# Investigation of the influence of negative temperatures on the technological properties of belite sludge

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**Abstract.** The paper describes the characteristics of belite sludge - a large-tonnage waste of alumina production. The influence of negative temperatures on the technological properties of the sludge was investigated. The regularities of sludge cooling during its excavation, long-term storage and in the technological process of structural layers' construction in winter conditions have been studied. Recommendations have been developed for the construction of foundations (coatings) from sludge and sludge-mineral materials at temperatures below minus 20°C. The implementation of research results helps to prolong the construction season, reduce material consumption and increase durability during construction, reconstruction and repair of transport infrastructure objects.

**Keywords:** Transport infrastructure, Transport, Construction of transport objects, Belite sludge, Sludge-mineral material, Winter period, Heat loss, Workability, Critical temperature.

## 1 Introduction

One of the ways to increase service life durability of road structures is the construction of monolithic pavement bases. The service life of non-rigid pavements with monolithic bases made of materials treated with mineral binders is 1.5-2.0 times longer than with bases made of discrete materials [1,2]. The growth in the pace of road construction is significantly constrained by the seasonal nature of the construction of such foundations. The most progressive method for arranging such bases is the method of early freezing, which is based on freezing the compacted material at the stage of formation of a coagulation structure, that is, before the formation of irreversible rigid crystalline bonds [3]. Moreover, the greatest effect is achieved by replacing Portland cement with slow-hardening clinker-free binders, for example, slag binders [4,5].

Belite sludge is of particular interest - a large-tonnage waste of alumina production, which, without additional costs for drying and grinding, due to the high content of belite ($C_2S$), has the properties of a slow-hardening binder. Recommendations have been developed for the use of this material in the construction of monolithic layers of road and airfield coating in summer time [6,7].

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The use of sludge in the construction of structural layers in winter period should help to increase the pace of construction by simplifying the technology and extending the construction season. In addition, an increase in the volume of use of this waste will help to improve the environmental situation.

## 2 Belite sludge properties

Belite sludge is formed during the production of alumina (aluminum oxide) from nepheline and bauxite ores by sintering. Alumina is isolated by hydrothermal leaching, and the sandy semi-product - sludge is fed to the dump through a sludge pipe. As a result of the technological process of alumina production, partial hydration of sludge grains occurs with the formation of hydrate shells on their surface, which are predominantly in a gel-like state. Depending on the processed ore, belite sludge is subdivided into nepheline and bauxite [8, 9].

In terms of phase composition, nepheline sludge is mainly a mixture of silicates, hydrosilicates (20-30%) and calcium hydroaluminates (3-5%), hydroferrites, carbonates. The $C_2S$ content in nepheline sludge is 70-85%. Bauxite sludge consists of $C_2S$ (40-55%), calcite, magnetite, hematite, hydrogarnet, gibbsite, perovskite, quartzite. Consequently, slimes are polymeric materials, in which the predominant presence of polyamorphic belite, β, cemented by a mass of hydrates, is clearly recorded. Belite gives sludge the ability, at the moment of compaction in a wet state, to turn into a waterproof monolith and increase its strength through many years. Belite sludge, depending on its activity, is subdivided into highly active (nepheline), active and low-active (bauxite) [10].

The physical and mechanical properties of belite sludge are presented in Table 1.

**Table 1.** Physical and mechanical properties of belite sludge.

| **Properties** | **Indicators** | |
|---|---|---|
| | **Nepheline sludge** | **Bauxite sludge** |
| Size module | 1.2-1.7 | 1.1-2.2 |
| True density. g/cm³ | 2.91 -3.04 | 3.00 – 3.16 |
| Bulk density when wet. kg/m³ | 900-1100 | 1110-1300 |
| Specific surface area. cm²/g | 300 – 750 | |
| Microporosity. microns | 35 - 60% at a pore size from 10 to 1000 | |
| Thermal conductivity coefficient at standard density. W / (m×K) | 0.57-0.66 | 0.60-0.70 |
| Optimum humidity.% | 23-26 | 22-25 |
| Average density in a compacted state at optimum moisture content under a load of 15 MPa. t/m³ | 1.8-1.85 | 1.85-1.9 |
| Compressive strength. MPa: | | |
| - immediately after compaction under a load of 15 MPa;<br>- after 90 days;<br>- after 1 year. | 1.0-1.2<br>4.0-6.0<br>9.0-10.0 | 0.7-1.0<br>3.0-5.0<br>7.0-8.0 |
| Ultimate tensile strength in bending. MPa: | | |
| - after 90 days;<br>- after 1 year. | 1.6-2.4<br>2.6-3.0 | 1.2-2.0<br>2.1-2.5 |

