Ecological engineering in the construction and exploitation of roads with technogenic materials

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Abstract. The article describes the developed engineering technological measures. They increase the operation life of road structures with the use of technogenic non-toxic materials. It is recommended to use activating additives to accelerate the process of road mixtures hardening. The introduction of gypsum anhydrite waste in an amount of 5\% into the crushed-nepheline road mixtures provides an increase in their strength characteristics by 1.8–2.2 times and increases the frost resistance of the road surface. This allows recommending the developed structure of region road pavement in regions with an average monthly air temperature of the coldest month from -15°C to -30°C. The conducted industrial tests of the proposed engineering technological measures confirmed the results of the research and provided their practical implementation in the technology of laying the lower base of the road pavement.

1. Introduction

One of the most important problems of the road industry in Russia is the extremely low durability of road structures. The actual life is significantly reduced compared to the standard life due to the rapid growth of intensity, speed and axial loads. This requires an annual increase in the volume of repairs and additional financial investments in the road industry. The successful development of the construction complex depends on the level of solving interrelated problems of resource and energy saving. Therefore, at present, one of the topical areas of construction materials science is the researches on the creation of new effective composites based on technogenic raw materials, characterized by low cost and meet modern requirements of durability and operational reliability\cite{1}.

The United States abandoned the production of its own cement clinker and almost stopped the development of limestone quarries, based on the interests of environmental protection. Cement clinker is imported from Mexico and produced by Blended Cements, mixing clinker with its own technogenic waste or products of their processing\cite{2,3}.

At the same time, leading Russian institutions have developed and tested technologies for the production of composite binders based on secondary industrial products\cite{4}.

From the position of providing raw materials, the construction industry should take into account the progressive increase in prices for natural mineral resources used in the production of binders and aggregates for cement\cite{5}. The most important raw material reserve of the construction complex is multi-tonnage secondary products of the industry. Their complex use will allow forming rational structures in new composite materials as a result of physical and chemical interactions\cite{6}.
Currently, there is a large shortage of sand and stone materials to solve the tasks, which only in the road construction of the Russian Federation reaches 5-6 million m³ [7]. In Russian and foreign practice of road construction such local constructional materials as soils reinforced with various binders are widely used. Lime metallurgical slags, waste of mining and volcanic production are widely used abroad [3, 8-10]. Up to 900,000 tons of lime is used annually to strengthen the soil in the road construction, which makes it possible to strengthen approximately 4-5 million m³ of soil. In the Federal Republic of Germany lime consumption in road construction reached 150 thousand tons in 1980 [3]. The materials strengthened by mineral binders are subject to cracking under the influence of time-varying temperature and humidity factors and are characterized by insufficient frost resistance [11].

To ensure frost resistance, fortified soils could be widely used in road construction. Scientific research in the field of improving the frost resistance of soils has been conducted for a long time. However, for the Siberian region, the problem of ensuring frost resistance of fortified soils in the structural layers of road pavement remains unsolved.

The analysis of the use of road construction materials with the involvement of industrial waste showed that there are two interrelated tasks to solve the problem of their utilization: providing the industry with cheap road construction materials and preventing the negative impact of waste on the environment.

2. Purpose of research
It is necessary to substantiate and develop practical recommendations to ensure frost resistance of soils reinforced with technogenic binders in the road construction in Siberia while solving environmental problems.

3. Obtained result
It was established by the results of the samples studies of sand-nepheline mixture that when used as a binder of one nepheline sludge, a slow set of strength of the samples is observed «figure 1». As additives activating nepheline sludge, gypsum anhydrite waste (GAW) of JSC “RUSAL Achinsk” was tested. Researches of the strength properties of samples prepared from sand-nepheline mixtures have shown that with the addition of crushed gypsum anhydrite waste in an amount of 5 - 20%, the strength of the samples increases by 1.8–2.2 times «figure 1». It is noted that even at minimum 3-5 % dosages of gypsum anhydrite waste in the road mixture, high compressive strength of samples at the age of 7 days is provided-6.1 MPa, 14 days -9.8 MPa and 28 days of hardening – 10.7 MPa. The kinetics of the compressive strength of the nepheline-sand mixture without GAW additives to 90 days reached only 6.3 MPa, while the compressive strength of the same samples with the addition of 5% GAW to 90 days of exposure was 15.0 MPa. The change in tensile strength at bending was similar and at a dosage of 5% GAW in nepheline-sand mixture at 90-day exposure was 2.8 MPa.

