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Mineralogical and granulometric composition of soils formed on the surface of iron ore tailings dumps

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Abstract. Hydraulic dumps for storing waste from primary and secondary iron ore processing (tailings dumps) were selected as objects for research. In the course of the study, data on the mineralogical composition of soil-forming rock samples of technogenic landscapes were obtained. This indicator is one of the main factors of soil formation when considering lithology at a lower hierarchical level. The mineralogical composition influences the content and ratio of nutrients and toxicants in soils, ion exchange processes, soil resistance to degradation and overall soil fertility. The mineralogical composition is the matrix of soil formation and regulates the transformation, migration and accumulation of matter, energy and information of the external environment and anthropogenic impact in the soil. The hydraulic filling method of waste storage has an impact on the spatial distribution of material in tailings dumps. First of all, a contrasting addition in terms of granulometric composition is distinguished due to the deposition of particles in aqueous conditions under the influence of a gravitational field. The deposition rate depends on the mass, size, shape and density of the particle substance, viscosity and density of the medium, as well as on acceleration, gravity and centrifugal forces acting on the particles. Despite a significant amount of research on the effect of mineralogical composition on soil development, this problem was not sufficiently studied. This determines the absence of generally accepted indicators of the development rate of soils formed on a man-made mineral substrate and the accumulation degree of biophilic elements in such soils.

Keywords: mineralogical composition, soil-forming rocks, tailings dump, soils of man-made landscapes, granulometric composition

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Минералогический и гранулометрический составы почв, формирующихся на поверхности железорудных хвостохранилищ

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Аннотация. Объектом исследования являются гидроотвалы складирования отходов первичного и вторичного обогащений железной руды (хвостохранилища). В ходе исследования получены данные минералогического состава образцов почвообразующей породы техногенных ландшафтов. Рассматриваемый показатель является одним из основных факторов почвообразования при изучении литологии на более низком иерархическом уровне. Минералогический состав оказывает влияние на содержание и соотношение в почвах элементов питания и токсикантов, процессы ионного обмена, устойчивость почв к деградации и общее плодородие почв. Он является матрицей формирования почв и регулирует трансформацию, миграцию и аккумуляцию в почве веществ, энергии и информации внешней среды и антропогенного воздействия. Гидроналивной способ складирования отходов оказывает влияние на пространственное распределение материала в хвостохранилищах. Прежде всего выделяется контрастное сложение по гранулометрическому составу из-за осаждения частиц в водных условиях под действием гравитационного поля. Скорость осаждения зависит от массы, размера, формы и плотности вещества частиц, вязкости и плотности среды, а также от ускорения, силы тяжести и действующих на частицы центробежных сил. Несмотря на значительное количество исследований по влиянию минералогического состава на развитие почв, данная проблема изучена недостаточно. Это определяет отсутствие общепринятых показателей скорости развития почв, формирующихся на техногенном минеральном субстрате, и степени накопления в таких почвах биофильных элементов.

Ключевые слова: минералогический состав, почвообразующие породы, хвостохранилище, почвы техногенных ландшафтов, гранулометрический состав

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Introduction

Kuzbass is one of Russia's most industrially developed regions. High concentration of industrial enterprises, combined with the unsustainable use of natural resources, has led to the creation of man-made landscapes on land that was once fertile. In the southern part of Kemerovo Region – Kuzbass, the EVRAZ United West-Siberian Metallurgical Plant (EVRAZ ZSMK) is located, a full-cycle facility that produces rolled metal for the construction, railway, and other industries. The raw material used is iron ore, which is processed at the Abagur beneficiation and sintering plant (formerly the Mundybash beneficiation plant). The ore processing generates waste (enrichment tailings) that is stored in hydraulic dumps. As a result, man-made landscapes have emerged in the region, where young soils are now beginning to form on their surfaces.

The mineralogical composition of soils is a key factor that directly influences their physical and chemical properties, as well as the processes occurring within them. It serves as a matrix for the development of soil properties, regulating the transformation, migration, and accumulation of matter, energy, and environmental information. Unlike other factors such as climate, topography, and vegetation, which determine the mechanisms and pace of soil formation, the mineral substrate provides the material foundation from which the soil profile develops [1; 2].

