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STUDY OF THE SOIL CONDITION OF RECLAIMED AREAS AFTER ILMENITE MINING IN ZHYTOMYR POLISSIA

The article investigates the physical and mechanical composition of the soils of reclaimed areas after ilmenite mining in Zhytomyr Polissia, in particular, the granulometric composition and moisture content of the soils of the reclaimed areas of the Irshansk Mining and Processing Plant. It also identifies soil types by their fractional composition. To carry out the research, 7 test areas were laid out: a control area undisturbed by mining, a dump of topsoil, a site after technical reclamation, and 4 sites after biological reclamation. In order to study the dynamics of reclaimed soil restoration, we selected sites reclaimed at different times. To determine the influence of tree species on the effectiveness of reclamation, we studied sites with plantations of Pinus sylvestris and plantations of Pinus sylvestris and Betula pendula reclaimed at the same time. For all the studied areas, we determined the granulometric composition of the soil by wet and sieve methods, and soil moisture content. The results of the study showed that the soils of the reclaimed areas are mostly sandy, sandy loam and clay loam. These soils are characterized by low water retention properties and low nutrient content. The study also indicated a correlation between the topography of the studied plots and moisture levels as well as the content of fine fractions in the soil.

The research revealed that soils in the areas disturbed by open-pit mining are undergoing significant transformations, which has a negative impact on their forest vegetation potential. To restore this potential, it is necessary to carry out high-quality technical and biological reclamation using modern advanced methods. To improve the effectiveness of reclamation of disturbed areas, it is beneficial to apply mineral and organic fertilizers, plant nitrogen-fixing plants, and add biochar to the soil fertile layer at the stage of levelling of the area.

Key words: ilmenite, mining, reclamation, granulometric composition, forest vegetation potential, moisture content of the soil.

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ДОСЛІДЖЕННЯ СТАНУ ҐРУНТІВ РЕКУЛЬТИВОВАНИХ ТЕРИТОРІЙ ПІСЛЯ ВИДОБУВАННЯ ІЛЬМЕНІТУ НА ЖИТОМИРСЬКОМУ ПОЛІССІ

У статті досліджено фізико-механічний склад ґрунтів рекультивованих територій після видобування ільменіту на Житомирському Поліссі, зокрема визначено гранулометричний склад та вологість ґрунтів рекультивованих територій Іршанського гірничо-збагачувального комбінату. Також встановлено типи ґрунту за їх фракційним складом. Для проведення досліджень було закладено 7 пробних площ: контрольна ділянка не порушена видобутком, відвал ґрунтово-родючого шару, ділянка після технічної рекультивації та 4 ділянки після біологічної рекультивації. З метою вивчення динаміки відновлення рекультивованих ґрунтів для дослідження було обрані ділянки рекультивовані у різний час. Для визначення видового впливу деревних порід на ефективність рекультивації було досліджено ділянки з насадженнями сосни звичайної та сосни звичайної і берези повислої, рекультивовані в один і той же час. Для всіх досліджених ділянок визначали гранулометричний склад ґрунту за вологим та ситовим методом, а також вологість ґрунту. Результати дослідження показали, що ґрунти рекультивованих ділянок переважно є піщаними, супіщаними та суглинками. Для цих ґрунтів характерними є низькі вологоутримуючі властивості та низький вміст поживних речовин. Виявлено залежність між рельєфом досліджених ділянок та вологістю ґрунту і вмістом у ньому дрібної фракції.

У результаті проведених досліджень виявлено, що ґрунти на територіях, порушених відкритим видобутком корисних копалин, піддаються значним перетворенням, що має негативний вплив на їх лісорослинний потенціал. Для відновлення цього потенціалу необхідно проведення якісної технічної та біологічної рекультивації із застосуванням сучасних прогресивних методів. Для підвищення ефективності рекультивації порушених територій може застосовуватися внесення мінеральних та органічних добрив, насадження азотфіксуючих рослин, додавання біочару до ґрунтово-родючого шару на стадії виположування територій.

Ключові слова: ільменіт, видобуток корисних копалин, рекультивація. гранулометричний склад, лісорослинний потенціал, вологість ґрунту.

