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The influence of clayey raw material and complex mineral binder composition on the properties of soil-concrete for road construction

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Abstract

Today, processing low-grade raw materials draws widespread interest. This aligns with the federal project "Circular Economy", which explores alternative raw material sources – overburden rocks and naturally occurring soils of similar composition – and practical processing technologies to replace traditional materials like crushed stone and sand. Based on the raw material characteristics, engineers develop soil-concrete formulations with a complex mineral binder to meet required physical-mechanical and water-physical properties. To study how the raw materials interact with binder components during composite synthesis, researchers apply a set of physicochemical analytical methods using high-precision equipment. They evaluate the raw material properties according to GOST 25100-2020 and test the synthesized composites per GOST R 70452-2022. Findings show that these procedures produce effective road-construction composites for road bases, achieving strength grades M40-M75 and frost resistance grades F10-F15. The proposed approaches support scaling the solution, including recycling mining waste – mainly clayey overburden rocks – into usable construction materials.

Keywords

clayey raw material; cement; polymer-mineral additive; complex mineral binder; soil-concrete; physical-mechanical properties; phase composition

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Introduction

The mining industry comprises a set of sectors engaged in exploration, extraction, and primary processing of minerals. Mineral extraction invariably leads to large-scale accumulation of waste. In Russia, the total annual volume of mining industry waste[1] reaches 8-9 billion tons. These anthropogenic formations not only occupy vast areas but also exert a multifaceted negative impact on the ecosystem: they pollute soils and water bodies with seepage flows characterized by low pH (1-3) and high mineralization (to 50 g/l); promote leaching of heavy metals and sulphate ions (to 30 g/l); alter the hydrological regime and microclimate of adjacent areas; and reduce biodiversity and land productivity [1]. Given the growing anthropogenic impact on the environment and the intensification of industrial production, the issues of rational use of material resources

[1] State Report "On the State and Protection of the Environment of the Russian Federation in 2024". URL: https://www.mnr.gov.ru/docs/o_sostoyanii_i_ob_okhrane_okruzhayushchey_sredy_rossiyskoy_federatsii/gosudarstvennyy_doklad_o_sostoyanii_i_ob_okhrane_okruzhayushchey_sredy_rossiyskoy_federatsii_v_2024_/ (accessed 23.06.2026).

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and minimization of environmental risks are becoming increasingly relevant. Today, the processing of low-grade raw materials is of particular interest [2-4], driven not only by the accumulation of anthropogenic waste across various industries but also by the emerging shortage of primary traditional resources, including those linked to mining restrictions [5].

The global trend towards sustainable development and circular economy necessitates a rethinking of approaches to material flow management [6, 7]. The traditional linear model of extraction – production – disposal proves inefficient: industrial waste volumes reach critical levels, posing serious environmental threats, while the depletion of natural deposits of strategically important raw materials challenges the long-term resource security of many industries. In this context, developing effective approaches to using anthropogenic raw materials is highly relevant [8-10].

Construction is one of the largest consumers of mineral resources [11, 12]. Under current conditions, various construction sectors are increasingly considering the use of secondary and anthropogenic raw materials [13-15]. An analysis of scientific publications in this area confirms the widespread nature of the problem and the active search for solutions [15-17]. Among different construction fields, road construction stands out as the largest consumer of anthropogenic waste [18-20], where millions of tonnes of various industrial wastes, including overburden rocks, undergo processing. Experience in using secondary and anthropogenic raw materials in road construction demonstrates the feasibility of effectively partially or fully replacing traditional raw materials without compromising the required final performance parameters of road structures [21-23]. However, despite their exciting potential, such wastes often require various treatment methods (sometimes a combination thereof) to ensure the proper quality of the final product [24-26].

Overburden rocks feature a heterogeneous composition and include sedimentary, igneous, and metamorphic rocks – ranging from clays and sands to crushed stone. Their chemical and mineral composition is characterized by a high proportion of clayey components, silica compounds, and oxides of aluminium, calcium, and magnesium [27, 28]. Therefore, using such materials in road construction in their original form is not feasible: requirements for water and frost resistance must be met, since clayey raw material forms a hydrophilic system and promotes accumulation of capillary moisture [29, 30]. The choice of a specific approach primarily depends on the functional purpose of the mineral raw material derived from overburden rocks. Researchers at the Belgorod State Technological University named after V.G.Shukhov have repeatedly conducted studies to develop engineering solutions for the effective use of overburden rocks in road construction. For example, in producing mineral powders for asphalt concrete, thermal treatment and mechanical activation of clayey raw materials were proposed [31]. For soil-concrete based on clayey raw material from overburden rocks, the effectiveness of various mineral binders or their combinations (lime, cement) with additives was shown; these additives help ensure cost-effective production of soil-concrete while meeting the required parameters [32-34]. The accumulated experience shows that, due to the variability of raw material properties, each case requires an individual approach.

Thus, the relevance of the study stems from the need to build a scientifically grounded basis for transitioning to a circular economy, where low-grade raw materials are regarded not as waste but as a valuable secondary resource. The study proposes approaches to chemical stabilization of various mineral systems using cement binder and polymer-mineral additive, and examines the mechanisms of phase and structure formation, considering the method of additive introduction. The results can be applied in implementing sustainable development strategies for industrial enterprises and in shaping state policy on the management of secondary material resources.

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Methods

To identify the key compositional features of diverse types of feedstock and to study the mechanisms of phase and structure formation in the final composite depending on the binder formulation, the study employed X-ray phase analysis, infrared spectroscopy, differential scanning calorimetry, and thermogravimetry.