Studying the mineralogical composition not only aids in understanding soil properties but also in grasping the genesis of newly forming man-made soils, as it sets the stage for the direction and intensity of soil-forming processes (humus accumulation, internal weathering, illimerization, podzolization, gleying, brunification, and more). Therefore, determining and accounting for mineralogical composition is essential when classifying soils [1; 3; 4].

The main aim of this work is to investigate the mineralogical and granulometric composition of rocks from primary and secondary iron ore enrichment tailings, where the formation of young soils (embryozems) is currently underway.

Objects and methods of research

The objects of the study were the hydraulic dumps of the Mundybash beneficiation plant (primary) (N53°13′28.90″ E86°16′04.01″) and the Abagur beneficiation and sintering plant (secondary) (N53°42′11.95″ E87°14′12.50″).

The Mundybash beneficiation plant was built between 1931 and 1935 to enrich iron ore from the nearby Telbes mine of the Kuznetsk Metallurgical Plant. The plant operated until April 2015, after which it ceased its activities. The hydraulic dump has presumably been out of operation since 2000.

The Abagur beneficiation and sintering plant processes primary concentrates and produces secondary concentrate. The plant's product is supplied to EVRAZ ZSMK. The production capacity of units *1* and *2* is 3.560 million tons of industrial products per year and 2.780 million tons of concentrate (from the mines of Gornaya Shoria and Abakanskoye Mine). The production capacity of unit *3* is 2.858 million tons of industrial products per year and 1.960 million tons of concentrate (from the Teiskoe mine and 10 % from the Gornaya Shoria mines). The studied hydraulic dump has been out of operation since 2001.

At each of the studied iron ore hydraulic dumps, four concentric zones were identified, differing in the degree of material dispersion (the mouth, main, near-core, and core zones). The upper part of the sedimentation basin (mouth zone) is characterized by a light mechanical composition and high drainage capacity. The main zone, formed by particles of medium dispersion, occupies most of the tailings area. The near-core and core zones, which are thixotropic or water-covered, form the accumulative center of the drainage basin. In each zone, samples were taken from a 0 – 40 cm layer, as this layer potentially acts as the accumulation zone for 90 % of root mass.

The mineralogical and petrographic compositions of samples from different sedimentation zones of the tailings were studied using an MBS-10 stereoscopic microscope (magnification 8 – 16) in reflected light. The study included the examination of external (macroscopic) characteristics and physical properties. In some cases, simple microchemical drop reactions and powder reactions were applied [5; 6].

Granulometric composition, as one of the important indicators of soil that affects many aspects of soil existence and functioning, was analyzed using the Kachinsky pyrophosphate method of sample preparation. The analysis focused on fractions of physical sand and physical clay with sizes greater than 0.01 mm (up to 1 mm) and less than 0.01 mm.

Research results

The hydraulic filling method of storing ore enrichment waste influences the spatial distribution of material in the hydraulic dumps. A contrasting structure in terms of granulometric composition is primarily distinguished due to particle sedimentation in aqueous conditions under the influence of the gravitational field. The rate of sedimentation depends on the mass, size, shape, and density of the particle substance, the viscosity and density of the medium, as well as acceleration, gravitational force, and centrifugal forces acting on the particles.

All sedimentation zones exhibit spatial heterogeneity in granulometric composition: an increase in the clay content and a decrease in sand fractions are observed from the mouth zone to the core zone (see Table). All samples consisted of fine earth, with no particles larger than 1 mm. The redistribution of clay fractions in the sedimentation zones at all research sites follows a similar pattern, with the relative quantities in each zone forming the following sequence: fine silt (about 50 %) – medium silt (about 30 %) – clay (about 20 %). The redistribution of fractions within the physical sand group across all studied sites is heterogeneous and depended on the type of disintegrated rock.

The mouth zone, located at the outer perimeter of the hydraulic dumps, is characterized by a sandy (Mundybash beneficiation plant) or sandy loam (Abagur sintering plant) granulometric composition. In this zone, soil formation is slow across all observation sites, so the soil cover mainly consists of initial embryozems. The vegetation cover is either absent or represented by isolated specimens of ruderal vegetation from the xerophytic ecogroup. In the physical sand fraction of the Mundybash plant hydraulic dump, just under 50 % of the particles are fine sand, while the remainder is equally divided between coarse-medium sand and coarse dust. A similar pattern of sand fraction distribution is observed in the hydraulic dump of the Abagur sintering plant. In general, it is worth noting that the highest degree of deflation and erosion processes is observed in this zone on the surface of the hydraulic dumps.