Formulation of the problem

Large areas of Ukrainian Polissia have been disturbed by open-pit mining, which has prompted the development of various methods to restore their condition. Since most of the region's territory is covered with forests, deforestation has a negative impact on the environment. Therefore, reforestation is an important part of the restoration of disturbed areas. The process of high-quality reclamation of the territories helps to achieve this goal. This type of restoration is mandatory in all areas that have suffered significant anthropogenic impact, pollution and disturbance. Reclamation is also popular in various areas of soil restoration [1]. It is worth noting that the growth and development of tree species directly depend on the granulometric composition and fertility of the soil.

In Ukraine, the main indicators of the forest vegetation potential of soils are vegetation levels. In Zhytomyr Polissia, an important factor in the condition of tree species is their growth and development, which in turn depends on the condition of the soil. According to research by V. V. Dehtiariov and S. P. Raspopina [2, 3], under conditions of sufficient moisture, one of the leading indicators of the forest vegetation potential of soils is the granulometric composition. It is the most important factor in soil classification. The physical and chemical properties of soils are mainly determined by their fractional composition, and the percentage of fractions determines the type of soil.

Analysis of classifications of soil granulometric composition

Today, there are various soil classifications based on granulometric composition. N. A. Kachynskyi [4] developed a classification of soils by granulometric composition based on the percentage of clay to particles of other fractions (Table 1) and a classification of fractions based on the diameter of soil particles (Table 2).

Table 1

Soil classification by granulometric composition (by N.A. Kachynskyi, 1965) [4]

Soil name by granulometric composition	Content of physical clay, %		
	Type of soil formation		
	Podzol	Steppe	Solonetz
Loose sandy	0-5	0-5	0-5
Linked sandy	5-10	5-10	5-10
Sandy loam	10-20	10-20	10-15
Light clay loam	20-30	20-30	15-20
Medium clay loam	30-40	30-45	20-30
Heavy clay loam	40-50	45-60	30-40
Light clay	50-65	60-75	40-50
Medium clay	65-80	75-85	50-65
Heavy clay	80-100	85-100	65-100

Table 2

Classification of mechanical elements of soil-forming rocks and soils (by N.A. Kachynskyi, 1965) [4]

Fraction	Diameter of the particles, mm	Fraction	Diameter of the particles, mm
Pebbles	> 3	Dust: - coarse - medium - fine	0.05-0.01 0.010-0.005 0.005-0.001
Gravel	3-1		
Sand: - coarse - medium - fine	1-0.5 0.50-0.25 0.25-0.05	Silt: - coarse - fine	0.001-0.0005 0.0005-0.0001
		Colloids	< 0.0001

The basis of this classification is the ratio of physical clay to physical sand in the soil. This distribution is called a two-member distribution. The three-member soil classification also includes a fraction of coarse dust (0.05-0.01 mm), the percentage of which is quite high in Ukrainian soils. One of the most common is the three-member classification developed by M. M. Hodlin [5] (Table 3).

Table 3

Soil classification by granulometric composition (by M.M. Hodlin, 1940) [5]

Soil groups by granulometric composition	Soil subgroups by granulometric composition	Particles, mm		
		>0,05	0,5-0,01 (coarse dust)	<0,01
Sandy	Sandy	90	6	6
	Dusty-sandy	90	6	6
	Clay-sandy	75-90	15	15
Sandy loam	Sandy loam	40-60	30-45	10-20
	Sandy-sandy loam	45-70	20-35	10-20
	Dusty-sandy loam	25-50	40-60	10-25
Sandy loam-clay loam	Sandy-light clay loam	30-60	10-30	25-40
	Sandy-medium clay loam	20-40	20-40	35-50
	Sandy-heavy clay loam	10-20	20-40	45-60
Coarse dust - clay loam	Light clay loam	25	55-65	20-35
	Medium clay loam	15	50-60	30-50
Dust-clay loam	Dusty- light clay loam	20	40-50	30-45
	Dusty- medium clay loam	10	35-45	40-55
	Dusty- heavy clay loam	5	30-40	50-65
Clay	Clay	10	35	60-80
	Heavy clay	10	25	70-90
	Sandy-clay	10	30	60-80

Currently, the most common in Ukraine and the CIS countries is the classification of N. A. Kachynskyi [4] for soils of the vegetation layer and clay soils. The classification of S. S. Morozov for dusty (including loess and loess-like) soils and the classification of Ye. M. Serheiev for the characterization of sandy soils are also widely used. There are also classifications of gravelly soils by N. I. Ivanov, large fragmented soils by A. I. Sheko, sandy soils by V. D. Lomtadze, and sandy and clay soils by V. V. Okhotin [6]. Tables 2-4 show the soil classifications used in the study.

