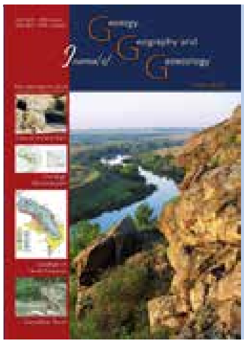

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The suitability of physical and chemical properties of rocks for land reclamation in different subzones of the Ukrainian Steppe

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Abstract. The study of the properties of disturbed soils and rocks makes it possible to establish the parameters of the natural fertility of the studied substrates, to detect limiting factors, and to determine a set of restoration measures. The tested overburden rocks with the largest stratigraphic share of the open-pit quarries of the Nikopol manganese and Kerch iron ore deposits were loamy-like loess (Quaternary) and grey-green clay (Neogene). There is a certain parametric relationship between texture, density, porosity, the structural and physical state of different models of artificial reclaimed profiles. The composition and properties of rocks of edaphic structures of technosoils differ according to zonal natural and climatic conditions of the subzones of the Ukrainian Steppe. Loess-like loam and grey-green clay of the Kerch iron ore deposit are distinguished by a higher bulk density, lower porosity, and wilting moisture compared to samples from the Nikopol manganese ore basin. The use of the rotor complex leads to mechanical destruction and an increase in the content of small particles of rocks. Self-compacting processes occur to a large extent in multilayer structures. This pattern is observed at the boundary of the backfill differentiated in texture layers of technosoils. This indicates the existence of a barrier that prevents the relationship of edaphic properties between substrata stratums. Optimal ratio of clay minerals provides a rather high capacity of grey-green clay for water absorption. The model of technosoil composed of grey-green clay differs in a larger number of water-resistant micro-aggregates. The best conditions for land reclamation are connected with including grey-green clay in two- and three-layer constructions of technosoils, providing a waterproofing effect.

Key words: manganese and iron ore deposits, rocks properties, artificial reclaimed profile, waterproofing effect.

Придатність фізико-хімічних властивостей гірських порід для рекультивації земель в різних підзонах Українського Степу

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Анотація. Вивчення складу і властивостей порушених ґрунтів і гірських порід дає змогу встановити параметри природної родючості досліджуваних субстратів, виявити обмежувальні фактори, визначити комплекс відновлювальних заходів. Досліджені розкривні породи кар'єрів Нікопольського марганцевого та Керченського залізорудних родовищ представлені лесоподібними суглинками (четвертинний період) і сіро-зеленими глинистими глинами (неоген). Існує певна параметрична залежність між текстурою, щільністю, шпаруватістю, структурним і фізичним станом різних моделей штучно рекультивованих профілів. Склад і властивості гірських порід едафічних структур техноземів відрізняються відповідно до зональних природно-кліматичних умов підзон Степу України. Лесоподібні суглинки та сіро-зелені глини Керченського залізорудного родовища відрізняються більшою щільністю, меншою пористістю та вологістю в'янення порівняно із зразками Нікопольського марганцеворудного басейну. Використання роторного комплексу призводить до механічного руйнування та збільшення вмісту дрібних частинок гірських порід. У багатошарових конструкціях значною мірою відбуваються процеси самоущільнення. Така закономірність спостерігається на межі відсипки в текстурних шарах техногрунтів. Це свідчить про існування бар'єру, що перешкоджає взаємозв'язку едафічних властивостей між шарами ґрунту Оптимальне співвідношення глинистих мінералів забезпечує досить високу здатність сіро-зеленої глини до водопоглинання. Модель технозему, складеного із сіро-зеленої глини, відрізняється більшою кількістю водостійких мікроагрегатів. Найкращі умови для рекультивації пов'язані з включенням сіро-зеленої глини в дво- і тришарові конструкції техноземів, що забезпечує водотривний ефект.