The data presented indicate that nepheline and bauxite slimes have similar properties, which predetermines the same area of their application. In ordinary form (without additional grinding), compacted at an optimal moisture content of 22-26%), sludge in terms of strength, with a standard hardening period of 90 days, corresponds to the M40-M60 brands. At the same time, the tendency towards further gaining strength remains due to the large reserve of unhydrated binder.

## 3 Theoretical and experimental research

For the development of winter technology, it is necessary to study the effect of frost effects on the density of the sludge, establish its freezing point, study the compaction of the sludge in the range of negative temperatures, the regularities of material cooling during the excavation process, long-term storage and in the technological process of structural layers' construction in winter period.

The effect of frost exposure on the density of sludge and sludge-crushed stone material was studied by fixing the change in the volume of samples after freezing using a specially designed device. During the experiment, the methods of mathematical planning were used. The density of the material after freezing was characterized by loosening coefficient ($L_c$).

$$L_c = \frac{\gamma^I}{\gamma} \tag{1}$$

where: $\gamma$ is the highest material density before freezing, g/cm³, $\gamma^I$ is the material density after freezing, g/cm³.

The loosening coefficient (output parameter) is a function of three main factors: the moisture content of the material (15 - 24%), its initial density (1.34 - 1.6) and the freezing temperature (minus 5 - minus 50 ° C).

The results of the experiment showed that $L_c$ decreases by a maximum of 0.01, which indicates an insignificant decompaction of materials from frost exposure. Moreover, at a standard density, at any values of humidity and freezing temperature, samples from sludge and sludge-crushed stone material practically do not loosen up. This effect is explained by the presence of hydrate shells on the surface of the sludge grains, which are predominantly in a gel-like state, which take on the pressure from the frozen water and squeeze out part of the unfrozen water into the reserve pores, since the sludge has high microporosity in Table 1 [4, 11, 12]

The temperature of the onset of freezing of the sludge was determined by the thermoelectric method using the methods of mathematical planning of the experiment. In the experiment, the humidity varied from 15 to 26%, the density of the skeleton from 1.35 to 1.6 g / cm³ and the content of water-soluble alkaline compounds from 0.32 to 0.52%. Based on the experimental data, the temperature of the onset of freezing of belite sludge was set at minus 2°C.

Compaction was studied by pressing samples from sludge with optimal moisture content under a standard load of 15 MPa for 3 minutes at temperatures ranging from 20 to -10°C.

Compaction was characterized by the compaction coefficient ($C_c$), which was defined as the ratio of the density of the material after compaction at a given temperature to its standard density. It was found that with a decrease in temperature, the compaction decreases, but even at - 6°C, compaction coefficient ($C_c$) is 0.98, which meets the regulatory requirements for road bases. At temperatures up to - 2°C inclusive, the sludge is compacted in the same way as at positive temperatures, which, taking into account the set temperature of the beginning of its freezing, is the basis for taking the temperature - 2°C as critical.

Thermo-technical calculations for the heat loss of sludge during its transportation by rail in dump type gondola cars, in dump trucks, as well as during long-term storage in a stack were performed by the finite element method using a set of programs for calculating a non-stationary nonlinear field in a three-dimensional setting [13]. It has been established that the sludge can be used for the construction of foundations in winter, if it is in the dump cars no longer than:

- 3 days at an average (during transportation) air temperature ($T_a$) -10ºC and the initial temperature of the sludge at the moment of the end of loading ($T_i$) 5ºC;
- 1.5 days at an average (during transportation) air temperature ($T_a$) - 20°C and the initial temperature of the sludge at the moment of the end of loading ($T_i$) 10°C;
- 1 day at an average (during transportation) air temperature ($T_a$) -30°C and the initial temperature of the sludge at the moment of the end of loading ($T_i$) 15°C.