There are also other classifications reflected in such regulatory documents as the European standard ISO 14688, the US soil classification, the international classification system World Reference Base for Soil Resources (WRB), etc. According to the ISO 14688 standard [7], particle size is the basis for the classification of mineral soils, where fractions are used to identify the mechanical composition of the soil.

Formulation of goals

Determining the granulometric composition of the soil is essential for solving practical issues. Granulometric composition influences such important characteristics of soil properties and condition as plasticity, porosity, shear resistance, compressibility, shrinkage, swelling, capillary rise, and water permeability [8]. This parameter defines the physicochemical, mechanical, and water-physical properties of soils. The growth and development of forest plant species is also influenced by soil moisture content, which is essential for maintaining water balance, temperature regulation, and the quality of physical and chemical processes.

The aim of the study is to determine the physical and mechanical composition of soils of reclaimed areas after ilmenite mining in Zhytomyr Polissia.

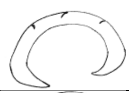
The object of the study is the soil of reclaimed areas after ilmenite mining by the Irshansk Mining and Processing Plant.

Description of the study area

Soil sampling after the reclamation of the ilmenite mining area in Zhytomyr Polissia was carried out on the territory of a branch of Irshansk Mining and Processing Plant of PJSC UMCC. The study area was chosen because the Irshansk ilmenite deposit is one of the largest in Ukraine and covers large territories of Zhytomyr Polissia. To conduct the research, 7 sampling areas were selected on the territory of the enterprise's mining concession (Fig. 1). The test plots were established to study the growth and development of tree stands in the areas after the forestry-type biological reclamation carried out by the company for 30 years (Fig. 2).

Table 4

Determination of the granulometric composition of soil and soil-forming rock by the "wet" method

Soil gradation by mechanical composition		Morphological features of the sample during rolling	
Sand		When moistened, the cord cannot be formed; the ball cannot be rolled	
Sandy loam	Light	Very difficult to roll into a ball, easily breaks up into mechanical elements	
	Heavy	No cord is formed by rolling, the ball is rolled easily	
Clay loam	Light	When rolling, a cord can be formed, but it immediately breaks up into short, inflexible parts	
	Medium	When rolling, the cord forms well, but it breaks when bent into a ring	
	Heavy	When rolling, the cord forms well, it is easily bent into a ring, but cracks form on top	
Clay	Light	It can be rolled into a ball and a cord, which does not break when bent into a ring, but gives 2-3 small and shallow cracks	
	Heavy	Plastic mass, when rolled, the cord forms well, can be easily bent into a ring, does not crack	

The study area belongs to Zone I of mixed forests. The Irshansk ilmenite deposits are considered the largest source of titanium ore in Europe. Ilmenite concentrate was first produced at the plant in 1956, and work to restore the land and return it to land users began in 1971. The reclamation of the disturbed areas continued in the following years. Therefore, today there are sites that were reclaimed at different times. This allows us to assess how the potential of the restored soil and the condition of trees changes over time since the reclamation of the territories. During this period, the company carried out water and forestry reclamation on its territory. Most attention was paid to the forestry reclamation. This is due to the fact that preparatory work began with deforestation in large areas, the depth of quarrying is shallow, and overburden was mostly leveled and placed in the mined space, which creates the preconditions for forest reclamation. This type of reclamation is an effective environmental protection measure and allows us to return the land disturbed by ilmenite mining to productive use, significantly reduce environmental pollution from wind and water erosion, and restore the economic and aesthetic value of the areas where mining operations were carried out.

Regardless of the type of reclamation, any complex of reclamation works is carried out in two stages: technical and biological. Through technical reclamation, the disturbed land is prepared for its further use: the surface is planned (pit walls are levelled, partial or complete backfilling of the mined space is done), roads, hydraulic and reclamation facilities are built.

Biological reclamation is carried out after technical reclamation and involves a set of measures aimed at improving the physical and agrochemical properties of soils on reclaimed land (liming, mineral fertilization, etc.).

