Ecological aspects of technogenic material application in road construction technologies

I I Shepelev¹, E N Eskova¹, S O Potapova¹, S V Khizhnyak¹ and N N Bochkov²

¹Krasnoyarsk state agrarian university, Mira Ave., 90, Krasnoyarsk, 660049, Russia
²LLC «Dolomit», Dubrovinskyst., 112, room 406, Krasnoyarsk, 660049, Russia

E-mail: Ekoing@mail.ru

Abstract. It is shown in the paper that various secondary technogenic products and industrial wastes are effectively used as cheap raw materials for the production of road construction material. The hardening kinetics of the nepheline-sand mixture compacted at different initial humidity was studied, which showed that when nepheline sludge used as a binder, a relatively uniform set of strength of the samples was observed for a long time. Analysis of the aqueous extract from nepheline sludge showed there are ions of \( \text{Ca}^{++}, \text{K}^+, \text{Na}^+, \text{CO}_3^{2-}, \text{HCO}_3^-, \text{SO}_4^{2-}, \text{Cl}^- \) in it. Using the method of biotesting confirmed the absence of toxic effects of the proposed technogenic materials for use in the strengthening soil of road pavement.

1. Introduction

Among the well-known road construction technologies, methods of the strengthening soil with mineral binders are allocated in a special group. Strengthening soil with mineral binders have received extremely a wide distribution in Russian and foreign practice of construction. This was due to the possibility of using a large range of binders (Portland cement, sludge Portland cement, lime, binders based on blast furnace and phosphorus sludge and waste from other metallurgical and chemical industries), the simplicity of making the binder in the strengthened soil and the possibility of achieving a high degree of homogeneous binder distribution in the soil [1-4].

Various studies have shown that the method of strengthening by the cement used in road construction is very effective and versatile, but it has some drawbacks. First, cement is a fairly expensive binder, which is a serious obstacle to the further expansion of the cement use in road construction. Secondly, due to the fact that the cement is an active quick-grabbing and fast-hardening binder, technological operations on the device of the cement base or coating must be performed in a very short time. This leads to a reduction in the length of the technological capture, reduced productivity and, ultimately, to a decrease in the pace and quality of work.

Thirdly, the cement base has excessively high rigidity, as a result of which in the process of operation it inevitably forms temperature and other cracks caused mainly by natural factors [5].

One of the ways to increase the crack resistance of the strengthened soil is the direction of construction of bases using slow-hardening binders obtained on the basis of industrial waste [6,7]. At the same time, various secondary technogenic products and industrial waste are effectively used as cheap raw materials for obtaining construction material, which, in turn, is one of the measures to combat environmental pollution. Earlier studies have established the technical feasibility and
economic efficiency of widespread use for strengthening the soils of fly ash and ash mixtures of thermal power plants, ground and ground granular slags [7, 8].

The advantages of the methods of strengthening soil by slow-hardening binders and of the strengthened base is the ease of installation of mixture of low-activity binders and immunity to excess water when mixing, the possibility of production work in the greater length of the technological hook, the lack of shrinkage and temperature cracks in the base, the possibility of correcting and improving the flatness of the base after several days of operation [5].

To study the structure and toxic properties of nepheline sludge and its mixture with limestone technogenic materials for their use in road construction technologies.

2. The obtained research results

The slow-hardening binding materials include binders made from white-containing sludge – waste alumina production [9]. The main component that causes the presence of binders in these wastes is bicalcium silicate (Belite). The sludge of chemical production contains it in the amount of 35-60%, the nepheline sludge of alumina production - 80-85%.

The phase composition of nepheline sludge of JSC “RUSAL Achinsk” is associated with the mineralogy of the initial nepheline ores (urtites of the Kiya-shaltyr Deposit) and technological conditions for the extraction of alumina from them. Nepheline sludge is characterized by the predominance of β-bicalcium silicate. According to X-ray phase analysis, nepheline sludge is mainly represented by larnite (β-Ca$_2$SiO$_4$, $d$=2.78; 2.74; 2.19 Å, JCPDS, 29-371) with a small admixture of rankinite (Ca$_2$Si$_2$O$_7$, $d$=5.48; 3.82; 3.04 Å, JCPDS, 23-124). It was also noted the presence of weak lines of soda (thermonatrite, Na$_2$CO$_3$×H$_2$O, $d$=5.29; 4.12; 2.44 Å, JCPDS, 8-448) and calcium carbonates (calcite, CaCO$_3$, $d$=3.04; 3.86; 1.912 Å, JCPDS, 47-1743) [9].

