodium phosphate significantly increases its strength, reaching 40.2 MPa at the age of 28 days.
- The optimum ratio of fluorangydrate and loam in the composition is 60/40.
- The compressive strength of the composition with this ratio is 8.9 MPa in the dry state and 7.3 MPa in the wet state at the age of 28 days.
- The water absorption of the composition was 6.82 % and the softening coefficient was 0.82.
- Physico-chemical studies have shown that the strength of the composition is provided not only by physical bonding but also by chemical interaction between fluorohydrate and loam.

The conducted research proves that fluorangydrate can be successfully used as a binder for stabilization of weak soils. This allows to reduce the cost of works due to the use of available and inexpensive material – fluorohydrate. It also provides an opportunity to recycle waste products of hydrofluoric acid production, reducing the environmental load. The use of fluorohydrate is the most promising for stabilisation of soils for pavement bases on roads of IV–V categories, where there are no increased requirements for strength and frost resistance.

The results of the study can be used in road construction for stabilization of soils, which will allow to create stronger and more durable roads at minimum cost and have a favourable impact on the environment. The use of fluorohydrate for soil stabilisation will improve the environmental situation in regions with a developed chemical industry by recycling industrial waste and reducing its disposal in landfills.

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Received 07.11.2024. Approved after reviewing 24.10.2025. Accepted 24.10.2025.