The soil cover of the studied areas is characterized by the distribution of typical for Ukrainian Polissia zone sod-podzolic soils of varying degrees of gleying with low content of organic matter and physical clay, the humus layer of which, according to DSTU 7906:2015 [9], is not very suitable for biological reclamation in terms of physical properties and chemical composition.

At Irshansk Mining and Processing Plant, overburden was developed using a complicated non-transportation scheme. The overburden is planned by filling the inter-ridge depressions of the slopes with enrichment tailings. After that, the surface of the dumps is bulldozed and forests are planted. For this purpose, such low-maintenance tree species as Scots pine (*Pinus sylvestris*) and hanging birch (*Betula pendula*) are used.

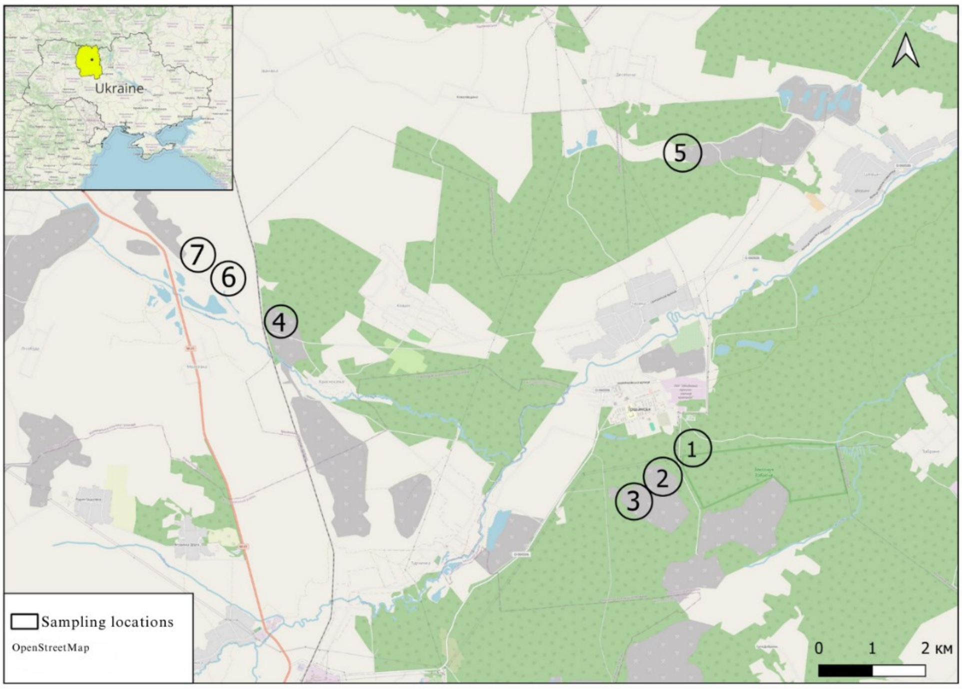


Figure 1. Map of sampling locations:
1 – Control plot not disturbed by mining; 2 – Dump of the soil and vegetation layer; 3 – 1-st year after technical reclamation (the soil and vegetation layer is levelled); 4 – 10 years after biological reclamation (planting of *Pinus sylvestris*); 5 – 20 years after biological reclamation; 6 – 30 years after biological reclamation (planting of *Pinus sylvestris*); 7 – 30 years after biological reclamation (planting of *Pinus sylvestris* and *Betula pendula*)

a) b) c)

Fig. 2. Plantations of *Pinus sylvestris* at different times after reclamation: 10 years; 20 years; 30 years

Research program

Sampling was carried out in 6 sites of reclaimed areas after ilmenite mining and 1 control site of undisturbed soils in the operational territory of the branch of Irshansk Mining and Processing Plant of PJSC UMCC. A total of 21 soil samples were collected.

An important part of soil testing is compliance with sampling requirements. According to State Standard of Ukraine DSTU 4287:2004 "Soil quality. Sampling." [10] and DSTU ISO 10381-2:2004 "Soil quality. Sampling. Part 2. Guidelines for sampling methods (ISO 10381-2:2002, IDT)" [11] there are such types of samples:

- disturbed (without preserving the soil structure);
- undisturbed (soil structure is preserved, special equipment is required).