The process of hardening of the binding nepheline sludge caused mainly due to hydration of the bicalcium silicate of sludge for scheme:

$$2(2\text{CaO}×\text{SiO}_2) + 3\text{H}_2\text{O} = 3,3\text{CaO}×2\text{SiO}_2×2,3\text{H}_2\text{O} + 0,7\text{Ca(OH)}_2$$ (1)

The differential thermal analysis of the sludge confirmed the presence of hydrosilicates in it. The stretched endothermic effects on the heating curves in the intervals of 100-400 and 500-800°C characterize the presence of various low-basic hydrosilicates in the sludge.

It should also be noted that the free lime formed during hydration of the sludge can serve in the strengthening soil as an additional source of formation of hydrosilicates and hydroalumination of calcium in the system soil-binder-water due to its chemical interaction with active silica and alumina, located in the fine clay of the soil. Thus the following mechanism of lime action takes place. The lime resulting from the hydration of bicalcium silicate increases the pH of the aqueous medium due to the dissolution and dissociation of Ca(OH)$_2$, which improves the solubility of silica and alumina contained in the soil, and causes their partial transition to the solution. Calcium ions combine water silicon dioxide and alumina with the formation of silicate hydrate and calcium hydroaluminate, which serve as additional links in the structure of strengthened soil.

It is noted that the studied samples of nepheline sludge contain 0.5-0.7% of water-soluble compounds. Analysis of aqueous extract from nepheline sludge, performed by the method of chemical analysis of soils, showed a dry residue content of 0.67%, pH=11.67 and the presence of ions Ca$^{2+}$, K$^+$, Na$^+$, CO$_3^{2-}$, HCO$_3^-$, SO$_4^{2-}$, Cl$^-$. As shown by studies of the hydration kinetics in the system of sand- nepheline sludge binder-water, during the first five minutes after preparation of water suspension pH increases from 9.2 to 10.62, and the loam- nepheline sludge binder-water — to 10.60. By this point, in the liquid phase a sufficient amount of Ca$^{2+}$ ions and in a smaller amount of SiO$_3^{2-}$ ions - and even in a smaller amount of AlO$_2^-$ ions – have already appeared.

The observed further continuous increase in the content of Ca$^{2+}$ for seven hours and a rapid decrease in the content of AlO$_2^-$characterize the formation of calcium hydroaluminate. The pH value
of the liquid phase determines the possibility of this process. It is known [10] that hydroaluminate stand out in solid phase at a pH of 11.91 and below mainly in the form of hydrates.

Microphotographs of nepheline sludge clearly show individual particles of larnite (figure 1A), and the microphotographs of the road mixture clearly show individual particles of nepheline sludge with crushed limestone overburden rocks from Mazul mine it can see what's inside sludge particles there are large cavities (up to 50-100 μm) empty or sprouted by lamellar crystals of calcite (figure 1B).

**Figure 1.** Microstructure of fresh nepheline sludge particles (anshlif, epoxy resin): A) nepheline sludge; B) nepheline sludge with crushed limestone technogenic rocks; increase: A – ×250; B – ×500.

The structure of the new formations that occur in the studied system soil-binder-water in the initial period of hydration (24 hours) is not stable: the formation of hydroalumination — mainly hexagonal, and hydrosilicates — gel. Therefore, during the specified period of time, sufficiently strong contacts between the particles of the solid phase of the system are not provided. The number of these contacts in the non-dense mixture cannot be large because, in nepheline sludge binders in the non-dense mixture, there are few points of contact between the particles in which these contacts can occur. Therefore, the non-compacted mixture of soil, nepheline sludge binder and water needs during the first 24 hours of its preparation to maintain some mobility and compaction. In addition, after 24 hours of hydration in the binder there is the predominant amount of non-hydrated bicalcium silicate sludge, indicating the possibility of further long-term hardening of the system. This is confirmed by the preservation for a relatively long period of time workability, compaction and the ability to further hardening of soil mixtures, strengthened with nepheline sludge binders, and, consequently, the possibility of increasing the permissible duration of the technological process for the device base of the strengthened soil. To study the physical and mechanical properties of road mixtures strengthened with nepheline sludge, the samples from the mixtures were formed under pressure of 5-20 MPa immediately after preparation of the mixtures to maintain their workability and ability to further hardening for a long time.

