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The Construction Of Roadbeds on Permafrost and in Swamps from Reinforced Soils of Increased Strength

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Abstract

The paper presents the history of the transport infrastructure of the West-Siberian oil and gas complex in the last century and ways to solve the problems of road construction in the twenty-first century. The development of the territory of Siberia and the North in the present period is constrained by the low rates of development of the transport structure. One of the reasons for this lag is the lack of regulatory documents to substantiate transport structures in the harsh climatic and difficult soil and geological conditions based on the use of new modern road-building materials. The development of new resource-saving materials, structures and technologies based on local building materials, products and industrial waste using modern methods and research methods in materials science is an aim of current study. The general research methodology consisted of theoretical, laboratory and field studies. The developed designs and technologies for the construction of embankments in permafrost and in swamps using geotechnical holders filled with unsuitable soils (thawed and frozen waterlogged peat and clay soils) can reduce the volume of work and the cost of construction by one and a half to two times while increasing the service life of structures. The experimental sites of embankments constructed between 1995 and 2009 in the wetlands of the Uvat Group of deposits in the Tyumen Region and in permafrost in the areas of Novy Urengoy have been observed for more than ten years. The artificial stone material tested in Murmansk and Surgut based on the strengthening of local soils with inorganic binders with polymer additives using modern technologies allows it to be used instead of imported stone materials and reinforced concrete slabs for the construction of structural layers of road pavements, reinforcing slopes, as well as in hydraulic structures. The new artificial stone material is characterized by high strength and durability in areas with a temperature gradient of the external environment of more than 100 (from +50 to -50 °C).

Keywords: Substandard Soil; Geosynthetics; Polymer Additives; Frost Resistance; Strength.

1. Introduction

The transport component in the arrangement of the territories of Siberia and the Arctic determines the pace of development and therefore is one of the key points of the entire rather complex system of industrial development in these areas. In this case, the most important link in the transport support is road transport. Assessing the work done in recent years to create a transport infrastructure, first of all, it is necessary to dwell on the scientific and technical problems of the 60s of the last century that road builders faced and whose solutions opened the way to solving the whole problem of transport support during the development of the northern territories. The natural features of the area predetermined these problems. Difficult natural conditions are areas with a harsh climate and extraordinary,

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unconventional geology. Siberia and the Arctic, located in three road-climatic zones, is one of the few corners of the globe, where, along with the Arctic and sharply continental climate, its entire territory is occupied by permafrost, peat bogs and wetted "substandard" soils. The most important features are permafrost (Figure 1) and a great amount of swamp and lakes.

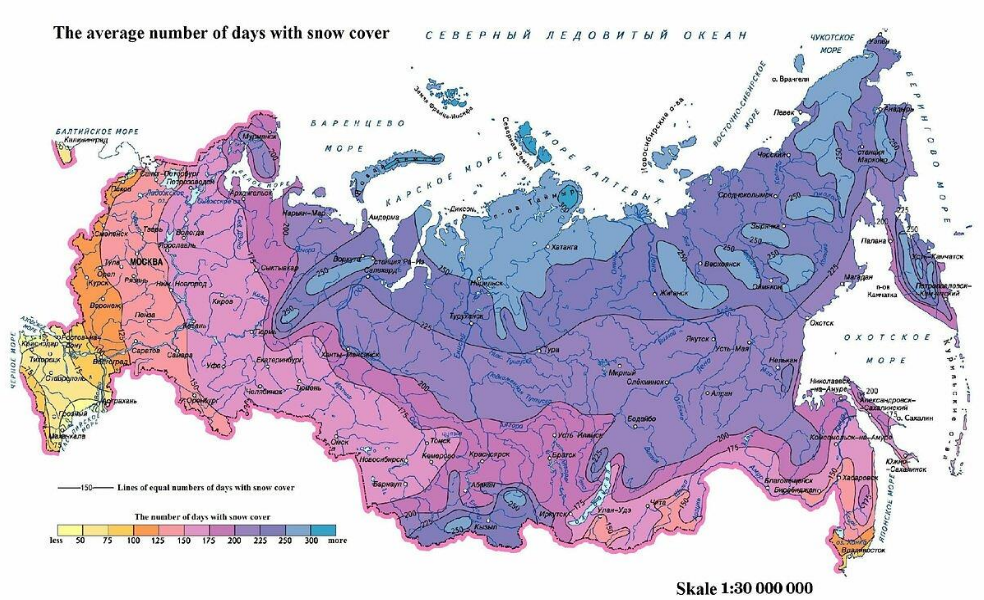

Figure 1. Map of permafrost in Russia (65% of the territory)