Ключові слова: родовища марганцевої та залізної руди, властивості гірських порід, штучні профілі рекультивації, водотривний ефект

Introduction

Land reclamation is a very important process of restoration of the soil's quality such as soil fertility, minerals, nutrients, moisture to make it reusable again, to restore its ecological integrity (Buta et al., 2019). The development of technologies for biological land reclamation depends on the edaphic characteristics of rock substrates. Peculiarities of creation of artificial constructions of two-, three- and multilayer profiles depend on the direction of development of reclaimed mine lands. A pre-condition for an effective land reclamation program is the characterization of properties of soil and other materials in terms of their limitations to plant growth and potential impacts on environment quality (Bell, 2004). At the same time, the natural resource limitations (such as topsoil availability) may limit the degree to which the historical land cover can be re-established (Limpitlaw and Briel, 2014). That is why, a majority of mining companies view closure and reclamation planning as an integral part of the operating plan to return the land to a stable condition to minimize potential negative environmental impacts and to allow alternative land use opportunities (Warhurst and Noronha, 2014). Construction of mine soils with good quality soil materials and desirable physical properties is essential to attain productivity levels necessary for bond release (Dunker and Darmody, 2005). A prerequisite is the use of technology of selective formation of heaps of overburden and fertile soil layer to create edaphic conditions during the first technological stage (Bouma, 2006; Terekhov et al., 2021). This stage of reclamation involves the formation of the dump profile and surface planning, while the stage of crops cultivation is biological (Tarika and Zabaluev, 2000). Recommendations resulting from cooperative research of Dnipro State Agrarian University and Pokrov Mining Company have been adopted by all strip-mining operations in the Nikopol manganese deposit replacement. The need for high efficiency of reclamation measures contributed to the transition from the technology of uncontrolled dumping to the technology of selective removal of overburdened rocks (Litvinovet al., 2019). Taking into account edaphic factors allows one to use these effects against the background of low-cost and rehabilitation technologies of biological land reclamation (Kuter, 2013; Kasztelewicz, 2014; Xu et al., 2014). Usually, the natural overgrowth of dumps and subsequent formation post – mining landscapes occurs by zonal type (Yeterevska et al., 2019). The formed man-made soils can be considered as soils – analogues intended to be returned to the original state according to all the laws of soil fertility.

The purpose of the work. The purpose of the work is to assess the suitability of physical and chemical properties of rocks for land reclamation in different subzones of the Ukrainian Steppe.

Material and methods of research

The reclamation of disturbed mine lands was conducted in one technological cycle with the process of manganese and iron ores mining in the southeastern part of Ukraine (Fig. 1).

Fig. 1. The panorama of the disturbed mine lands first stage reclamation

The tested overburden rocks with the largest stratigraphy share of the exposed strata in the Pokrov and Kamysh – Burun land reclamation stations were loamy like loess (Quaternary) and grey-green clay (Neogene). A variety of composition and properties of rocks is observed even within one geological period. Thus, the thickness of loamy-like loess is divided into 2–4 tiers, heterogeneous in physico-chemical properties. However, loamy-like loess tiers are mixed in the process of ore mining. This causes some variety in their texture and physico-chemical properties. Separate stratigraphic tiers of Pliocene and Miocene sediments are also heterogeneous in lithological and chemical composition. Part of these sediments is represented by complex carbonate and non-carbonate sediments due to such peculiarities of formation with different degrees of salinity by multicoloured clays, sandy-clay sediments, multigrain quartz sand with pebbles, boulders, and marls.

Artificial reclaimed profiles were evaluated in the model lysimeter and field experiments in the northern and southern parts of the steppe zone of Ukraine. The first model consists of any rock substrate. The second model uses an acceptable substratum underneath a black soil mass layer 0.3–0.7 m thick. The third model consists of 3–4 layers: 0.5–0.8 m black soil mass on top of 0.3–0.5 m loess-like loam (LLL) on top of 0.3–0.5 m of grey – green clay (GGC) as waterproof non-saline substrate. 1.0–1.2m thick sand (S) can be included as a water accumulative layer as well (Fig. 2).