Experimental data on the hardening of the nepheline-sand mixture show that in the initial control period (7 days), the optimal compaction pressure of the mixture with sludge is 15 MPa (figure 2). Higher pressure practically does not increase the density and strength of the material. The limit strength of compressive and the limit strength of tensile in bending remain almost at the same level.
The study of the hardening kinetics of nepheline-sand mixture compacted at different initial humidity showed that when nepheline sludge is used as a binder there is a relatively uniform set of strength of the samples for a long time. Thus, the strength of the tested samples for compression by 90 days reached at different humidity from 3 to 10 MPa, and by 6 months, respectively, to 12-19 MPa. With an increase in the hardening period from 1 month to 6 months, the strength of the samples from the nepheline-sand mixture gradually increased at a humidity of 10% from 2.5 to 17 MPa. The change in the tensile strength in bending samples based on nepheline sludge has a similar nature of dependencies at different initial humidity. Bending strength at 10% humidity and different periods of hardening of samples from nepheline-sand mixture reached the following values: 1.5 MPa — 1 month of hardening; 3.2 MPa — 3 months; 5.7 MPa — 6 months.

Laboratory studies of nepheline sludge have shown that it has the property of forming a water-resistant monolith at the time of compaction, which has a certain initial strength and is capable of further long-term hardening with a uniform increase in strength. The compacted and hardened nepheline sludge of JSC “RUSAL Achinsk” on durability and frost resistance satisfied the requirements imposed to the materials strengthened by inorganic binders that give the basis to make the preliminary conclusion about possibility of its use for the device of the bases of highways.

However, for the use of nepheline sludge as a component of the road pavement it is necessary to confirm the absence of toxic properties [11]. Initially, studies of nepheline sludge for radioactivity were conducted. It was determined that nepheline sludge has a relatively low specific activity of natural radionuclides (66.9 Bq/kg), which does not exceed the hygienic standard established for industrial waste used in the manufacture of construction materials of class 1 370 Bq/kg.

Assessment of the complex effects of toxic substances that make up the nepheline-sand mixture was carried out, taking into account the reaction of biological test objects. The use of nepheline sludge in road pavement can become a significant risk factor for the environmental health of the surrounding areas due to the possible migration of toxic substances into adjacent environments - primarily in the adjacent soil layer and adversely affect the soil biocenosis.

As representatives of the soil microflora strains of microorganisms most commonly found in the soils of the Krasnoyarsk region were selected. By the method of biotesting we have confirmed the absence of significant toxic effects of the aqueous extracts of the specially prepared compacted samples of nepheline-sand mixture on soil ciliate Colpodapoda and the community of soil algae of the division Chlorophyta.

3. Conclusion
Studies have shown that as a cheap raw material for the production of road construction material, various industrial wastes can be effectively used, such as nepheline sludge of alumina production and overburden limestone mining. Laboratory studies of nepheline sludge have shown that it has the
property of forming a water-resistant monolith at the time of compaction, which has a certain initial strength and is capable of further long-term hardening with a uniform increase in strength. The compacted and hardened nepheline sludge of JSC “RUSAL Achinsk” on durability and frost resistance satisfied the requirements imposed to the materials strengthened by inorganic binders that give the basis to make the preliminary conclusion about possibility of its use for the device of the road base. Nepheline sludge having a relatively low specific activity of natural radionuclides and the absence of toxicity can be effectively used in road construction technologies as a binder in strengthening the soil of the road base. This is also confirmed by the conducted research on biotesting of these technogenic materials with the use of test microorganisms. The use of non-toxic technogenic materials in road construction technologies can reduce their impact on the environment in their locations.

References

[1] Lesovik R V et al. 2007 Integrated waste management of South Africa Industrial and civil construction 8 30-2
[2] Rahman I A 2001 Foreign experience in regulation of investment and construction activities Construction economics 6 37-45
[3] Li C A et al. 2010 review: The comparison between alkali-activated slag (Si+Ca) and metakaolin (Si+Al) cements Cement and concrete research 40(9) 1341-9
[4] Roy D M 1999 Alkali-activated cements. Opportunities and challenges Cement and concrete research 29(2) 249-54
[5] Bezruk V M 1971 Strengthening soils in road and airfield construction (Moscow: Transport) p 246
[6] Berdov G I 2015 Perspective directions in improvement of technology and construction materials based on mineral binders News of Universities. Construction 4 45-56
[7] Stolboushkin A Y et al. 2011 Resource saving complex processing of technogenic mineral raw materials in the production of construction materials News of Universities. Construction 1 46-53
[8] Gedeonov P P and Yudina L V 1994 Ash and mineral compositions on the basis of fuel industry wastes for road construction Building materials 2 16-8
[9] Shepelev I I et al. 2014 The use of waste alumina production in the construction of roads in Siberia Ecology of industrial production 2 22-7
[10] Shepelev I I et al. 2015 The use of waste alumina production in order to improve the performance properties of road mixture Bulletin of the TGASU 1 182-93
[11] Pichugin A P et al. 2005 Ecological problems of effective use of waste and local raw materials in construction Construction materials 5 2-4