The sludge, which is in dump type cars for a longer time, will have an average volume temperature below the critical one (-2 ºC) so it is advisable to take it out, place and store in the track warehouses and use it in summer period.

Calculations have shown that when transporting sludge in a heavy-duty vehicle with a body heated by exhaust gases, its temperature does not decrease significantly, and at low (up to 2°C) initial temperatures of the material, its average volumetric temperature even rises by 0.1 - 1.2°C.

Analysis of the calculated temperature and technological parameters of sludge stored in the warehouses showed that, provided that the material is excavated in summer and the surface of sludge is insulated, for example, with 20–25 cm thick fast-hardening foam (FHF), the material remains workable throughout the winter period [13].

To study the regularities of the cooling of the slime layers, a laboratory experiment was carried out to simulate the two-sided (top and bottom) freezing of the material [11]. Sludge of optimal moisture content (25%), at given initial temperatures ($T_i$) 0, 10, 20°C was placed in asbestos columns with a diameter of 14 cm and a height of h - 7, 15, 25, 35 cm, which were installed on a frozen soil base and insulated along the entire lateral surface. The columns were frozen in a climatic chamber at air temperatures ($T_a$) 10, 15, and 25 °C.

The analysis of the experimental results showed that the cooling of the upper part of the columns occurs most intensively. Therefore, the time spent on cooling the upper part of the columns from the given initial temperature to its critical value minus 2°C is taken as the permissible time interval (t). According to the experimental data according to the method [14], which allows approximating the experimental points by hyperbolic curves, an empirical dependence was obtained

$$T= [(-6{,}19 \text{ X } 10^{-3} \text{ X } T_i{}^{2} + 0{,}4673 \text{ X } T_i +2{,}07) \text{ X } T_a{}^{-2} + 5{,}25 \text{ X } 10^{-5} \text{ X } T_i{}^{2} +5{,}75 \text{ X } 10^{-4} \text{ X } T_i +0{,}008] \text{ X } h^{1{,}3} \qquad (2)$$

For the convenience of determining the values of t, this dependence was nomogrammed in fig. 1.

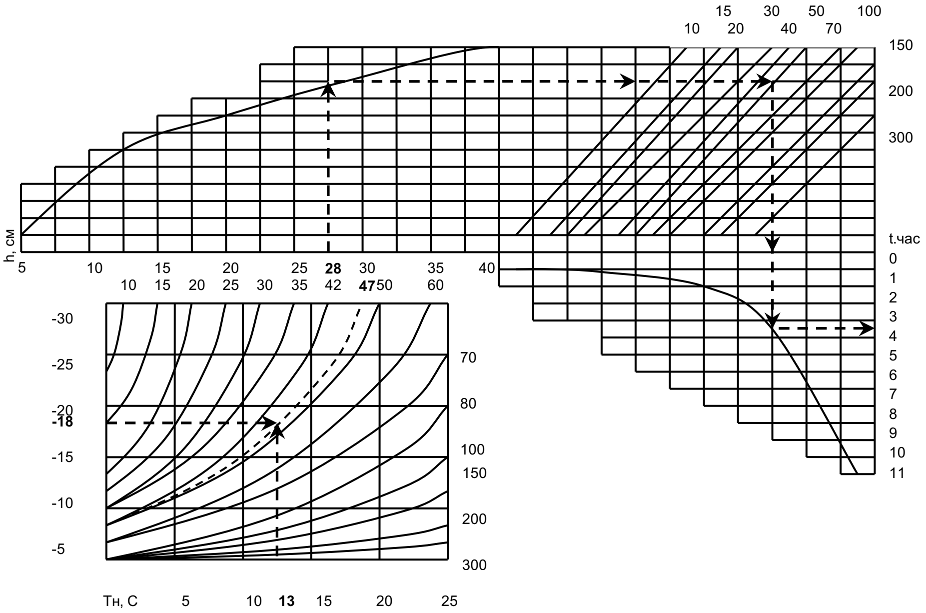

**Fig. 1.** Nomogram for determining the permissible time interval for carrying out technological operations for the construction of a pavement layer from belite sludge at negative air temperatures.

On the nomogram, dotted lines show an example of determining t with the following initial data: the initial temperature of the sludge $T_i$ = 13 ° C, the air temperature $T_a$ = 18°C, the thickness of the sludge layer in the loose condition h = 28 cm. d - dimensionless parameter, determined using the values of $T_i$ and $T_a$.