X-ray phase analysis of the samples was carried out using an ARL 9900 WorkStation spectrometer with an integrated diffraction system. The phase composition was investigated by X-ray diffractometry on powder samples in the 2θ range of 4-56° and 8-80°. The instrument enables X-ray fluorescence analysis of elements from B to U using an X-ray tube with a Rh anode, and X-ray phase analysis in the 2θ angle range of 8-80° using a tube with a Co anode. Data processing was performed with the following software packages: UniQuant 5.56, Siroquant Version 3.0, ICDD DDVIEW 2010, ICDD PDF-2 Release 2010, Difwin, and Crystallographica Search-Match.

IR spectroscopic analysis was conducted using a VERTEX 70 Fourier-transform IR spectrometer for qualitative material analysis and phase composition identification. Since the studied materials are loose solid rocks, the samples were pressed into pellets from a mixture of the material and potassium bromide. The result was absorption spectra in the range of 400-4000 cm^{-1}.

Calorimetric and thermogravimetric studies were performed using a STA 449 F1 Jupiter instrument (NETZSCH) for each sample within a single experiment that combined the study of phase transitions, decomposition reactions, and material composition – in particular, for soil-concrete. Sample analysis was carried out using corundum crucibles in the temperature range of 25-1000 °C at a heating rate of 10 °C/min in an inert gas (N_2) atmosphere.

To assess the feasibility and effectiveness of engineering approaches for producing road soil-concrete based on the studied mineral raw material varieties, soil-concrete formulations were prepared in accordance with GOST 23558-94[2], and a set of their physical-mechanical properties was studied depending on the quantity and formulation of the binder used, including an additive widely applied in road construction for soil stabilization. Compressive strength and flexural tensile strength of the stabilized soils were determined in accordance with GOST 10180-2012[3]; frost resistance was evaluated using the method specified in GOST 10060-2012[4].

The deformation modulus was computed using the formula

$$E_o = \sigma / \varepsilon_b,$$

where σ is the stress in the soil-concrete sample; ε_b is the total strain caused by the stress.

To evaluate the effectiveness of various binders for producing road soil-concrete, the study examined three mineral raw material samples (Tables 1, 2) [35].

Three cement systems, differing in formulation and production method, were used as binders to produce soil-concrete specimens. The binders were produced by grinding in a ball mill. Binder B1 was produced without any additive and contains 85 % clinker and 5 % gypsum. Binder B2 was obtained by dry mixing of binder B1 with 10 % polymer-mineral additive. Binder B3, or complex mineral binder (CMB 32.5N II, in accordance with GOST R 70196-2022[5]), was produced by co-grinding 85 % clinker, 5 % gypsum, and 10 % polymer-mineral additive.

The following materials were used to form the binder formulations:

- Portland cement clinker produced by Belgorod Cement JSC (Belgorod);
- natural dihydrate gypsum ($CaSO_4 \cdot 2H_2O$) from the Novomoskovsk deposit;
- polymer-mineral additive (PMA) produced by Nickel LLC (Saint Petersburg).

[2] GOST 23558-94. Crushed stone-gravel-sand mixtures and soils treated with inorganic binding materials for road and airfield construction. Specifications.

[3] GOST 10180-2012. Concretes. Methods for determining strength using control specimens.

[4] GOST 10060-2012. Concretes. Methods for determining frost resistance.

[5] GOST R 70196-2022. Public roads. Complex mineral binders for soil stabilization and strengthening. Specifications.

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According to STO 13881083.002-2021[6], the polymer-mineral additive produced by Nickel LLC has the following chemical composition, wt.%: CaO 45.0±5.0; SiO_2 43.0±5.0; Al_2O_3 1.1±0.3; Fe_2O_3 1.4±0.3; MgO 1.1±0.4; F 4.4±1.0; other 4.0±1.0. In accordance with patents [36, 37] preceding STO 13881083.002-2021, the component composition includes activated silica, redispersible lignin-based polymer powders, calcium salts, and sodium salts.

Results dicussion

Based on the physical-mechanical properties (Table 1), the examined mineral raw material falls into three fundamentally diverse types: sample 1 – light silty loam; sample 2 – silty sandy loam; sample 3 – sand. Given the significant differences in plasticity index I_P and optimum moisture content W_{opt}, each soil type requires an individually tailored dosage of binder with additive to achieve the extreme values of the physical-mechanical and water-physical properties of the soil-concrete.

Table 1

Physical-mechanical properties of mineral raw material as a basis for soil-concrete, in accordance with GOST 25100-2020

Sample	Liquid limit W_L, %	Plastic limit W_P, %	I_P, %	Sand fraction content, %	W_{opt}, %	Dry density of the soil ρ_d, g/cm^3	pH	Soil type (according to classification criteria)
1	30	18.70	11.30	43	17.70	1.76	7.3	Light silty loam
2	19	12.88	6.12	55	11.00	2.01	7.0	Silty sandy loam
3	–	–	–	95	7.03	1.61	7.0	Sand

Based on the chemical composition data (Table 2), all three samples show a predominance of the aluminosilicate component. Compared to samples 1 and 3 (light silty loam and sand), the composition of sample 2 is characterized by significant variations in silicon dioxide (SiO_2) and calcium oxide (CaO).

Table 2

Chemical composition of mineral raw material as a basis for soil-concrete

Soil	Content, wt.%										
	SiO_2	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	TiO_2	P_2O_5	SO_3	Other
Sample 1	57.10	17.67	10.83	5.59	3.97	2.40	1.08	0.77	0.19	0.11	0.29
Sample 2	66.57	19.05	1.64	4.20	3.28	2.25	1.68	0.74	0.22	0.05	0.32
Sample 3	57.46	18.17	9.89	5.83	3.87	2.40	1.10	0.78	0.15	0.06	0.29

Based on the X-ray phase analysis results (Fig.1, *a*), the main components of the examined clayey raw material are quartz, clay minerals (kaolinite, nontronite, chlorite, hydromica), feldspars, mica (muscovite), and calcite.