The permafrost distribution area on Earth occupies up to 36 million km2 or about 25% of the land surface. In the Northern Hemisphere, permafrost occupies more than 22 million km2, of which the Russian Federation accounts for 11.45 million km2, which is 65% of the territory of the Russian Federation (Figure 1), including 85% of the territory of Siberia, 95% of the Republic of Sakha. The maximum thickness of frozen rocks reaches 1300-1500 m. Negative average annual rock temperatures at depths of 10 to 20 m are minus 12-15 °C and below. The almost complete absence of roads in most of the expanses of Siberia and the Far North makes it difficult to develop these regions and deliver any goods, even the most necessary, vital livelihoods of the local and visiting population. Communication between settlements is possible only on winter roads (on winters, on ice roads and on ice crossings.

The study area is characterized by the wide development of lake-bog peat deposits, extremely strong bogging (up to 80%) and graininess (up to 30%) and the exceptional monotony of the relief. It has a flat, very boggy surface, with ridges and ring-shaped microrelief. Lake-bog Holocene sediments are represented by peat of the upper type (Figure 2). Upper bogs are characterized by high and mixed swamp deposits with a convex and flattened-convex mesorelief, composed of peat of low decomposition and friable composition. In depth they belong to medium (from 2.0 to 4.0 m), deep (4.0-6.0 m) and very deep (more than 6.0 m) swamps and are characterized by the worst passability (impenetrable and impassable swamps) The physical and mechanical properties of soft soils vary over a wide range, with humidity up to 1800% and shear strength less than 0.005 MPa.

Figure 2. Landscape of the territory occupied by permafrost (Nadym)

At the first stages, the design and construction of roads in Western Siberia was based on regulatory documents developed for the conditions of the European part of the second and third climatic zones. According to SNiP - to bypass wetlands - naturally lost their practical meaning. Similar conditions for the construction of roads in Russia arose for the first time. The formation and development of transport infrastructure in Siberia since the sixties of the last century is associated with the production of hydrocarbon raw materials. The length of field roads and railways in the territory under consideration is more than 80%.

One of the features of these roads is that the pace of their construction is determined by the pace of development of the territory. In this regard, the question of a sharp increase in the pace of construction arose, which could not be ensured by traditional engineering solutions. By the end of the 90s, as a result of joint work of Soyuzdornin, its Omsk branch, TyumISI, and SibADI under the guidance of Professor Kazarnovsky, the main regulatory documents for the design, construction and maintenance of oil and gas field roads were created: "Research, design and construction of roads in areas of permafrost", VSN 84-90; "Instructions for the design and construction of roads of oil and gas fields in Western Siberia"; "Handbook for the design of road bed on weak soils" (to SNiP 2.05.02-85). These problems were solved by developing the roadbed and the technology of its construction, providing for the maximum use of peat soils at the base of earth fills, as well as local soils, including peat, as the material of the earth fill.

The massive use of peat soils at the base and body of the earth fills required an intensive and in-depth study of their properties, the development of regional type designs of wetlands and peat. This ensured that the solution, considered individual, was brought to the level of a mass, typical one. Along with this, significant work was carried out aimed at substantiating the possibilities and conditions for the use of overwetted local soils and pulverescent sand in the construction of the roadbed at the crossings over swamps and lakes. Methods are developed for producing artificial stone materials based on the use of reinforced soils for the construction of structural layers of pavements and strengthening works. Scientific substantiation and practical implementation of engineering and organizational solutions allowed a drastic reduction in the volume of earthworks, in the cost of construction by 1.5-1.9 times and in the energy intensity of construction by 2 times, and an increase in the pace by 2-2.5 times. The developed set of measures was implemented in full from 1966 to 1985. And it was not until 2005, that this area continued to develop based on new materials, unique road-building equipment and in-depth knowledge in the field of management of the formation of structures of reinforced soils. This made it possible to obtain an artificial stone material with characteristics close to cement concrete.