## 4 Experimental work

The construction of experimental sections of foundations and transitional type coatings from sludge and sludge-crushed stone materials was carried out in II-IV road-climatic zones, on roads of I-IV categories at air temperatures up to - 26°C. It was found that during the development of a sludge dump, in order to average the material according to the granulometric composition and lower the moisture content, it must be stacked, moving it by bulldozers from the settling pond to the embankment. After 7 - 8 hours of keeping the material in a stack, it acquires optimal moisture content, while maintaining a thawed state, and can be transported to construction sites [11].

The results of monitoring the heat loss of sludge during its transportation in dump trucks confirmed the correctness of the thermal engineering calculations. For example, during the experimental construction of the road "Entrance to the bone meal plant" in the Omsk region, bauxite sludge delivered from the sludge dump of the Pavlodar aluminum plant did not freeze over 450 km being transported by motor transport in winter and was fully used for the foundation at air temperatures below zero. Heating the truck bodies with exhaust gases not only significantly restrained the cooling of the material, but also prevented it from freezing to the inner surface of the truck bodies.

During the construction of a base made of nepheline sludge for concrete pavement on the II category road Omsk-Novosibirsk, sludge was delivered 750 km in gondola dump type cars by rail to Kargat station, and then 20-25 km by dump trucks with heated bodies, sludge was aligned by a motor grader in a layer of 35 cm (with a reserve for compaction) and tamped with a heavy pneumatic roller. All work was carried out in winter at air temperatures from - 10 C° to -25 ° C. During the construction process, the temperature and humidity of the sludge at various depths, the thickness of the frozen layer, the air temperature, the wind speed, the evenness and density of the finished base were monitored [13].

In general, it should be noted the fundamental convergence of the results of studying the heat loss of sludge during its transportation by rail and road transport in production conditions with the results of heat engineering calculations. For example, for a batch of sludge delivered by rail within 2.5 days, the temperature dropped by only 2.75 °C, but its average value after unloading from dump type cars was 2.7 ° C and all the material (48 dump type cars) was used for the foundation construction. Only in exceptional cases, when (for organizational reasons) the material for a long time was in the dump type cars (more than 3 - 5 days) at air temperatures below - 20, -30°C it was partially frozen. At the same time, the frozen part of the sludge was taken out to stack in the track warehouses, and the thawed sludge was used for the foundation.

At all experimental sites and in the process of industrial implementation it was possible to achieve the required compaction coefficient of 0.98-1.0. after 15-18 passes of a pneumatic roller weighing 25 tons (by one track). During the spring thawing of sludge bases, the speed of the construction transport was limited to 30 km/h, with its adjustment over the entire width of the layer. Before the installation of the concrete pavement, the design marks were specified, if necessary, the base was additionally profiled, with a pneumatic roller machine additional rolling (2-3 passes along one track). In total, from January to March, 5.7 km of sludge basement was built, which made it possible to significantly extend the construction season, preserve the subgrade during the thaw period, save 2.6 thousand tons of cement and 34.2 thousand tons of sand.

According to a similar scheme for the delivery of sludge at subzero temperatures, 4.6 km of foundation was built for a concrete pavement on the taxiways of runway-2 at Tolmachevo airport (Novosibirsk).

In the process of pilot construction and industrial implementation, a high efficiency of the method for arranging a sludge-crushed stone base using a cam roller DU-26 (for road compaction) was revealed [15, 16]. Its use made it possible to achieve high-quality processing of a crushed stone layer with a thickness of 18 cm for the entire thickness after 12-14 passes of the roller by one track with a compaction coefficient of crushed stone material of 1.0-1.04. Moreover, the high specific pressure of the roller ensured high-quality compaction at sludge temperatures below its critical value (-3, -7°C), which made it possible, without sacrificing quality, to significantly lengthen the technological capture. In addition, on this basis, as shown by production experience, it is possible to immediately open the movement of transport without limiting its speed. This effect was widely used in the construction of transitional pavements on oilfield roads [7].