Using IR spectral analysis (Fig.1, *b*), the stretching vibrations of bridging (Si–O–Si(Al) and non-bridging (Si–O, Al–O) bonds in the silicate and aluminosilicate groups of the mineral phases of the studied raw material were identified. The most intense absorption bands were recorded in the 900-1200 cm^{-1} range. The absorption bands at 3696 and 3621 cm^{-1} correspond to the stretching vibrations of hydroxyl groups (OH^-). For all three mineral systems, the presence is noted (Fig.1, *b*) predominantly of kaolinite (absorption bands in the wavenumber range 1120-690 cm^{-1}) and, to a lesser extent, of clay minerals (absorption bands in the wavenumber range 520-450 cm^{-1}); quartz

[6] STO 13881083.002-2021. Polymer-mineral additive NICOFLOK for mixtures with inorganic binders. Specifications.

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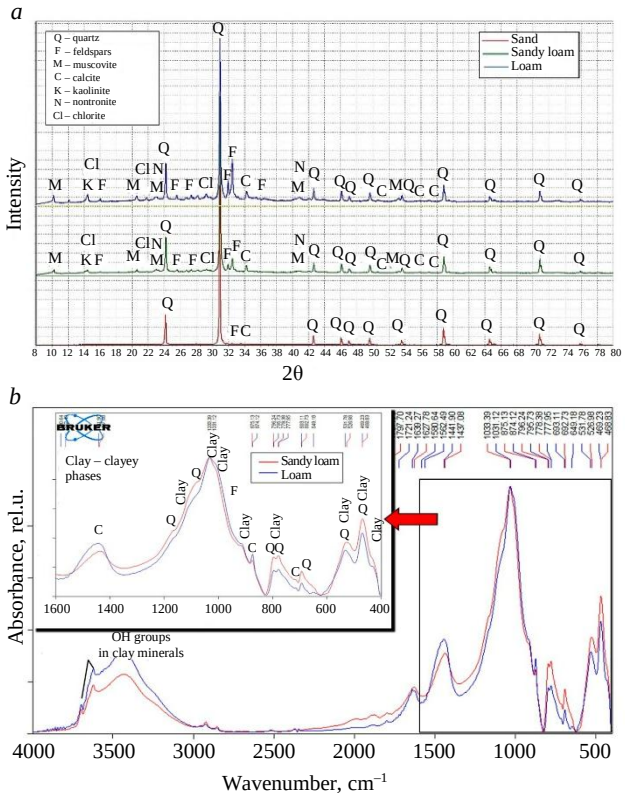


Fig.1. Mineral composition of the raw material used as a base for soil-concrete:
a – X-ray diffraction method;
b – IR spectroscopy method for light silty loam and silty sandy loam

(absorption bands in the wavenumber range 1170-690 cm^{-1}); and calcite (absorption bands in the wavenumber range 1450-710 cm^{-1}). For the light silty loam and silty sandy loam, an overlap of kaolinite absorption bands with those of other aluminosilicate phases is characteristic.

The sand spectrum is almost identical to the quartz spectrum, as evidenced by the main peaks (absorption bands in the wavenumber range 1170-460 cm^{-1}) (Fig.1, *b*). According to IR spectroscopy data, it is difficult to clearly identify minerals such as feldspars and micas due to the overlap of absorption bands in the wavenumber region corresponding to clay minerals and quartz. The results of the IR spectroscopic analysis are consistent with the X-ray phase analysis data.

A comprehensive study using X-ray phase and IR spectroscopic analyses, combined with the initial data on the physical-mechanical properties and chemical composition of the mineral raw material, made it possible to identify significant differences when transitioning between the varieties of the studied mineral raw material. Based on the data analysed, among the mineral raw materials studied, the light silty loam is characterized by the highest activity with respect to hydraulic binders. This feature is due to its particle-size distribution, in particular, the highest content of highly dispersed fractions compared to other samples, which have a potential ability to form cementing bonds. Consequently, the light silty loam will obviously require a smaller amount of binder to achieve the required physical-mechanical parameters. In contrast, the sand will exhibit lower activity, and to achieve the required physical-mechanical parameters of the soil-concrete based on it, a larger amount of binder will probably be required compared to other types of raw material. At the same time, the crucial role in selecting rational soil-concrete formulations based on clayey raw material is assigned to the intended use of soil-concrete and, consequently, the operating conditions (intensity of applied loads, moisture conditions, and the frequency of transitions through 0 °C). The most rational, resource-efficient, and simple option from a practical application standpoint for the specified raw material varieties in road construction is the arrangement of base layers.

Based on a comprehensive analysis of the effect of various binder formulations and their concentrations on the physical-mechanical properties of the soil-concrete samples, it was observed for the studied mineral systems that the most effective soil-concrete formulations are those using the complex mineral binder (B3, Fig.2). For mineral systems in the form of light silty loam and silty sandy loam with a high proportion of clay component, the use of 4-6 % CMB is sufficient, whereas for sand, the use of at least 8 % CMB is required. At the same time, according to the compressive strength and frost resistance indicators, in accordance with GOST 23558-94, soil-concretes of strength grades M40-M75 and frost resistance grades F10-F15 can be obtained.