Since the beginning of the 21st century, a new stage in the design and construction of roads based on resource-saving materials and technologies began. The experience, practical data, adjustment on their basis of theoretical statements during the previous years are the basis for the development of science, and therefore the improvement of standards. At the same time, the norms themselves, of course, in some cases are not perfect, especially since they were created 30-50 years ago, when the road conditions, construction materials and equipment were completely different. From the standpoint of this experience and the prospects for the creation of transport infrastructure in Siberia and the Arctic, it is necessary to intensify scientific research and reduce the time it takes to put it into practice in design and construction. This article summarizes the results of research in this area over the past 40 years.

The general methodology of scientific research consisted of: studying the state of the issue, developing theoretical prerequisites, laboratory and model studies, pilot production construction and monitoring of roads built according to the developed new designs and technologies.

Theoretical studies were carried out on the basis of fundamental sciences: thermophysics, soil mechanics, resistance of materials, physicochemical mechanics of disperse structures, mechanics of granular media, physical chemistry, probability theory, etc. The obtained mathematical and physical models made it possible to substantiate new materials, structures and technologies for the construction of the subgrade and the construction of road pavement for roads in permafrost zones and in swamps. And verification of research results and optimization of structural and technological solutions was carried out by analyzing monitoring materials of these objects.

The developed set of measures was fully implemented in the Tyumen region from 1966 to 2017 (Figure 3). The region is located in the natural zones of the Arctic deserts, tundra, forest-tundra (north and the center of the Yamalo-Nenets Autonomous Okrug), taiga (south of the Yamalo-Nenets Autonomous Okrug, Khanty-Mansi Autonomous Okrug, and the north of the southern part of the Tyumen Oblast), mixed forests and forest-steppe (center and south of the south parts of the Tyumen region). The area of the Tyumen region (with autonomous regions) is 1,435,200 km^2 with a population of 3 million 800 thousand people.

Figure 3. Pilot production in the Tyumen region from 1966 to 2017: (1) Tyumen; (2) Uvat; (3) Surgut, (4) Nizhnevartovsk; (5) Beloyarskii; (6) Nadym; (7) Urengoi

2. Materials and Methods

2.1. The Roadbed in the Permafrost Zone and in Swamps Based on Geotechnical Materials and "Substandard" Soils

The experience of building a roadbed on peat bogs in Western Siberia shows that the service life of the roads is much less than the normative, and the cost of repairs and maintenance is much more. This is due to the fact that when designing earth fills, the values of the design characteristics of weak soils are taken from regulatory documents, in most cases not corresponding to real field parameters. The reason for this is the low level of organization of engineering and geological surveys, or even their absence. In the swamps, in general, three special requirements are imposed on road structures that determine the choice of design and technological solutions and design schemes: the base of the roadbed must be stable, i.e., the uplift or the extrusion of weak soil from the base of the earth fill (not counting when extrusion is provided by the technology of work) is not allowed; base sediments during the operational period should not cause unacceptable distortion of the longitudinal and transverse profiles; elastic deflections and variations of the structure from the static and dynamic effects of the transport load should be limited in amplitude and frequency by the conditions of long-term strength of the pavement.

There are two fundamentally different approaches to solving the problem of constructing crossings over swamps and other deposits of weak soils. The first method involves the development and removal of the peat base and its replacement with mineral soil, the second is the method of "floating earth fill", allowing for the use of weak soil at the base. According to the former, weak soils are excluded from the work and the load from the structure is transferred to the underlying, more durable layers. In cases where the structure does not allow for significant subsidence of the base, such a decision seems to be quite reasonable, but requires a significant amount of soil, and increases construction time and cost.