Two types of soil substrates used as a control: a) black soil mass (BSM); b) a mixture of accumulative and first transitional soil horizons of the zonal black soil (ZBS). Traditional research methods were applied to estimate the physical and chemical properties of the soil and rock samples (Kharytonov et al., 2004). It is known that some overburdened rocks can provide a satisfactory medium for the establishment and maintenance of vegetation provided that the input of nitrogen to the system is adequately catered for through the cultivation of nitrogen-fixing plants (Bell, 2004). That is why during the first part of April each year from 1997 to 2015, the legume-grass mix was drill-seeded on each technosoil construction.

Fig. 2. Artificial model constructions of technosoils

The multicomponent grass mixtures were grown at the following artificial soil profiles managed in special cylinders: black soil mass (BSM), 0–150 cm; loamy-like loess (LLL), 0–150 cm; grey-green clay, 0–150 cm; BSM (0–50 cm) + LLL (50–150 cm); BSM (0–50 cm) + GGC (50–150 cm); BSM (0–50 cm) + Sand (50–70 cm) + LLL (70–150 cm); BSM (0–50 cm) + LLL (50–100 cm) + Sand (100–120 cm) + GGC (120–150 cm). The statistical assessment of the model experiments was made using Statistica 6 soft.

Results and their analysis

The results of texture analysis of samples of loess-like loam and grey-green clay used in the model profiles at the Pokrov and Kamysh-Burun land reclamation stations are shown in Table 1.

Table 1. Overburden rocks texture

Rock	Particle size of rocks (mm) and their content (%)						Particles sum <0.01mm %
	1–0.25	0.25–0.05	0.05–0.01	0.01–0.005	0.005–0.001	< 0.001	
Loess-like loam *	0.78	3.08	37.31	7.65	12.95	38.23	58.83
Loess-like loam **	3.43	31.33	26.04	4.16	9.72	25.32	39.20
Grey-green clay*	0.88	1.58	26.69	7.41	9.67	53.77	70.85
Grey-green clay**	0.11	3.02	8.15	17.87	15.19	55.66	88.72

Note: *Nikopol Manganese ore Basin; **Kerch Iron Ore Deposit

Relative amount of sand (2.0–0.05 mm), silt (0.05–0.002 mm), and clay (< 0.002 mm) sized particles determine the texture of soil. The particle size distribution of the soils with loamy textures is generally ideal (Ghose, 2005). The main physical properties of soilmass and overburdened rocks of Nikopol manganese and Kerch iron ore deposits are given in tables 2 and 3.

Table 2. Main physical properties of the overburden rocks

Rocks	Bulk density, g/cm^3	Solid phase density, g/cm^3	Total porosity, %	Moisture of permanent wilting, %
Loess-like loam *	1.21	2.66	54.5	9.1
Loess-like loam **	1.51	2.68	43.7	8.7
Grey-green clay*	1.23	2.7	54.4	21.0
Grey-green clay**	1.40	2.72	48.5	14.1

Note: *Nikopol Manganese ore Basin; **Kerch Iron Ore Deposit

Loess-like loam and gray-green clay of the Kerch iron ore deposit are distinguished by a higher bulk density, but lower porosity and wilting moisture compared to samples from the Nikopol manganese ore basin. The impact of the density and porosity caused by different textures of substrates was found in the study of some structures of technosoils.

Table 3. Water-physical properties of soil profile compartments of the Nikopol manganese deposit (per 0–100 cm layer)

Substrata	Maximum hygroscopicity, %	The smallest moisture content, %	Range active moisture, %	Total moisture reserves, mm	Stocks of productive moisture, mm
BSM	6.3	28.6	20.2	337	238
LLL	6.8	25.5	16.4	352	186
GGC	15.7	42.1	21.1	552	313

It is known that mine soils with sandy textures cannot hold as much water or nutrients as finer - textured soils like loams and silts (Sheoran et al, 2010). In our case, grey-green clay seems ideal water accumulative substrata. Soil aggregation control soil hydrology, affect soil diffusion and the degree of nutrient availability to the soil (Heras, 2009) and constitutes a pathway of organic carbon stabilization and long - term sequestration (Six et al., 2004). Texture elements of rocks and bulk soil layer (mixture of H + Hp horizons) in the process of biological reclamation form structural aggregates (fragments and lumps) of different shapes and sizes.