According to the X-ray phase analysis data, no significant differences were identified between the initial raw material and the soil-concrete samples using various binder formulations (Fig.3, *a*). However, the use of IR spectroscopy allowed some differences to be revealed (Fig.3, *b*).

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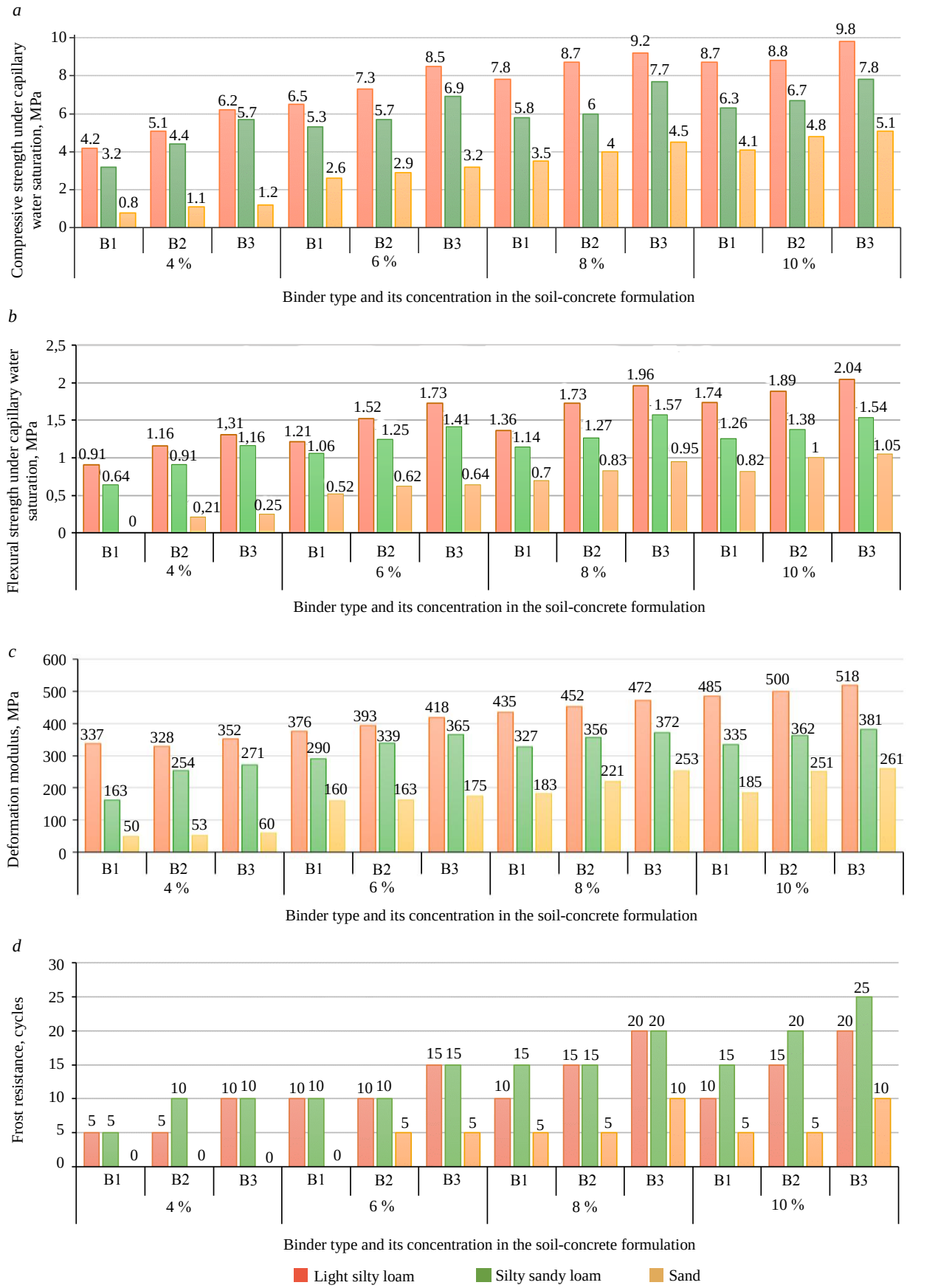


Fig.2. Physical-mechanical properties of soil-concrete samples as a function of the type of mineral raw material, as well as the formulation and concentration of the binder: *a* – compressive strength under capillary water saturation; *b* – flexural strength under capillary water saturation; *c* – deformation modulus; *d* – frost resistance

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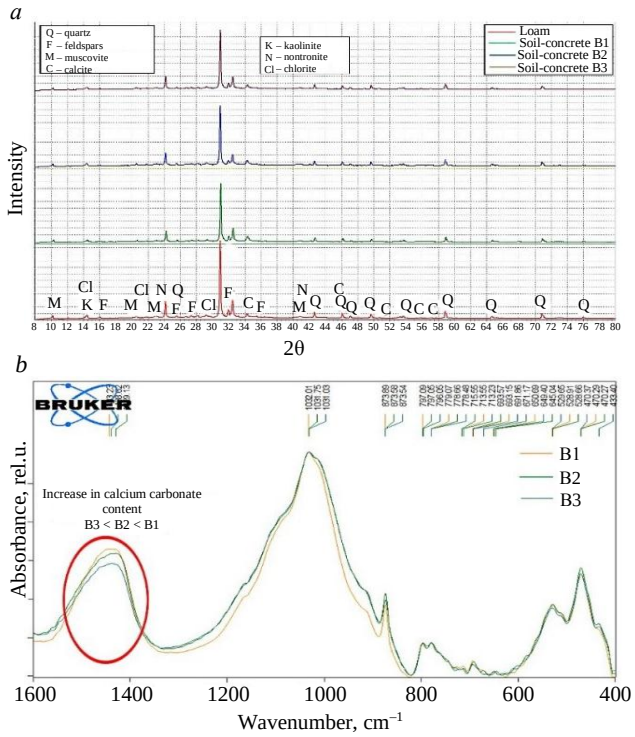