The influence of the input of activating additives in the strengthening of various soils with nepheline binder was studied.
Figure 1. Kinetics of changes in the compressive strength (a) and tensile strength at bending (b) of samples from sand-nepheline mixture (1) and with the addition of 5% gypsum anhydrite waste (2).

So it is noted that lighter soils (sands) require strengthening smaller dosages of gypsum anhydrite waste as part of a complex gypsum binder in an amount of 4-5.5% by weight. «figure 2». When strengthening heavier soils (loams, clays) to ensure the required strength characteristics (compressive strength of $R_{szh}$ more than 6 MPa), it is necessary to increase the dosage of GAW to 6-7.5%.

Figure 2. The effect of GAW additives in nepheline binder on the compressive strength with the strengthening of various soils (28-day exposure).

Analysis of the strength set kinetics of the samples of reinforced soil showed a similar character of hardening for sand, loam and clay, while the compressive strength at 28 days of hardening for sand was significantly higher than for clay samples «figure 2».

The tests of fortified soils for frost resistance showed that the input of 5% of gypsum anhydrite waste into the road mixture increases its frost resistance. At the same time, this mixture at the age of 28 days had a brand of frost resistance F25, which allows it to be used in the layers of the pavement base of the capital type in areas with an average monthly air temperature of the coldest month from -15°C to 30°C. The research of road mixtures allowed recommending the use of these technogenic materials in the construction of road pavement. The choice of construction technology was carried out taking into account the category of the road construction, the road-climatic zone, the type of soil, the
type of binder and additives, as well as the means of mechanization used. For this purpose, technological regulation was developed for the complex of works on the device of the lower layer of the base from the crushed stone mixture of the fraction 0-40mm treated with 30% nepheline sludge with the addition of 5% gypsum anhydrite waste. Limestone of Mazul mine was used as a crushed stone component for the base of the road pavement. As part of limestone, calcium carbonate accounts for 50-95% of its mass. The rest is represented by minerals: ankerite, quartz, traces of Muscovite. Nepheline (belite) sludge, which is a waste of alumina production, was used as a binder in strengthening the crushed stone component. According to the granulometric composition, nepheline sludge of the current production is a fine-grained material with a grain size of 0.08-3 mm. Nepheline sludge due to its high porosity and good water-holding capacity at a humidity of up to 20% is slightly frozen, and can be used without additional processing. It is easily accessible for excavation even in winter and is suitable for transportation in road and rail transport. Mineralogy of nepheline sludge is presented by more than 80% of dicalcium silicate $2\text{CaO} \times \text{SiO}_2$ providing the sludge with it knitting activity. When compacting wet nepheline sludge current production and crushed-sand mixture have the ability to consolidate into a monolithic water-resistant material and further gain strength over time. The activity of nepheline sludge is significantly increased with the introduction in its composition gypsum-containing additives, which, depending on the properties and quantities play the role of activators of hardening and increase the strength properties of mixtures on the basis of the sludge. As a gypsum-containing component, gypsum anhydrite semi-product is used for the base of the road pavement - a production waste of fluoride aluminum of the Achinsk alumina plant, presented at 93-95% by a mixture of anhydrite, gypsum and semi-aqueous calcium sulfate. The distribution of minerals in the gypsum anhydrite semi-product has the following quantitative composition: $\text{CaSO}_4 \cdot 59.0\%$, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \cdot 30.4\%$, $\text{CaSO}_4 \times 0.5\text{H}_2\text{O} \cdot 5.4\%$. Anhydrite wastes are slowly hardening cement. To increase the activity of the gypsum anhydrite component, it must be crushed in a ball mill and subsequently mixed with wet nepheline sludge. Engineering technological measures included the following operations:

- at first nepheline sludge (30% by weight.) and gypsum anhydrite waste (5% by weight.) at an air temperature not lower than 0°C were added to the crushed-sand mixture (65% by weight.).
- mixing of the mixture was carried out on the construction area of an industrial enterprise, with the help of an auto grader DZ-98. Nepheline sludge was delivered to the place of mixing in a wet state. Gypsum-containing component is in a dry powdered state. In most cases, before laying the mixture, additional moisture was not required. If the mixture prior to loading had a lack of humidity, then it is wetted.
- then the mixture was loaded in the places of preparation by the front loader and delivered to the place of work by dump trucks, and the laying of the mixture is carried out by the paver ROADTEC RP-230 «figure 3».

![Figure 3. Loading of road mixture by the loader in dump trucks on the production area (a) and its](image-url)
laying by the paver in the base of the road pavement (b).

Structural and chemical transformations of the action of gypsum anhydrite waste in the composition of gypsum-nepheline binder at the first stage can be represented by the interaction of calcium sulfate with the calcium aluminate and calcium hydroaluminate contained in the sludge:

\[ 3\text{CaO} \cdot \text{Al}_2\text{O}_3 + 3(\text{CaSO}_4 \cdot 2\text{H}_2\text{O}) + 26\text{H}_2\text{O} = 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O} \]  

\[ 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{H}_2\text{O} + 3(\text{CaSO}_4 \cdot 2\text{H}_2\text{O}) + 19\text{H}_2\text{O} = 3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O} \]  

The ettringite formed at the first stage as a result of the reaction (2) accelerates the process of hardening of the road crushed stone-nepheline mixture with the addition of gypsum anhydrite waste. In the subsequent stage at 14-28 daily age of the samples the gradual hydration of bicalcium silicate with the formation of its hydrated forms (\( \text{Ca}_2\text{SiO}_4 \cdot \text{H}_2\text{O}, \text{Ca}_{1.5}\text{SiO}_{3.5} \cdot \text{H}_2\text{O}, \text{Ca}_2\text{SiO}_4 \cdot 0.35\text{H}_2\text{O} \)) occurs [6].

In the construction of the pavement base, it is important that the road hardening mixtures retain a certain mobility and compaction during the day. It is noted that the duration of the technological gap between the preparation and compaction of road mixtures in the case of the use of nepheline slurries without activators was up to 48 hours; with the use of additives of gypsum anhydrite waste was reduced to 6-7 hours. This time was enough to perform road construction work on laying the base of the pavement and at the same time provided workability of the road surface.

The use of nepheline sludge as a component of the road mixture is due to the absence of toxic properties in it, which is confirmed by studies by an experimental method of biotesting, according to which the sludge is classified as non-hazardous waste for the environment. It should also be considered that sludge acquires a monolithic state similar to the concrete of the M300 brand in the process of laying the base of the road pavement. In addition, nepheline sludge has a low specific activity of natural radionuclides (66.9 Bq/kg) and does not exceed the hygienic standard established for industrial waste used in the manufacture of construction materials of class 1 370 Bq/kg.

4. Conclusion

Researches have shown that to ensure the required performance properties of road crushed stone-nepheline mixtures, it is necessary to use activating additives that accelerate the hardening process and increase the quality parameters of hardened materials.

The use of engineering technological measures for the input of additives with gypsum anhydrite waste into the road mixture in an amount of 5% accelerates the process of structure formation and provides an increase in the strength characteristics of the sample by 1.8–2.2 times. At the same time, high frost resistance is achieved, which makes it possible to recommend the developed hardening mixture for use in the layers of the base of the road pavement of the capital type in areas with an average monthly air temperature of the coldest month from -15°C to -30°C.

Industrial tests were conducted for the preparation of developed solid mixtures. Industrial tests on the device of the road base of the experimental sections of the road were carried out. They confirmed the practical recommendations on the results of scientific research. The strength of the developed hardened road mixtures is on average 1.5 times higher than that of the samples from the road mixtures of the base made according to the traditionally used construction technology.

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