Their shape, size and ratio serve as an indication that reflects the characteristics and fertility of individual horizons of technosoils. The data reflected structural and aggregate state of technosoils at the Pokrov land reclamation station are shown in Table 4.

Table 4. Microagregate size of soil and rock particles

Technosoil	Type of screening *	The size of aggregates, mm (%)									Structural coefficient	The total number of waterproof units, %
		>10	10–7	7–5	5–3	3–2	2–1	1–0.5	0.5–0.25	<0.25		
LLL	DS	27.8	11.8	12.1	10.6	9.3	11.1	6.1	5.3	5.9	2.0	65.6
	WS			2.2	3.8	6.8	14.3	15.8	22.7	34.4		
GGC	DS	38.8	5.8	10.6	11.1	9.7	7.2	3.8	7.7	5.3	1.3	78.2
	WS			1.7	4.3	12.2	15.2	18.7	26.1	21.8		
BSM	DS	21.7	12.2	11.1	9.5	10.1	18.2	4.3	6.7	6.2	2.6	62.3
	WS			3.5	4.9	6.7	11.6	14.8	20.8	37.7		
BSZ	DS	17.7	9.8	7.4	11.5	10.7	10.8	8.3	7.6	16.2	1.9	58.3
	WS			0.6	1.1	11.2	15.1	12.2	18.1	41.7		

DS – dry sieving, %; WS*– wet sieving, %*

It was found that after dry sieving of loess-like loam samples the sum of aggregates from 0.25 to 10 mm was 66.2 %, grey-green clay – 55.9 %. According to the results of wet sieving, the model of techno-soil from grey-green clay stands out, where the sum of water-resistant units was 78.2 %. The profile distribution of the substrata bulk density and porosity is shown in table 5.

Table 5. Physical properties of soil and rocks in lysimeters

Depth, cm	BSM			LLL			GGC		
	*A**	*B**	*C**	*A*	*B*	*C*	*A*	*B*	*C*
0–10	1.11	2.56	56.6	1.23	2.62	53.1	1.29	2.68	51.9
10–20	1.13	2.59	56.4	1.20	2.61	54.0	1.27	2.70	53.0
20–30	1.17	2.60	55.0	1.28	2.64	51.5	1.31	2.71	51.7
30–40	1.25	2.63	52.5	1.35	2.66	49.2	1.35	2.72	50.4
40–50	1.29	2.68	51.9	1.41	2.68	47.4	1.35	2.71	50.2
50–60	1.34	2.65	49.4	1.47	2.68	45.1	1.37	2.70	49.3
60–70	1.35	2.66	49.2	1.51	2.67	43.4	1.39	2.70	48.5
70–80	1.38	2.67	48.3	1.51	2.68	43.7	1.42	2.71	47.6
80–90	1.40	2.69	48.0	1.53	2.70	43.3	1.47	2.71	45.8
90–100	1.42	2.70	47.4	1.53	2.69	43.1	1.54	2.73	43.6

*Note. A – bulk density, g / cm^3; B – solid phase density, g / cm^3; C – total porosity, %.

Certain differences in the distribution of the main physical indexes of soil profiles with depth were found in the study of three structures of technosoils (Table 6).