Fig.3. Results of phase composition analysis of soil-concrete based on light silty loam with various binder formulations, using X-ray diffraction and IR spectroscopy:
a – X-ray diffraction pattern; *b* – infrared spectra

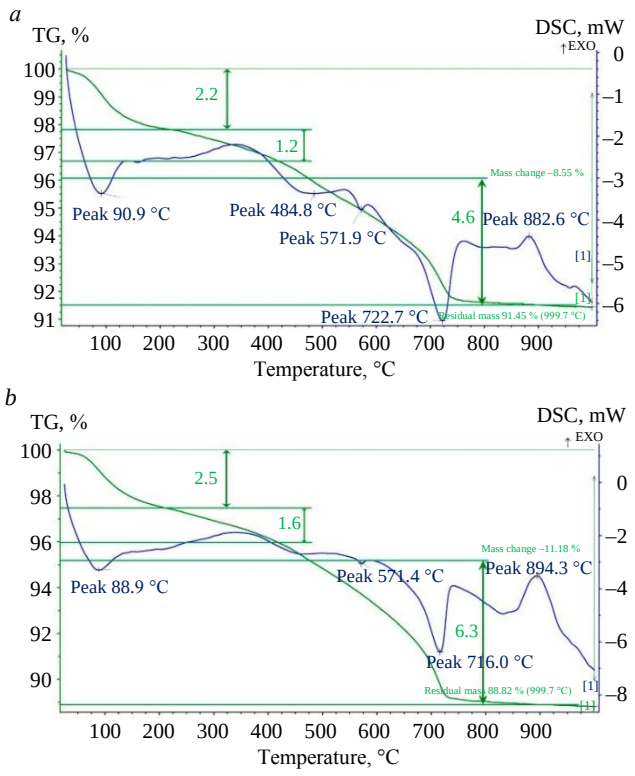


Fig.4. Results of the sample studies using DSC and TG:
a – light silty loam; *b* – soil-concrete based on light silty loam at 28 days of age

Minor deviations in the spectra in the wavenumber range 900-1200 cm^{-1}, which practically do not affect the region of silicate and aluminosilicate groups of the soil mineral phases, indicate the stability of the main framework structure. As a result of obtaining the difference curve in the specified range, the image is of little informational value. A visible difference between the obtained spectra is noted in the absorption bands in the wavenumber range 1400-1500 cm^{-1} and around 875 cm^{-1}, characteristic of calcium carbonates (Fig.3, *b*). Compared to the initial raw material, these are noticeably more abundant in the soil-concrete formulations, and, depending on the binder formulation, their amount increases in the following order: soil-concrete using B3 → soil-concrete using B2 → soil-concrete using B1.

In the case of soil-concrete based on heavy silty loam, the most informative methods for analysing the phase and structure formation processes as a result of binder hydration were differential scanning calorimetry (DSC) (Fig.4) and thermogravimetry (TG) (Table 3).

Since the light silty loam constitutes 90 % or more of the soil-concrete, the obtained curves are quite similar (Fig.4). Due to the presence of up to 10 % binder containing cement in the soil-concrete formulation, a certain amount of hydrated formations is identified. The processes occurring as a result of hardening are similar to those in cement systems but differ in the depth of the effects and greater mass loss.

The DSC method revealed six main thermal effects characterising the physicochemical transformations in the studied material. The endothermic effect in the 50-120 °C range with a maximum at 90 °C is due to the mass loss of the sample caused by the removal of adsorbed and structural water (Fig.4, *a*). The next effect at 485 °C, accompanied by a mass reduction up to 700 °C, is associated with the dehydration of clay minerals (kaolinite, nontronite, chlorite) – the removal of hydroxyl groups and the transformation of their crystal lattices. The overlapping processes above 700 °C represent the continuing dehydration of the clay minerals, which is superimposed by the following endothermic effect at 723 °C – corresponding to the decomposition of calcite ($CaCO_3$). The polymorphic

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transition of quartz at 572 °C – a reversible transformation of α-quartz into β-quartz – is recorded as a separate endothermic peak. The endoeffect at 883 °C is presumably associated with the formation of spinel ($MgAl_2O_4$ or similar compounds) as a result of the thermal decomposition of clay minerals. Additional processes manifested in the temperature range are characteristic of structural changes in the hardened cement paste (Table 3) and are due to the presence of cement in the soil-concrete formulation. The mass losses for the initial mineral raw material in the form of light silty loam amount to about 9 %; for the soil-concrete based on it – over 11 % (Fig.4, *b*). The temperature range of the study was divided into characteristic intervals considering the influence of the cement binder component, which made it possible to differentiate the effects related to the mineralogical composition of the initial mineral raw material and the hydration/dehydration processes of the hardened cement paste.

Table 3

Change in mass of the initial raw material samples and the composite based on it on the 28th day according to the temperature ranges

Temperature range, °C	Mass loss, %		Process
	Light silty loam	Soil-concrete	
25-220	2.2	1.1	Removal of moisture and dehydration of the CSH gel and calcium hydrosulphoaluminates
220-420	2.5	1.6	Dehydration of C_4AH_{13} (and possibly C_3AH_6)
475-900	4.6	6.3	Loss of structural OH groups of C-S-H and decomposition of vaterite and calcite

The temperature range of 420-475 °C shows a comparable mass loss for both samples, but it does not provide significant information due to the absence of portlandite in them. Comparison of mass changes in other temperature intervals (Table 3) indicates a substantial content of calcium hydrosilicates, hydroaluminates, and calcium carbonates in the soil-concrete, which is confirmed by IR spectroscopy (see Fig.3, *b*).