The results of monitoring the heat loss of sludge in the process of pilot construction and industrial implementation confirmed the reliability of theoretical and experimental studies. The largest heat losses were recorded in the process of compaction of the material, since after distribution over the frozen base, the area of its heat transfer significantly increases. Therefore, it is extremely important to determine the permissible time interval (t) for carrying out this operation and the permissible length of the technological capture (L). The following factors are of decisive importance: the temperature of the sludge and air, the wind speed, the thickness and width of the layer to be laid and the performance of the driving machine (roller).

The length of the technological capture can be roughly determined for specific construction conditions at the beginning of each shift according to the formula

$$L=\frac{P}{h\times b}\times t \tag{3}$$

where P is the hourly productivity of the roller, m3/h, *h* -layer thickness in a dense body, m, *b* - width of the compacted layer, m, *t* is the permissible time interval for performing technological operations (h), determined by the nomogram in fig. 1.

Comparison of the t indicators determined from the nomogram in fig. 1 with field observation data showed that under production conditions the time for the distribution and compaction of the sludge layer is 5-10% more, which is quite acceptable for practical purposes and goes into the safety margin [11].

**Table 2.** Values of t, determined from the nomogram and the results of measuring the temperatures of the sludge in production conditions.

| **Experimental site number** | **Initial parameters** | | | | **Value of the admissible time interval t, hour** | |
|---|---|---|---|---|---|---|
| | **$T_a$ ,°C** | **$T_i$,°C** | **h, cm** | **V, m / sec** | **according to the nomogram** | **according to experimental construction data** |
| 1 | -26 | 11 | 30 | 5-6 | 2.5 | 2.7 |
| 3 | -12 | 4 | 18 | 4-6 | 1.5 | 1.6 |
| 4 | -7 | 1 | 22 | 4-9 | 3.1 | 3.3 |

On the basis of the studies performed and pilot experimental construction in the Krasnoyarsk Territory, Omsk, Novosibirsk, Tomsk and Pavlodar regions, recommendations have been developed that reflect the issues of the excavation of nepheline and bauxite sludge and the technology of installing bases (coatings) on roads of I - IV categories from sludge and sludge-crushed stone materials at negative, as a rule, not lower than - 20°C air temperatures [7, 10, 17, 18].

Construction can be carried out from sludge delivered to the road directly from the sludge dumps or from stack in the track warehouses, specially prepared in the summer for the winter production of work. The part of the stack to be used in the autumn months is allowed not to be kept in the warehouses, and the thickness of the fast-hardening foam coating on the material used in December, January, February and March should be approximately 10, 15, 20 and 25 cm, respectively.

Removal of sludge to the road or to the stack in the track warehouses must be carried out by heavy-duty dump trucks with bodies heated by exhaust gases. Sludge can also be transported year-round by rail over economically feasible distances.

The length of the technological capture for specific construction conditions is determined by the formula (3) using a nomogram in fig. 1., taking into account the productivity of the roller.

The distribution of sludge along the surface of the subgrade should be carried out with a heavy motor grader with a layer thickness taking into account the safety factor for compaction, which is 1.35 - 1.5.

It is necessary to compact the sludge with rollers on pneumatic tires with a mass of at least 25 tons. One lane needs 15-18 roller passes to achieve the required density, at least 0.98 of the standard. The compaction of the layer should be completed by the time the sludge cools down to a critical temperature not lower than minus 2°C. On the compacted layer, you can immediately open the movement of vehicles. During the spring thawing period, the speed should be limited to 30 km/h and adjusted across the entire width of the carriageway.

## 5 Conclusion

The temperature and technological parameters of excavation and storage of sludge for work in winter have been investigated. The regularities of sludge cooling have been studied and a technology has been developed for the device of monolithic layers of road pavements with its use at negative, up to - 20°C, air temperatures. The positive effect of re-compaction and transport loads on the character of hardening of belite sludge in the layers of road pavements has been established [19-21]. During the inspection of road sections with the use of belite sludge, it was found that the ultimate compressive strength of sludge and sludge-mineral materials is 7.5 - 14.5 MPa. At the same time, over the years, there has been a tendency towards a constant slow firmness increase [22, 23].

The correctness of the developed technical solutions was verified through the construction and inspection of experimental sites, as well as during the industrial implementation during the massive construction of hundreds of kilometers of roads of I-IV categories in II-IV road-climatic zones.