The second method is more economical, however, there is a problem with the stability of the earth fill, the settlement of the base and the period of consolidation. In this case, the transfer of the load of the earth fill to the swamp is carried out through a flexible stamp (earth fill bottom) and a rigid stamp (wood strip floor). The appearance of geosynthetic materials on the market was a revolution in the field of creating new designs of the roadbed in swamps with the transfer of load through a semi-rigid stamp. Over the past 10 years, a team of scientists led by Shuvaev deals with the development of new resource-saving roadbed structures in swamps using geotechnics and, mainly, local wetted cohesive peat and clay soils in the body of the earth fill, which have the greatest (up to 95%) distribution in Western Siberia and prohibited for use under current regulations [1-3]. A geosynthetic holder filled with “substandard” soil transfers and distributes the load on weak bases through a semi-rigid stamp, which 1.5-2 times increases the stability of the earth fill, reduces the settlement to 40% and accelerates the consolidation period by 1.5-2.0 times. Analysis of the work carried out on the Uvat Group of oil fields indicates the effectiveness of these developments. The result of the work is more than 50 road bed structures and platforms developed and tested on real objects built on weak bases using various geosynthetic materials (woven, nonwoven materials, geo-composites, etc.). Structures were developed under more complex soil and geological conditions (swamp depth, peat moisture, shear resistance, hydrogeology, etc.) than in the Middle Ob region. Figure 4 shows the comparative cost and reliability of the main structures of the road bed in swamps developed over the past 50 years.