According to the X-ray phase analysis (XRD) data (Fig.5, *a*), no clinker phases or hydration products, including portlandite $Ca(OH)_2$, were detected in the soil-concretes based on silty sandy

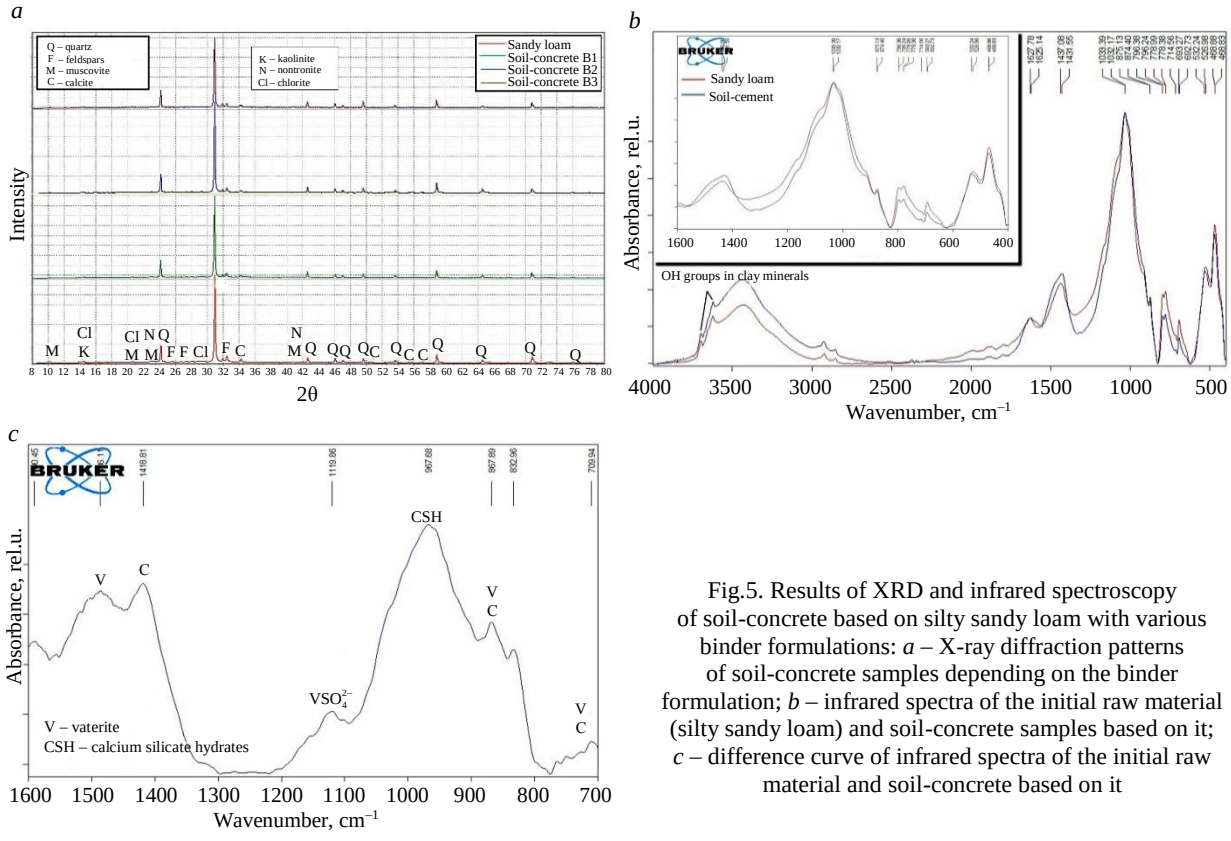


Fig.5. Results of XRD and infrared spectroscopy of soil-concrete based on silty sandy loam with various binder formulations: *a* – X-ray diffraction patterns of soil-concrete samples depending on the binder formulation; *b* – infrared spectra of the initial raw material (silty sandy loam) and soil-concrete samples based on it; *c* – difference curve of infrared spectra of the initial raw material and soil-concrete based on it

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loam with various binder formulations. The diffraction patterns of the initial raw material and the soil-concretes show a high degree of similarity. The mineralogical composition of the samples includes quartz, feldspars, muscovite, clay minerals (kaolinite, nontronite, chlorite), and calcite, which indicates a high similarity to the composition of light silty loam. The presence of calcium carbonate in the raw material may be due to the carbonation process of calcium-containing compounds.

The absence of crystalline new formations, detected by XRD, is probably due to their nanoscale dispersion, which does not allow the phases to be detected by standard X-ray diffraction methods.

When using IR spectroscopy (Fig.5, *b*), no significant differences between the initial raw material and the soil-concrete samples were also found. Only a more detailed analysis of the spectra in the wavenumber range of 400-1600 cm^{-1} allowed some differences in the spectral line after hardening to be identified. Here, a decrease in the intensity of absorption bands in the ranges of 620-800 cm^{-1} and 1050-1400 cm^{-1} is noted, as well as an increase in intensity in the region of 900-1000 cm^{-1}, where the absorption bands of calcium silicates and calcium hydrosilicates are located (Fig.5, *b*).