The widespread use of sludge made it possible to extend significantly the construction season for the construction of road and airfield monolithic structural layers, to reduce the shortage of stone materials and binders, to reduce the material consumption for road layers, to increase its bearing capacity and durability, as well as to improve the environmental situation by increasing the volume of utilization of these industrial waste.

## References

1. V.M. Bezruk, *Soil strengthening in road and airfield construction* (Transport, M., 1971)
2. D. Fohs, E. Kinter, Public Roads **36(4)**, 75-82 (1970)
3. M.I. Khigerovich, N.E. Mushtaeva, M.S. Karasev, Car roads **9**, 4-5 (1969)
4. S.A. Mironov, E.G. Glazyrina, *Influence of early freezing on the strength and deformation characteristics of concrete. Winter concreting and heat treatment of concrete* (Stroyizdat, Moscow, 1975)
5. A.S. Popolov, *Experience of using granular slags in road construction in France. Express - information. Car roads. Foreign experience* (Scientific and technical information center of the Ministry of Autoroads of the RSFSR, Moscow, 1984)
6. B.V. Belousov, V.M. Beskrovny, A.A. Lytkin, *The use of belite sludge for the construction of road bases in Siberia. Production and use of stone materials from rocks and industrial waste in road construction* (Road research institute, Moscow, 1984)
7. *Guidelines for the construction of road bases and transitional pavements using belite sludge in the oil and gas regions of Western Siberia* (Ministry of Transport Construction of the USSR. Moscow, 1986)
8. I.V. Loginova, A.V. Kyrchikov, *Hardware - technological schemes in the production of alumina* (Ekatirenburg, 2011)
9. E. Ercag, R. Apak, Journal of Chemical Technology and Biotechnology **70(3)**, 241 – 246 (1997)
10. *Industry road methodological document 218.3.043 - 2015. Guidelines for the use of natural belite sludge in road layers* (Federal Road Agency: Rosavtodor of the Ministry of Transport of the Russian Federation, Moscow, 2015)

11. A.A. Lytkin, *The use of belite sludge for the construction of layers of road pavements at negative temperatures: dissertation abstract for the candidate degree of doctor in technical sciences: 05.23.11* (Moscow, 1990)
12. I.A. Kirienko, *Theoretical substantiation of hardening of cement mortars and concrete in the frost* (Kiev, 1962)
13. A.A. Lytkin, *Development of the technology for the construction of road foundations at negative temperatures from nepheline sludge delivered to construction sites in winter by rail: Research report (conclusion) DG-DO-89-17; № GR 01890041059; inventory number 02900017209* (Omsk branch of Road research institute, 1989).
14. V.D. Polezhaev, *Continuous-frame and parametric methods for constructing manifolds as applied to the modeling of multifactor processes: dissertation abstract for the candidate degree of doctor in engineering 05.01.01* (Kiev engineering institute, 1989)
15. V.M. Beskrovny, *Method for the construction of road and airfield foundations № 2926211/29 – 33 Bulletin №35.118* (1982)
16. V.M. Beskrovny, B.V. Belousov, A.A. Lytkin, Road research institute Moscow, 93-102 (1984)
17. *Guidelines for strengthening soil and other materials with slow-hardening binders at low positive and negative temperatures* (Ministry of Transport Construction of the USSR, Road research institute, Moscow, 1985)
18. *Departmental building codes 84-89. Survey, design and construction of highways in permafrost areas* (Ministry of Transport Construction, Moscow, 1990)
19. A.A. Lytkin, Scientific peer-reviewed journal: Bulletin of SibADI **3(55)**, 125-132 (2017) https://doi.org/10.26518/2071-7296-2017-3(55)-125-132
20. A.A. Lytkin, Materials Science Forum **992**, 79-85 (2020)
21. B.V. Levin, B.S. Lisyuk, K.L. Lutsenko, A.A. Lytkin, World of roads, Ecology. New technologies, 91-100 (2020)
22. B.V. Belousov, A.N. Gavrilov, A.S. Afonin, World of roads **23** (2016)
23. A.A. Lytkin, G.B. Starkov, E.Ya. Wagner, Scientific peer-reviewed journal: Bulletin of SibADI **17(6)** (2020) https://doi.org/10.26518/2071-7296-2020-17-6-764-776