Sampling methods, depending on the purpose of the research, are divided into:

- spot sample - taken at 1 spot (may be disturbed or not);
- slot sample - taken as a vertical slot within a layer or other subpart that is preliminarily considered homogeneous (disturbed sample);
- stratified sample - a combination of single samples from layers or sub-layers that are preliminarily considered homogeneous (disturbed sample);
- cluster sample - a combination of small consecutive single samples taken close to each other (disturbed sample);
- spatial sample - a combination of small consecutive single samples taken over an area (disturbed sample).

To study the granulometric composition of soil samples from the disturbed areas, we chose the cluster sampling method, which is comprised of 5 spot samples taken by the envelope method on 2x2 m areas and mixed in appropriate proportions, as it allows us to study the general condition of the soil over a large study area.

The sampling location is also important. Regardless of the purpose of the research, samples should not be taken closer than 50 meters from roads, near mineral fertilizer warehouses, piles of organic and mineral fertilizers, or in areas with vegetation that is sharply different from the background.

Sampling was carried out at a depth of 0-20 cm, which is due to the minimum depth of the root layer in Polissia, where the predominant soil types are sod-podzolic, sandy, and clay-sandy soils [12].

Among the existing methods for determining granulometric composition of soil are the following:

1. The pipette method is based on considering the settling velocity of particles of different sizes in a liquid medium and taking samples from a suspension from a depth determined by the size and density of the solid phase particles at a certain temperature.
2. The field method is carried out organoleptically (by touch), with visual identification of external features characteristic of both dry and wet soil conditions.
3. Dry method - the composition is determined by crushing a lump of soil in the palm of one's hand and rubbing it into the skin with a finger. The firmer, harder the lump, the more particles rubbed into the skin, the "heavier" is the granulometric composition of the soil.
4. Wet method - to identify the soil sample, it is necessary to moisten it to a doughy state and rub it on the palm of one's hand with a finger. The degree of plasticity of the soil and the number of grains of sand that can be felt to the touch are indicators of the granulometric composition.
5. The sieve method involves sifting air-dry soil samples through a set of sieves installed one after the other in order of decreasing mesh size. Each sieve retains only those particles that are larger than the mesh size of that sieve but smaller than the mesh size of the upper sieve. By weighing each fraction obtained in this way, we determine its mass and the percentage of this fraction relative to the mass of the original sample. The technology for determining the granulometric composition of soils in Ukraine and abroad is practically the same, with the only differences being in the mesh sizes of the sieves used for sieve analysis and the interpretation of the results.

In the course of the study, the granulometric composition was determined by wet and sieve methods.

The following methods are used to determine soil moisture content:

1. Organoleptic (used in field conditions). This method is used to test the soil by touch and for its ability to roll into a ball and cord.
2. Weight (gravimetric). It involves drying a soil sample at a temperature of 105°C to a constant mass.
3. Electrometric. The moisture content is determined by the electrical conductivity of the gypsum block or the resistance (of a transistor) placed in the soil. This involves measuring the cooling or heating rate of a sensor placed in the soil, or considering the heating level of a constant power sensor over a certain period of time. This method is based on the correlation between moisture content and temperature of the soil.
4. Radiometric. It is based on the use of a stream of fast protons that are slowed down and scattered by hydrogen atoms contained in soil moisture. The flux of slow thermal neutrons, the density of which depends on soil moisture, is measured by detectors and then the volume moisture content of the soil is determined using a calibration graph.
5. Tensiometric. It is based on the use of devices that determine the absorption capacity of the soil. The device's slotted ceramic vessel filled with water is placed in the soil. The water from the device is transferred to the soil until equilibrium is established between the absorption capacity of the soil at a given level of moisture content and the absorption capacity of the device, which depends on the degree of vacuum in it.

To determine the soil moisture content during the study, we chose the weight method, in which soil samples are dried in a drying oven at a temperature of 105°C to a constant mass.

Thus, the following methods were chosen to study the moisture content and granulometric composition of soils in the reclaimed areas of ilmenite mining:

1. Cluster sampling by the envelope method according to DSTU 4287:2004 and DSTU ISO 10381-2:2004.
2. Determination of soil moisture content by the weight method in accordance with DSTU B V.2.1-17:2009.
3. Determination of granulometric composition by the wet method.
4. Determination of granulometric composition by the sieve method.