In the IR spectra, a decrease in the intensity of absorption bands in the ranges of 620-800 cm^{-1} and 1050-1400 cm^{-1} is observed, as well as an increase in intensity in the region of 900-1000 cm^{-1} corresponding to the absorption bands of calcium silicates and calcium hydrosilicates (Fig.5, *b*). Based on the difference curve constructed between the spectra of the soil-concrete and the initial mineral raw material (silty sandy loam), a distinct peak at 968 cm^{-1} was recorded, associated with the absorption bands of the CSH gel (Fig.5, *c*). Additionally, two characteristic peaks at 1419 and 1485 cm^{-1} were identified, corresponding to calcite and vaterite. The absence of peaks characteristic of portlandite is consistent with the XRD data.

According to the XRD (Fig.6), in the soil-concrete based on sand, regardless of the binder formulation, along with the characteristic minerals of the soil-concrete base (quartz, feldspars),

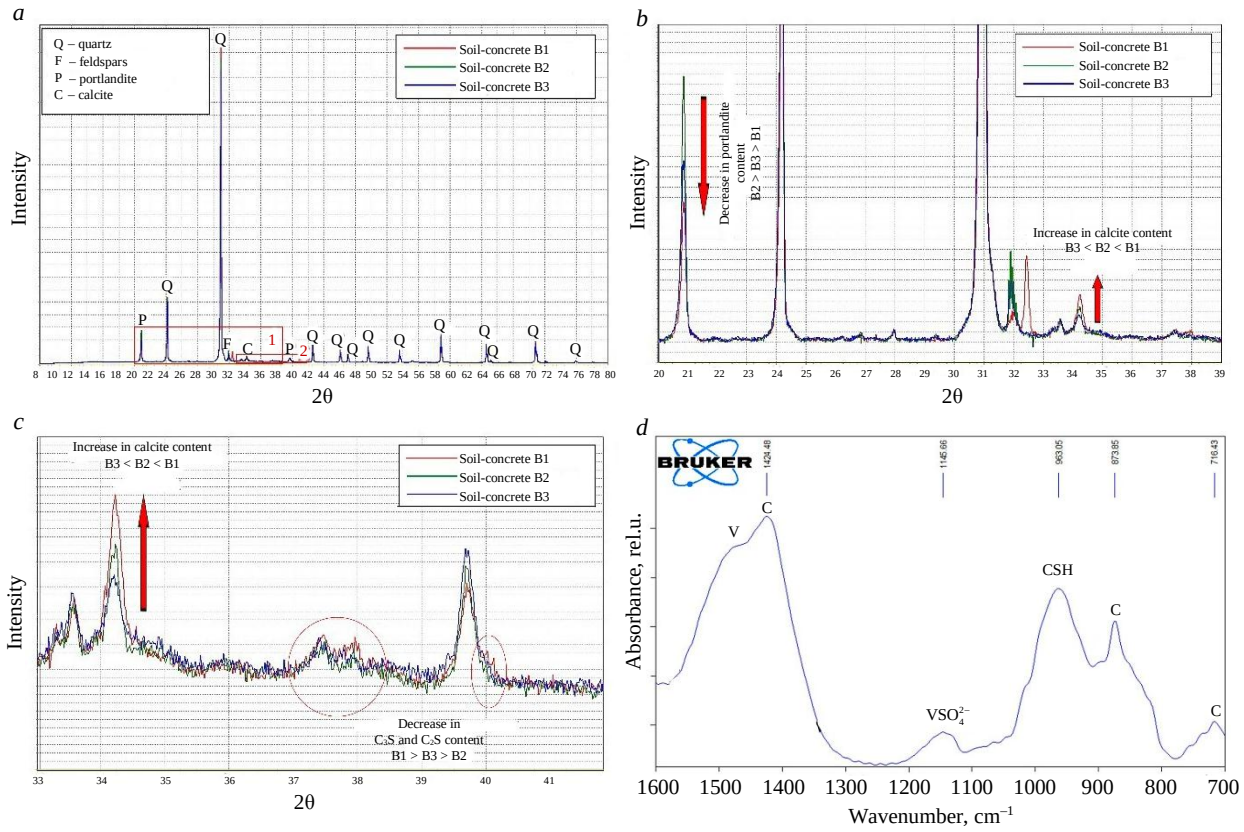


Fig.6. Results of phase composition analysis of soil-concrete based on sand with various binder formulations, using XRD and IR spectroscopy:
a – general X-ray diffraction pattern; *b* – fragments of the X-ray diffraction pattern in the 2θ range of 20-39°; *c* – fragments of the X-ray diffraction pattern in the 2θ range of 33-42°; *d* – IR spectrum

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portlandite, calcite, and calcium silicates (alite, belite) are identified. For easier comparison of the X-ray diffraction patterns, the curves are normalized to the intensity of the main quartz reflection with d = 3.35 Å.

Depending on the binder formulation used to produce soil-concrete, fluctuations in the quantitative content of portlandite $Ca(OH)_2$ (based on the main peak at d = 4.94 Å) were detected. Thus, the soil-concrete produced with binder formulation B2 is characterized by the highest content of portlandite, while that with binder B1 has the lowest content. In turn, the soil-concrete produced with binder B3 shows the highest intensity of the main reflection peak of calcite ($CaCO_3$), which is a product of the carbonation of portlandite formed during cement hydration; the lowest intensity is observed for binder B1. As a result, the sand-based soil-concrete using cement without an additive (B1) contains the minimum amount of portlandite and the maximum amount of calcite. When an additive is used, depending on the method of its introduction, the portlandite/calcite ratio increases towards portlandite. Thus, the use of an additive in binders B2 and B3 inhibits the conversion of portlandite into calcite, promoting reactions between $Ca(OH)_2$ and the amorphous silica present in the additive, followed by the formation of calcium hydrosilicates. This accounts for the improvement in the physical-mechanical properties of the soil-concrete.