Table 6. Profile distribution of physical properties of models of technosoils

Depth, cm	BSM+LLL			BSM+Sand+LLL			BSM+LLL+Sand+GGC		
	*A**	*B**	*C**	*A*	*B*	*C*	*A*	*B*	*C*
0–10	1.14	2.54	55.1	1.14	2.57	55.6	1.15	2.51	54.2
10–20	1.15	2.56	55.1	1.17	2.58	54.7	1.17	2.52	53.6
20–30	1.21	2.53	52.2	1.22	2.63	53.6	1.31	2.53	48.2
30–40	1.22	2.55	52.2	1.28	2.63	51.3	1.33	2.56	48.0
40–50	1.28	2.55	49.8	1.31	2.66	48.9	1.35	2.55	47.1
50–60	1.37	2.68	48.9	1.37	2.71	45.8	1.40	2.66	47.4
60–70	1.41	2.67	47.2	1.39	2.72	46.0	1.42	2.67	46.8
70–80	1.41	2.69	47.6	1.41	2.69	44.6	1.41	2.67	47.2
80–90	1.43	2.70	47.0	1.45	2.72	44.1	1.42	2.68	47.0
90–100	1.43	2.69	46.8	1.48	2.73	43.2	1.43	2.67	46.4

*Note. A – bulk density, g / cm^3; B – solid phase density, g/cm^3; C – total porosity, %.

Self – compacting processes occur to a large extent in multilayer structures. This pattern is observed at the boundary of the backfill differentiated in texture layers of technosoils. This indicates the existence of a barrier that prevents the relationship of edaphic properties between horizons. The content of humus and nitrogen in rock samples taken in the open – pit quarry of the Nikopol manganese ore deposit is low (Table 7).

Table 7. Chemical properties of black soil and overburden rocks of Nikopol manganese ore deposit

Substrata	Humus, %	Total N, %	Mobile P, mg/100 g	Exchange potassium, mg/100 g
Black Soil	1.62±0.17	0.12±0.06	1.38±0.15	22.4±1.3
LLL	0.39±0.08	0.02±0.01	1.06±0.13	10.2±0.91
Sand	0.08±0.01	0.003±0.001	0.03±0.01	4.1±0.74
GGC	0.14±0.04	0.01±0.003	0.24±0.08	53.1±1.6

Exchange potassium content in grey-green clay is 2 and 5 times higher than in black soil and loamy-like loess. However mobile phosphorus content in clay is 5 times low compared to loamy - like loess.

It was established that the resources of humus and macronutrients determine the profile nutrient regime of technosoil model constructions (Table 8).

Table 8. The nutrient regime of the model construction of the technosoils

Depth, cm	Model construction of the technosoils											
	BSM+LLL				BSM+Sand+LLL				BSM+LLL+Sand+GGC			
	*C**	*D**	*E**	*F**	*C*	*D*	*E*	*F*	*C*	*D*	*E*	*F*
0–10	2.22	0.19	1.47	34.7	2.07	0.16	1.42	33.5	2.41	0.22	1.46	35.5
10–20	2.13	0.18	1.54	33.8	2.01	0.16	1.37	33.2	2.47	0.21	1.49	34.8
20–30	2.08	0.16	1.51	29.5	1.93	0.15	1.32	31.5	2.38	0.19	1.50	32.6
30–40	2.11	0.16	1.44	25.3	1.85	0.14	1.26	28.1	2.31	0.14	1.46	31.1
40–50	1.97	0.14	1.44	24.2	1.72	0.11	1.21	27.7	2.29	0.13	1.44	27.4
50–60	0.66	0.06	1.21	13.3	0.08	0.006	0.06	4.5	1.18	0.06	1.21	17.6
60–70	0.58	0.06	1.21	12.7	0.08	0.006	0.05	4.7	1.12	0.05	1.19	16.4
70–80	0.58	0.05	1.17	12.4	0.51	0.04	1.13	11.7	1.03	0.05	1.16	15.7
80–90	0.51	0.04	1.15	12.3	0.48	0.04	1.13	11.3	0.72	0.03	1.11	14.2
90–100	0.46	0.04	1.14	12.2	0.44	0.03	1.12	11.2	0.68	0.03	0.09	13.1
100–110	0.45	0.03	1.12	12.2	0.41	0.03	1.12	11.2	0.09	0.008	0.09	47
110–120	0.45	0.03	1.11	11.9	0.37	0.02	1.11	10.9	0.09	0.008	0.08	4.8
120–130	0.42	0.02	1.10	11.8	0.32	0.01	1.06	10.8	0.19	0.02	0.35	57.6
130–140	0.42	0.01	1.09	11.7	0.31	0.01	1.03	10.7	0.19	0.01	0.31	57.2
140–150	0.41	0.01	1.09	11.7	0.31	0.01	1.02	10.7	0.17	0.01	0.29	56.1