The mineralogical composition includes both primary and secondary minerals. The mineral composition of the Mundybash plant hydraulic dump is characterized by the presence of magnetite fragments less than 0.5 mm (about 10 %), and occasionally up to 1.5 mm; isolated inclusions of molybdenite; numerous calcite crystals, including marble fragments ranging in size from 1.5 to 2.0 mm and smaller; serpentine fragments (1.5 to 2.0 mm) about 10 – 15 %; isolated talc flakes; pyroxenes less than 5 %; and rare quartz. For the Abagur sintering plant, the mineral composition includes magnetite dust (about 5 – 10 %); isolated occurrences of iron slag and chalcopyrite; isolated pyrite; calcite crystals, and a dominance of marble fragments; quartz around 10 %; muscovite about 20 %; pyroxenes around 1 – 3 %; and rare occurrences of amphibole and gypsum (selenite).

Granulometric composition of sludge from tailings dumps

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Sedimentation zone	Predominant soil type	Particle size distribution, %, diameter, mm							
		1.00 – 0.25	0.25 – 0.05	0.05 – 0.01	0.01 – 0.005	0.005 – 0.001	0.001 – 0.0001	Physical clay (<0.01 mm)	Physical sand (<0.01 mm)
Hydraulic dump of the Mundybash Beneficiation Plant									
IV	E. initial	23.31	42.35	24.77	3.41	4.63	1.52	9.6	90.4
III	E. organo-accumulative	0.42	6.60	65.52	10.15	13.32	3.99	27.5	72.5
III	E. turf	3.94	19.67	36.42	14.55	20.20	5.21	40.0	60.0
I	E. coarse-humus-accumulative gley	0.49	0	43.04	21.10	28.03	7.34	56.5	43.5
Hydraulic dump of the Abagur Sintering Plant									
IV	E. initial	22.67	33.41	19.61	8.96	12.44	2.91	24.3	75.7
III	E. organo-accumulative	28.91	16.40	26.03	9.11	14.23	5.32	28.7	71.3
III	E. organo-accumulative gley	4.10	0	25.54	28.42	34.65	7.30	70.4	29.6
I	E. organo-accumulative gley	0.96	0	26.05	27.35	36.94	8.71	73.0	27.0

N o t e. E. – Embryozem; *I* – Core Zone; *II* – Near-core Zone; *III* – Main Zone; *IV* – Mouth Zone.

The presence of secondary minerals, such as goethite and hematite, is characteristic of the sedimentation zone of the tailings, although they occur infrequently.

Based on observations, organo-accumulative embryozems have formed in the main sedimentation zone of the two hydraulic dumps [7; 8]. The surface is covered with ruderal vegetation from the xerophytic ecogroup, with a total projected coverage not exceeding 2 – 5 %. The total physical sand content in this zone ranges from 71 to 90 %, and the granulometric composition of the hydraulic dumps corresponds to light loam. Nevertheless, the redistribution of sand fractions differs across each site: at the Mundybash beneficiation plant tailings dump, the predominant fraction is 0.05 – 0.01 mm (approximately 90 %), while at the Abagur sintering plant, it is 1.00 – 0.25 mm (about 39 %) and 0.05 – 0.01 mm (about 36 %). Erosion processes are evident on the surface, with rills 15 to 40 cm deep and clear signs of deflation processes.

The mineralogical composition of the Mundybash beneficiation plant zone consists of fragments smaller than 0.5 mm (about 10 %) of magnetite and iron slag, with a dominance of calcite crystals and marble fragments less than 0.5 mm (occasionally 1.0 – 1.5 mm); serpentine fragments less than 0.5 mm (rarely 1.0 – 1.5 mm) make up about 5 %; isolated flakes of talc and quartz; pyroxene fragments 1.0 – 1.5 mm and smaller (about 1 – 5 %). Goethite presents as a secondary mineral, albeit rarely. The mineralogical composition in the main zone of the tailings dump is identical to that of the mouth zone, although the fragments are smaller (less than 0.5 – 1.0 mm). In the dust fraction: magnetite (about 5 – 10 %), with calcite, quartz, and muscovite dominating; pyroxenes are present, and secondary minerals are absent.