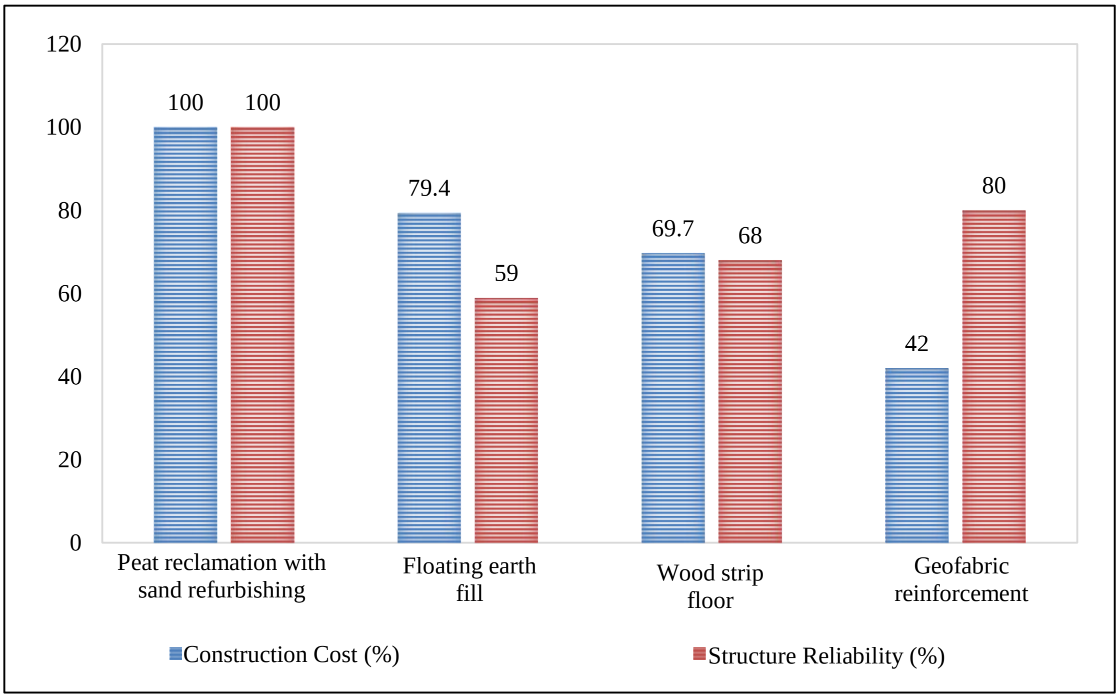

Figure 4. Comparative cost and reliability of various earth fill designs

In the permafrost zone, the design of the road bed is carried out mainly on the first principle while preserving the natural base of the earth fill in a frozen state. This is ensured by an earth fill height of 2.8 m; in this case, the road bed plays the role of a heat insulator. We have developed more than 40 designs (as an example, Figure 5), where the lower part of the earth fill is made from "substandard" soils enclosed in a holder from an insulating material (Figure 6). In this case, the height of the earth fill is reduced to 1.20 (according to the snow-free conditions), which leads to a decrease in the volume of soil. In addition, the use of "substandard" soils, located in the immediate vicinity of the work site, reduces financial costs, significantly accelerates the pace of construction and significantly reduces environmental risks.

The reasons for road failures under these conditions are not so much the impact of vehicles as the impact of natural factors on the road. Over the past 50 years, the practice of creating a transport network in special conditions has shown that the transition to the use of "substandard soils" for the construction of embankments will give significant financial savings and increase the pace of construction. An acute problem is the creation of methods and methods for controlling the processes of formation of soil massifs. This allows you to design reliable and durable structures [5].

The existing methods for constructing the subgrade have the following disadvantages: single-layer structures are used for the calculation; one-dimensional problems are solved; only final precipitations are considered, not considering that they occur in time. As a result, insufficiently reliable calculations. We have developed a comprehensive model for controlling the formation and functioning of the soil embankment from “substandard” soils at the stage of the entire life cycle of the road and verification of its theoretical background in laboratory and field conditions [5-7] showed its applicability as the basis for creating a regulatory design complex, the construction and operation of permafrost roads. The physical foundations of mathematical modeling were: the law of conservation of energy (heat balance) in the form of a heat equation taking into account the heat of phase transitions, the equation of moisture balance in different phases, which determine the moisture saturation in different parts of the considered area, and also the equations that determine stress and strain [8-11].

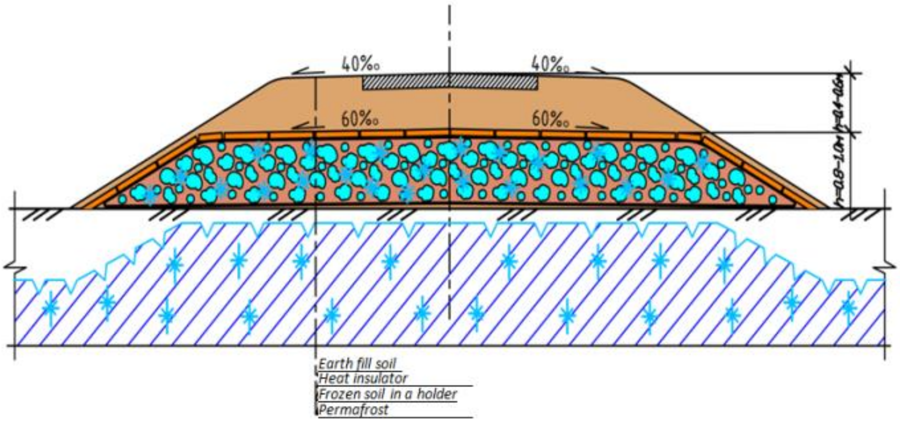

Figure 5. Road bed using "substandard" soils in a holder from a heat insulator in the lower part of the earth fill

Figure 6. The construction of the lower part of the embankment from frozen ground in a holder made of geosynthetics with a heat insulator (N-Urengoy, Pestsovoe deposit)

2.2. Structural Layers of Pavements Made of Artificial Stone Materials Based on Local Soils Reinforced with Inorganic Binders

The main material in the Russian Federation for the pavement course is a stone material. In world practice, for the installation of similar courses in 95% of cases, reinforced soils and cement concrete are used. They provide high reliability, increase the service life by 3-5 times compared with stone materials and reduce the amount of work on the maintenance and repair of pavements.