By constructing the difference curve of the infrared spectra of soil-concrete and sand, the phases of vaterite and calcium hydrosilicates were identified (Fig.6). The spectra do not show fundamental differences regardless of the binder formulation used.

Using a linear model, the identified dependencies were clearly demonstrated (Fig.7). Upon transitioning from light silty loam to sand, a decrease in the content of clay particles in the studied mineral systems is observed, which leads to a reduction in the strength parameters of the soil-concrete formulations. Consequently, the slope of the graphs relative to the X-axis becomes less steep.

As a result, a pattern was revealed: the rate of increase in the compressive strength of the soil-concrete samples, when using binder formulations from B1 to B3, rises with an increase in the clay component content in the raw material, which is characterized by its plasticity index (Fig.7, *b*). The graph demonstrates a close fit to a linear relationship – the linear approximation coefficient exceeds 0.99.

Conclusion

The conducted study showed the effectiveness of using a complex mineral binder produced by co-grinding cement clinker, gypsum, and a polymer-mineral additive for making soil-concretes based on clayey raw material. A comparative analysis of the set of physical-mechanical properties revealed the possibility of halving the binder consumption and effectively utilizing low-grade clayey raw material to produce soil-concretes of grades in terms of strength M40-M75 and frost resistance F10-F15. Such soil-concrete formulations are recommended for constructing base layers of both lightweight

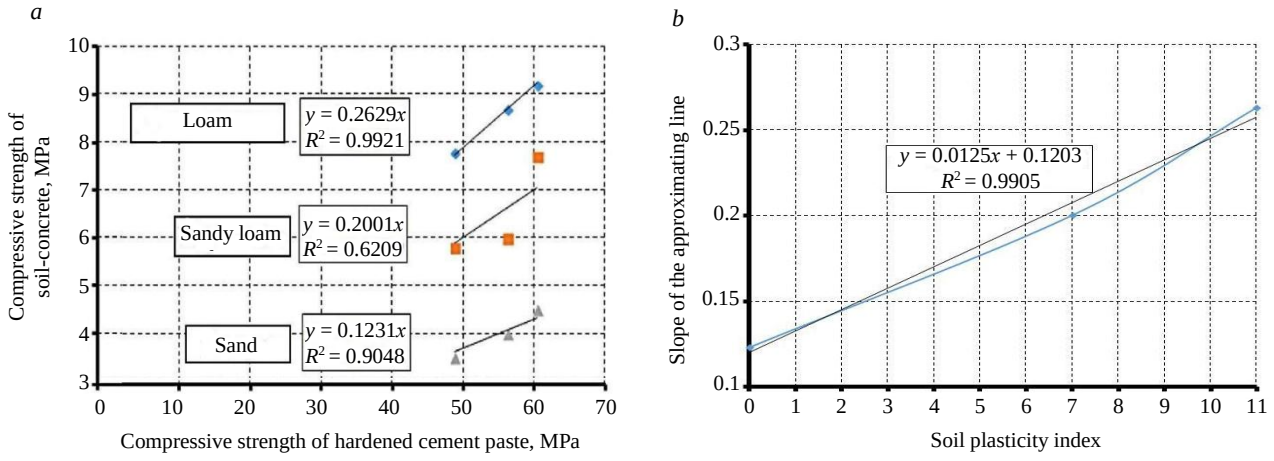


Fig.7. Dependences of the compressive strength of soil-concrete samples on the clay fraction content in the raw material and on the binder formulation used (*a*); variation of the graph slope coefficient vs. the plasticity index of the initial mineral system (*b*)

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and heavy-duty types of road pavements, with the optimal CMB content in the soil-concrete being 4-6 % for light silty loam and silty sandy loam, depending on the type of road pavement and the required grade of the final material; for sand, the content should be ≥ 8 %. Considering the replacement of traditional primary resources (e.g., sand) in the lower base layer, the economic benefit from using clayey raw material may reach to 15 % of the total estimated construction cost.

Based on the data about phase and structure formation in soil-concrete samples, we found that using CMB provides a pronounced synergistic effect: the components of the polymer-mineral additive interact with the binder and improve the soil-concrete properties for all the mineral raw material types considered. The clay particle content in the initial raw material plays a key role in forming a dense and strong structure. In composites based on mineral systems with a high proportion of clay component, secondary cementing products are formed in addition to the primary ones. These arise as a result of pozzolanic reactions between aluminosilicate clay minerals and calcium hydroxide. A clear dependence is observed: the lower the proportion of quartz and other minerals, the more noticeable the contribution of secondary cementing products. The use of the polymer-mineral additive enhances this effect. The maximum result is achieved when using CMB produced by co-grinding with the additive, as it contains amorphous silica, which also participates in pozzolanic reactions and promotes the formation of additional cementing products. The most pronounced effect with CMB is explained by the uniform distribution of the additive not only in the binder but also in the soil-concrete mixture.

Thus, the obtained positive results allow concluding that the use of a complex mineral binder with a polymer-mineral additive is effective for producing soil-concretes based on clayey raw material. Given the similarity in composition and properties between the considered anthropogenic raw material (as a basis for soil-concretes) and overburden rocks, as well as the available data on the patterns of phase and structure formation depending on the raw material type, the proposed approaches can be recommended for the utilization of clayey waste from the mining industry. Considering the volume of mineral resource consumption in road construction, the active use of overburden rocks will not only yield a significant economic benefit but also make a substantial contribution to improving the environmental situation.

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