The near-core zone serves as a distinct transitional boundary marked by the predominance or significant increase of physical clay in the granulometric composition. This increase is due to the specific conditions of hydraulic filling in the hydraulic dump and the sedimentation of rock particles, as well as the influx of fine dust fractions resulting from erosion processes during rainfall. The shift in granulometric composition from medium loam to medium clay (see Table) leads to the formation of turf and organo-accumulative or organo-accumulative gleyic embryozems (with traces of iron oxides due to seasonal waterlogging) on the surface of the hydraulic dumps. As a result, differences are observed in the ecogroups of ruderal vegetation that have formed. In the main zone, mesoxerophytic or xeromesophytic groups dominate, with a projected coverage of up to 10 %, and on the Mundybash plant hydraulic dump, up to 50 %.

The mineralogical composition of the beneficiation plant tailings dump consists of particles smaller than 0.5 mm of iron slag and magnetite (about 10 %); fragments of coal and slag; calcite crystals and marble fragments measuring 1.0 – 0.5 mm and smaller (about 3 %); isolated quartz and talc flakes; and numerous fragments of modern vegetation. Secondary minerals are absent. The mineralogical composition of the near-core zone of the sintering plant tailings dump is identical to that of the mouth zone but has some distinct features: mineral fragments are smaller (less than 0.5 – 1.0 mm); magnetite dust content is about 5 – 10 %; quartz and calcite dominate; pyrite content is around 0.5 %; secondary minerals are absent.

In each of the studied sites, the core zone is the final accumulation zone for clay particles. In the analyzed samples, the physical clay content ranges from 56 to 73 %. While the proportion of fractions within the physical clay remains relatively stable, a redistribution in favor of finer particles can be assumed. The physical sand fraction lacks coarse-medium and fine sand (1.00 – 0.05 mm), with the entire portion consisting of coarse dust (0.05 – 0.01 mm). The heavy granulometric composition hinders filtration and leads to prolonged stagnation of meltwater and rainwater. Currently, two types of gleyic embryozems have been identified on the surface of the core zone (see Table). The difference in embryozem formation across sites is due to the duration of the post-technogenic period, the lithogenic properties of the rocks, and the productivity of the plant communities [9; 10]. The resulting phytocenoses belong to the xeromesophytic/mesophytic ecogroup, with occasional hygrophytes (such as bulrush, sedge, and others). However, during drought periods (when moisture is deficient), these plants either die or remain in a suppressed state.

The mineralogical composition of the core zone of the primary beneficiation tailings dump consists of iron slag and magnetite particles smaller than 0.01 mm (about 1 – 3 %); indeterminate mineral particles smaller than 0.01 mm; as well as modern plant fragments (about 15 %). Secondary minerals are absent. The mineralogical composition of the near-core zone of the tailings dump formed during secondary beneficiation is characterized by the same composition as the previous dominant zones in the relief. However, it has some distinguishing features: a predominance of mineral fragments smaller than 0.5 – 1.0 mm, the presence of magnetite dust (about 5 – 10 %), and a dominance of calcite and quartz. Secondary minerals are absent, as in the previous two sedimentation zones.

Results and discussion

Despite the considerable number of studies on the influence of mineralogical composition on the development of soils formed on the surfaces of iron ore tailings dumps, this issue remains insufficiently studied [11 – 14]. This explains the lack of generally accepted indicators for the rate of soil development on man-made mineral substrates and the accumulation of biophilic elements in such soils.

The most common primary minerals dominating the large fractions of natural soils are quartz, calcite, and micas. It is important to note that this set of minerals serves as an indicator of favorable soil formation processes on the surfaces of man-made landscapes [15 – 17]. The physical properties of soils depend on these primary minerals, which already act as a reserve source of ash elements for plant nutrition. As they undergo transformation, secondary minerals are formed (simple salt minerals, oxide and hydroxide minerals, and clay minerals). Simple salt minerals (calcite, magnesite, dolomite, gypsum, and others) determine the qualitative and quantitative composition of soil salinization. Oxide and hydroxide minerals, due to their large surface area, absorb significant amounts of phosphorus, making it less available to plants. Clay minerals (montmorillonite, kaolinite) and hydromicas, which dominate the fine-dispersed fractions, together with humic acids, improve the water-physical properties of soils, act as sources of mineral nutrients for plants, and determine the soil's absorptive capacity [8].