The practice of construction in Siberia in the 70s-80s and the results of numerous surveys of the SoyuzdorNII (Research Institute) and experts from the Research, Development, Production and Diagnostic Center in the north of the Tyumen region point to the high efficiency of using reinforced soils in road structures on roads and at airfields [12-15]. Thus, the service life of road pavements to overhaul on the Tyumen-Tobolsk highway was 28 years, and on the runways of airports in Nadym, Surgut, Nizhnevartovsk, and Tyumen it ranged from 24 to 31 years. Road pavements, made of stone materials, are characterized by low reliability and durability and they are deficient in Russia. Geographically, road construction has moved to the north-eastern regions of the country (to Siberia). The pace of road construction increased sharply. The intensity of car traffic and the average speed have increased several times, the load on the axle increased to 15-20 tons, tires became tougher. In the changed conditions, despite the urgent need for the widespread introduction of local reinforces soils (RS) in road construction instead of expensive imported materials based on rocks (concrete, rubble, gravel, etc.), the rates and volumes of implementation do not satisfy the increased production needs.

The use of Local Reinforced Soils (RS) in road construction has non-industrial and industrial bases. In the first case, the main technologies are the methods of mixing the soil with the binder on the road and in the quarry mixing plants. In this case, the formation of the material in the structural layer of the pavement is open-air in adverse field conditions. This does not ensure the receipt of material with high physical and mechanical parameters and year-round organization of work production.

The lack of frost resistance of RS for the harsh conditions in the present time has been solved by introducing polymer additives into its composition, which activate the processes of cement stone formation and reduce the complexity of technological operations. In addition, optimization of the mineral component and the processes of formation of the structure of the material at the stage of compaction of cement-soil mixtures significantly increase the strength of the structural layers of the pavement.

In practice, modern, automated mixers and kits allow optimized compositions of the original mineral soils to be prepared. Reviewing the requirements for compaction of soil + binder + additive mixtures is due to a unique compacting technique that is incomparable with rollers of the 50s.

Over the past fifteen years, foreign scientists have obtained a number of surface-active additives (surfactants), actively influencing the formation of road-building materials. On the basis of the Industrial University of Tyumen, scientific and practical studies were conducted on the effect of additives and stabilizers of foreign production in strengthening the soil [15-17]. The encouraging results of improving the physical and mechanical properties of reinforced soils were obtained. The most interesting are the additives “Nano Terra Soil” (Germany) and the stabilizer LBS (USA). But the cost of the additive, the cost of transportation and customs duties significantly reduce the economic component. Approbation of domestic additives "Dortsem" and "ANT" (Volgograd) showed the high efficiency of the second. Table 1 presents the physical and mechanical parameters of reinforced soil with cement using the ANT additive of domestic production. Samples were formed both using standard methods and with a change in the method of compaction of the mixture. At the same time, the compaction parameters corresponded to the characteristics of modern compaction machines.

Table. Physical and mechanical parameters of soil reinforcement with cement using ANT additives and reinforced compaction

No.	RS Composition		Compaction Technology	Compressive Strength, MPa	Water Saturation, %	Frost Resistance Coefficient after 75 Cycles	RS Strength Classification	
	Cement, %of soil weight	ANT additive,% of soil weight					Grade by GOST 23558-94	Class by SN 25-74
1	10	------	Standard	2.3	5.6	0.63	M 20	Class 2
2	10	------	Reinforced	2.8	4.9	0.68	M20	Class 2
3	10	0.007	Standard	3.3	4.0	0.79	M 20	Class 2
4	10	0.007	Reinforced	4.2	3.8	0.83	M40	Class 1
5	12	------	------	4.1	5.5	0.79	M40	Class 1
6	12	------	Reinforced	5.2	3.2	0.85	M40	Class 1
7*	12	0.007	Standard	5.8	3.3	0.88	M60	Class 1
8*	12	0.007	Reinforced	8.4	2.2	0.94	M80	Class 1
9*	15	------	Standard	6.2	5.0	0.77	M60	Class 1
10*	15	------	Standard	7.1	2.4	0.86	M60	Class 1
11*	15	0.007	Reinforced	10.6	2.0	0.94	M100	Class 1
12*	18	0.007	Reinforced	16.6	1.2	0.93	M150	n/c
13*	20	0.007	Reinforced	21.2	1.2	0.94	M200	n/c