Presentation of the main material

In the process of studying the granulometric composition of soil samples by the wet method, we determined that the soils of samples 4, 6 and 7 broke up during rolling, the cord and ball could not be rolled, samples 2 and 3 were very difficult to roll, the ball immediately broke up, sample 1 rolled well into a ball, but no cord could be formed, sample 5 formed a cord during rolling, which then broke up. Therefore, according to the gradation of soils by mechanical composition (Table 4):

1. the soils on the areas that were reclaimed 10 (No. 4) and 30 (No. 6 and 7) years ago are classified as sands;
2. the soils at the dump of soil and vegetation layer (No. 2) and soils in the 1st year after technical reclamation (No. 3) are categorized as light sandy loam;
3. the control sample (No. 1) is heavy sandy loam;
4. the soil of the area that was subjected to biological reclamation 20 years ago (No. 5) is characterized as light clay loam.

The results of determining the granulometric composition of the soils of the studied areas by the sieve method are presented in Table 5.

Table 5

Results of determining the granulometric composition of soils of the sample areas

Soil sampling area	Soil fractions (sieves), mm and content, %.							
	<0,25 mm	0,25 mm	0,5 mm	1 mm	2 mm	3 mm	5 mm	7 mm
1. Control sample	48	38	12	2	-	-	-	-
2. Dump of the soil and vegetation layer	30.5	48	18.5	3	-	-	-	-
3. 1-st year (technical reclamation)	41.5	40	14	4	0.5	-	-	-
4. 4. 10 years after reclamation	27.5	54	14	3.5	1	-	-	-
5. 5. 20 years after reclamation	43	29	17	5	4	1.5	0.25	0.25
6. 30 years after reclamation (growth of *Pinus sylvestris*)	51.5	42	6	0.5	-	-	-	-
7. 30 years after reclamation (growth of *Pinus sylvestris* and *Betula pendula*)	36.5	39	17	6	1	0.5	-	-

A percentage diagram is shown in Figure 3 for a qualitative analysis of the content of different fractions in the soil samples.

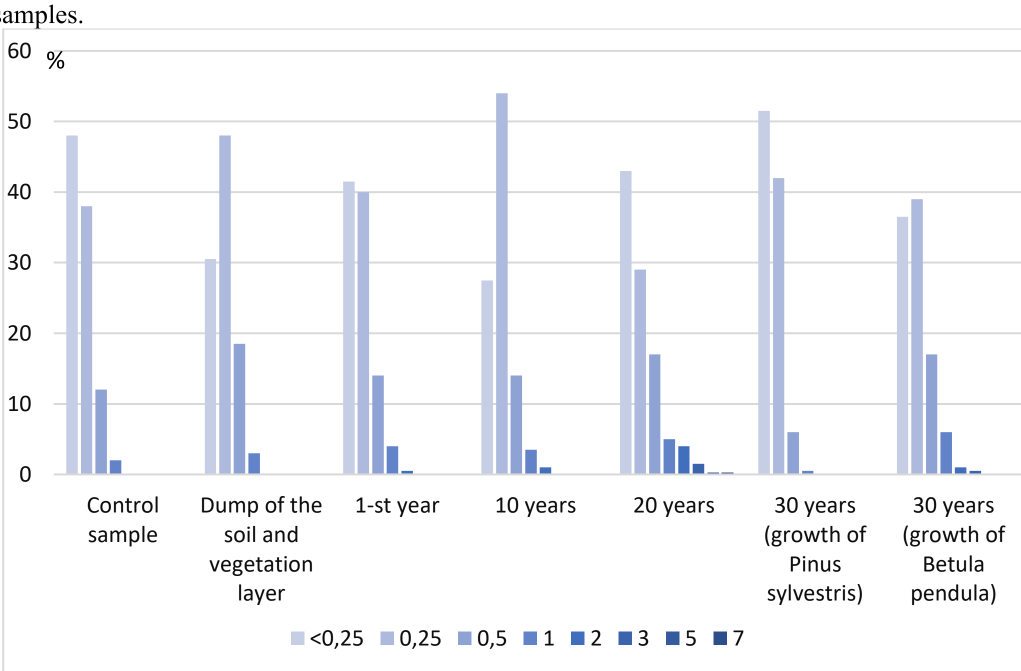


Fig. 3. Percentage ratio of soil fractional composition of the studied areas

Based on the results of the study of the granulometric composition of the soils in the study areas, we can conclude that the predominant fraction in each of the soil samples is the fraction of 0.25 and <0.25 mm. According to the classification of M. M. Hodlin (Table 3), the division of these samples into groups by granulometric composition is as follows:

1. The control sample and the areas of the 1st year, 20th and 30th year (the place of Pinus sylvestris growth) after the reclamation can be classified as sandy-sandy loam soil.
2. Soil samples from the dump of soil and vegetation layer and from the areas of 10 and 30 (the place of growth of Scots pine (Pinus sylvestris) and Hanging birch (Betula pendula)) years after reclamation are dusty-sandy loam soils.

According to Table 2 (classification of mechanical elements of soil-forming rocks and soils (by N. A. Kachynskyi, 1965), the sand fraction prevails in all samples.

The soils of samples 1, 2, and 3 should be similar in terms of mechanical properties, as the areas are quite close to each other, but we can see some differences in the soils that were deposited in the dump (sample 2), which is characterized by a lower content of fine fractions, which may be due to their leaching by rainwater and weathering from the surface of the dump. Comparing the soil of the 1st year after technical reclamation (No. 3) with the control sample (No. 1), we can say that it has not actually changed its mechanical properties.

As for biologically reclaimed areas, they are characterized by certain differences that are mainly related to the technologies used during the technical stage of reclamation. The area that was reclaimed 10 years ago is dominated by sandy soils with a moisture content of 5%, these conditions adversely affect the condition of Scots pine, which has not taken root well, and there are significant areas where the seedlings have not taken root at all.

The study of soil moisture content in the selected samples shows sufficient moisture supply to the plants. Moisture content depends on soil properties, the condition of its surface, the amount of precipitation, and the factors that determine the intensity of moisture evaporation.

The results of moisture measurements (Table 6) showed that the soils of the areas 1 year after technical reclamation and 30 years after biological reclamation had a higher level of moisture content compared to other samples. This is likely due to the peculiarities of the relief of the sampling sites, as these samples belong to sandy - sandy loam soils and have low absorption capacity.

Table 6

Results of soil moisture measurement

Sampling depth, cm	No. of the weighing bottle (sample)	Mass of the weighing bottle, g			$W = \frac{A-B}{B-C} \cdot 100$, %	$K_w = \frac{100+W}{100}$
		empty (C)	with damp soil (A)	with dry soil (B)		
0-20	1	111	131	130	5	1.05
0-20	2	110	131	130	5	1.05
0-20	3	108	128	126	11	1.11
0-20	4	112	132	131	5	1.05
0-20	5	107	127	126	5	1.05
0-20	6	109	129	127	11	1.11
0-20	7	120	140	137	17.6	1.176

A-B – mass of moisture, g; B-C – mass of dry soil, g; K_w – coefficient of conversion of laboratory test results to completely dry soil.

Conclusions

Currently, the issue of the negative impact of mining activities on soil conditions is quite relevant for Zhytomyr Polissia. A number of factors impede a thorough study of this issue, such as the variety of technological options for mining, the location of deposits, the choice of development system, methods of technical and biological reclamation, etc. It is particularly important to study the forest vegetation potential of the soils of reclaimed areas, as it largely determines the condition and properties of future forest plantations.

Using the example of the Irshansk mining and processing plant as a case study, we analyzed the soil of reclaimed areas after ilmenite mining for fractional composition and moisture content. The study found that the soils of the reclaimed areas can be classified as sands, sandy loams and light clay loams of medium and fine fraction. These soils are characterized by low water retention properties and low nutrient content.

Soils of these types are typical for Zhytomyr Polissia, and they are considered to be unproductive and of low value. Due to the disturbance by open-pit mining of ilmenite deposits, large areas of the soil and vegetation layer are removed and placed in dumps, where the soil is subjected to additional leaching of fine fractions, which increases water permeability.

Thus, the soils of the areas after ilmenite mining in Zhytomyr Polissia require additional attention in the process of biological reclamation to improve their forest vegetation potential. Therefore, additional methods of biological soil reclamation should be applied before planting trees to improve the quality characteristics of the tree stands, which is the main goal in restoring areas disturbed by the mining industry, where forestry type of reclamation is used.

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