Calcite is a key indicator of pedogenic transformations in the soils of man-made landscapes [18; 19]. The presence of carbonates throughout the profile clearly reflects the transformation of the original substrate during the soil formation process. The highest calcite concentrations are observed in the mouth, main, and near-core zones of the Mundybash tailings dump. The quantity and variety of calcite forms reflect the intensity of soil formation processes and the transformation of the original substrate. Calcite content is determined, on one hand, by more favorable hydrological conditions (flushing water mode), and on the other hand, by the likely extended duration of soil formation in areas subject to periodic flooding in the core zone.

The presence of secondary minerals (goethite), which form as a result of pyroxene oxidation and hematite dehydration (in the mouth and main zones of the tailings dumps), indicates the intensity and speed of weathering processes. It can be assumed that nearly all iron-containing minerals, upon alteration due to water and humic acid exposure, are transformed into limonite. Additionally, the weathering of iron oxides (magnetite, hematite, goethite), which are found in the mineral composition of the studied tailings dumps, may lead to the release of iron into pore water and its precipitation as ferrihydrite [20 – 22], as well as the formation of iron hydroxide in water and its precipitation in aquifers. Ferrihydrite is further transformed into hematite, with goethite also possibly forming. The type of final mineral depends on the physical and chemical factors influencing the functioning of the hydraulic dumps from iron ore beneficiation waste (temperature, *p*H levels, Fe(III) concentration in solution, and the nature and quantity of accompanying anions). Hematite content reaches a maximum in a slightly alkaline environment and a minimum in moderately acidic conditions. Increasing temperature and decreasing moisture accelerate ferrihydrite transformation and increase the hematite-to-goethite ratio [22]. When in contact with water containing sulfides, iron hydrosulfide forms, which can adsorb onto the surface of mineral grains and transform into iron oxides. In more complex processes, iron oxide FeO_2 may also be involved.

The mineral skeleton of the soil, which primarily consists of quartz, calcite, and primary and secondary iron minerals, serves as the foundation within which the majority of chemical, physicochemical, and biochemical processes essential to soil formation occur on the surface of the studied tailings dumps. Soil formation, as a form of biological weathering, leads to transformations in the granulometric composition, while periodic water infiltration results in the redistribution and change of fraction ratios. For example, winter infiltration in gray forest soils leads to the averaging of fractions to 0.01 mm and increases the mobility of silt, which enhances the transformation of soil-forming rocks [23].

A more intensive soil formation process is currently observed on the mineral substrate surface of the Mundybash beneficiation plant hydraulic dump. Over a pragmatically acceptable time period, coarse-humus-accumulative and turf embryozems have formed there. This is due to the more balanced granulometric composition of the rocks, consisting of no more than 60 % physical clay, which does not impede the seasonal infiltration of the root layer and allows for the filtration of excess moisture into the lower horizons. When the physical clay content exceeds 60 % in both the near-core and core zones of the Abagur sintering plant hydraulic dump, an aquiclude forms almost at the surface of the mineral layer (within the 10 – 30 cm layer), leading to water stagnation, especially during the spring and autumn periods. This phenomenon slows the soil formation processes on the surface of the tailings dumps. As a result, only organo-accumulative embryozems have formed over an extended period in these areas, indicating an unsatisfactory soil-ecological condition under stagnant water modes.

Conclusions

Mineral transformations are dynamic in the soils of man-made landscapes formed from the waste of primary and secondary beneficiation of ferrous metal ores. The mineral component of the soil-forming rock from primary beneficiation waste is primarily composed of magnetite, calcite, quartz, and talc flakes, and it undergoes minimal changes between sedimentation zones. In the secondary beneficiation tailings dump, the mineral component is more homogeneous across zones, consisting mainly of muscovite, quartz, calcite, and magnetite dust. The formation of secondary minerals (goethite and hematite) is characteristic of the main and mouth sedimentation zones of both tailings dumps. It is assumed that hematite forms through the dehydration of iron hydroxides. Hematite develops via a ferrihydrite phase, a process typical of soils (especially in humid regions), and under certain hydrothermal conditions, goethite may also form.

Even with a favorable mineralogical composition of the soil-forming rock, the soil formation process is slowed due to the granulometric properties of iron ore tailings dumps. When the physical clay content in the rock exceeds 60 %, only organo-accumulative embryozems form within a pragmatically acceptable time frame (no less than 20 years).

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