* New reinforced soil (RS) compositions and compacting technology

Figure 7. Construction of a pavement of reinforced soil on an oilfield road in the Murmansk region K-V-PP "Lotta"

3. Results and Discussion

Analysis of the results of Table 1 shows the effectiveness of the introduction of ANT additives and reinforced compaction. Thus, the compressive strength increased by 40-80% due to the introduction of a surfactant and by 20-40% due to non-standard compaction. At the same time, there is a significant decrease in water saturation up to 2% and an increase in frost resistance up to 0.94. The obtained positive results on the additive "Nano Terra Soil" (Germany) were reported at an extended meeting of the board of the Ministry of Transport of the Russian Federation, where on the instructions of I.E. Levitin, Minister of Transport, was built an experimental site at the MADI (STU, Moscow) test site and in the Murmansk region (Figure 3).

The results of control tests conducted by MADI (STU), confirmed the materials of our research. During the construction of the pilot site, the preparation of the cement-soil mixture was carried out using a Bertoli Italian soil-mixing plant, the mixture was distributed by an asphalt paver, and compaction was done using combined rollers. Coarse sand was used as a starting material. At a cement dosage of 10% by weight of the soil, the NTS additive was 8 and 10% by weight of the binder. The test results of 28-day-old samples are as follows: compressive strength was from 11 to 13 MPa, bending tensile strength — from 2.5 to 3 MPa, frost resistance coefficient — at least 0.85, water saturation — no more than 4%. Compressive strength of samples with the addition of NTS is 80% more compared to samples with cement alone. At the same time, a decrease in the period of curing is almost twofold. Analyzing the preliminary results of the study of the effect of NTS and ANT additives on the properties of cement soil, we can assume that these materials belong to universal polymeric additives of the surfactant class, which increase the adhesive strength and the formation of a solid crystallization structure of the binder. A significant improvement in the physical and mechanical parameters, and especially frost resistance, made it possible to expand the scope of reinforced soils not only in road construction but also in hydraulic engineering and underground engineering structures (Fig. 8).

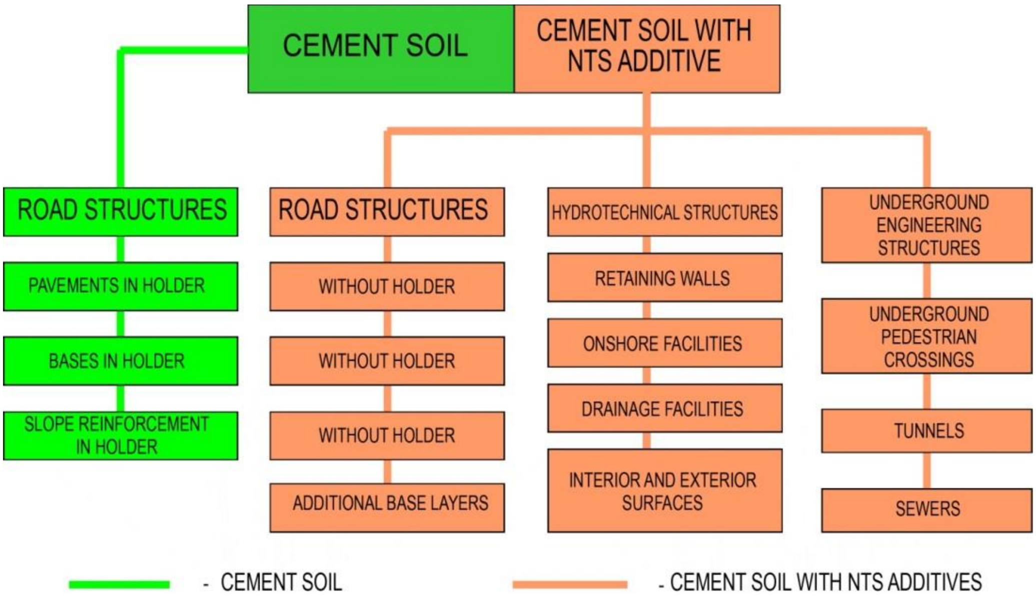

Figure 8. Use of soil reinforced with cement with additives NTS (Germany) and ANT (Volgograd)

The second basis for the development and improvement of the use of reinforced soils is its industrialization in two areas:

- Production of mixtures on mobile, semi-stationary and stationary plants and their laying on the road with sets of machines only in the summer period;
- Prefabrication of assembled products and structures and construction of structural elements of the road from them throughout the year (prefabricated pavements and bases, artificial structures, strengthening of slopes, road development, etc.).

Considering the above, a group of scientists from TyumISI from 1970 to 1985 under the leadership of Professor Lintser, investigated industrial ways to strengthen the soil. Technological methods were developed on the basis of powerful (for that time) machinery and equipment in the field of building materials as applied to the specifics of reinforced soils. The study of achievements in the field of production of construction and road-building materials and strengthening of soils allowed us to establish the following.

In order to realize the existing achievements in the field of the building materials industry, first of all, the evaluation criteria and the level of RS properties were changed in quantitative and qualitative terms. Firstly, the modern standard level of the properties of reinforced soils did not allow implementing the technology of their use in prefabricated structures and products, since the maximum allowable ultimate compressive strength is 6.0 MPa, the flexural strength is 0.4 MPa. Secondly, the methods of production of RS and structures exclude year-round work, except for regions with very favorable climatic conditions (south of the country). Thirdly, the requirements for road construction exclude the use of RS in critical elements, which also narrows the scope of their application.

To implement the idea of industrial application of RS, in TyumISI two problems were solved:

- Were created the technological bases of the industrial application of reinforced soils based on the use of the latest achievements in the field of building materials, taking into account the specifics of RS;
- Were developed materials science bases for obtaining RS optimal in structure and properties satisfying their industrial applications, and constructive bases, including the principles of design and calculation of road structures and realizing the possibility of maximal use of RS for industrial applications.

Technological bases are formed in the form of two schematic diagrams of industrial application of RS: the method of preliminary preparation of mixtures and the factory method of producing structures and parts. Considering the specific properties of soils: the fine grain size, the presence of a clay-colloidal part, salt content, etc., the first step for the two schemes is the directional transformation of properties, called soil modification. The modification involves the creation of optimal initial soil properties and can be performed in one or several ways. In some cases, the modification process can be combined with the preparation of mixtures and their subsequent storage.

The resulting high-strength reinforced cement-based soil has the following properties:

- Consumption of binder 14-25%;
- Plasticity number <7;
- E_y from 50×10^2 to 100×10^2 MPa;
- $R_{compres}$ from 10 to 50 MPa;
- R_{bend} from 3.0 to 8.0 MPa.

These properties allow the use of this material in prefabricated pavement structures and in strengthening the slopes of embankments. There is no great experience in the use of cement soils in prefabricated structures. Developments of Zhuravlev [4], Lintser [5, 6], Mateykovich [7] and Kretov [8], who proposed options for the use of prefabricated road constructions from high-strength cement soil, as well as pilot construction, showed a great promise of this area in road construction. Today, the most realistic possibility seems to be the mass use of structural elements made from steam-cured cement soil in road construction.

4. Conclusions

Analyzing the above, it is necessary to make a conclusion about the continuation and expansion of scientific and technical research in the field of development and implementation of resource-saving materials, structures and technologies in transport construction in Siberia and the Arctic in the following areas:

- Conducting experimental and innovative works on the construction of the road bed and pavements in the swamps and in areas occupied by permafrost using local “substandard” road-building materials;
- Developing methods for designing structures and technology for the construction of the road bed, pavements, and artificial structures;
- Implementing pilot development works and developing methods for quality control of design, construction and maintenance of transport structures and facilities and their monitoring for the period of the life cycle;
- Conducting experimental and innovative works of pavement structures using artificial stone materials.

5. Conflicts of Interest

The authors declare no conflict of interest.

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