*Note: C – humus, %; D – total N, %; E – mobile phosphorus, mg/100 g; F – exchange potassium, mg/100 g

The results of determining the productivity of legume – grass mixes in artificial profiles of technosoils were obtained in the model experiment (Fig.3).

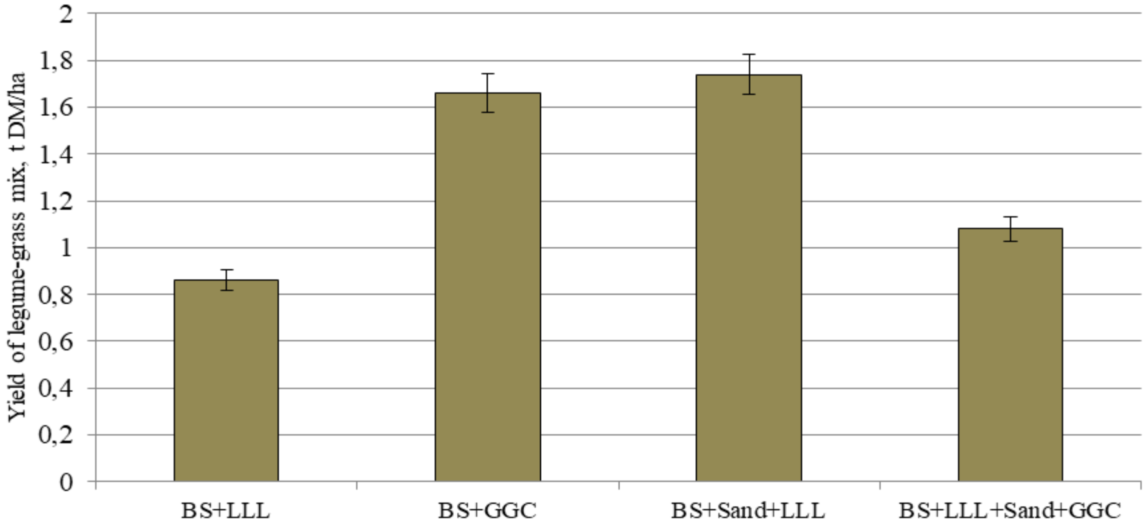

Fig. 3. Yield of legume-grass mix in the artificial soil profiles, t / ha

The best conditions for the formation of the productivity of legume-cereal mixture were fixed in two- and three-layer constructions of technosoils, providing a waterproof effect. The results of the study indicate the functioning of artificial profiles of technosoils is due to the specific dynamics of the structural and aggregate state. The content of humus and nitrogen in rocks of the Kerch iron ore deposit is low (Table 9).

Table 9. Chemical properties of black soil and rocks

Substrata	Humus, %	Total N, %	P, mg/100g		Absorption capacity, mg-eqv/100g
Black soil	1.81	0.12	71.36	1.71	26.7
Loamy - Like Loess	0.36	0.03	6.4	1.11	14.0
Grey - Green Clay	0.8	0.07	10.0	1.4	27.5

The total phosphorus level and absorption capacity of cations in grey-green clay exceeded those of loess-like loam by 1.6 and 2 times, respectively. Peas were grown in the field experiment on the tested rocks of the Kerch iron ore deposit during four years (Fig.4).

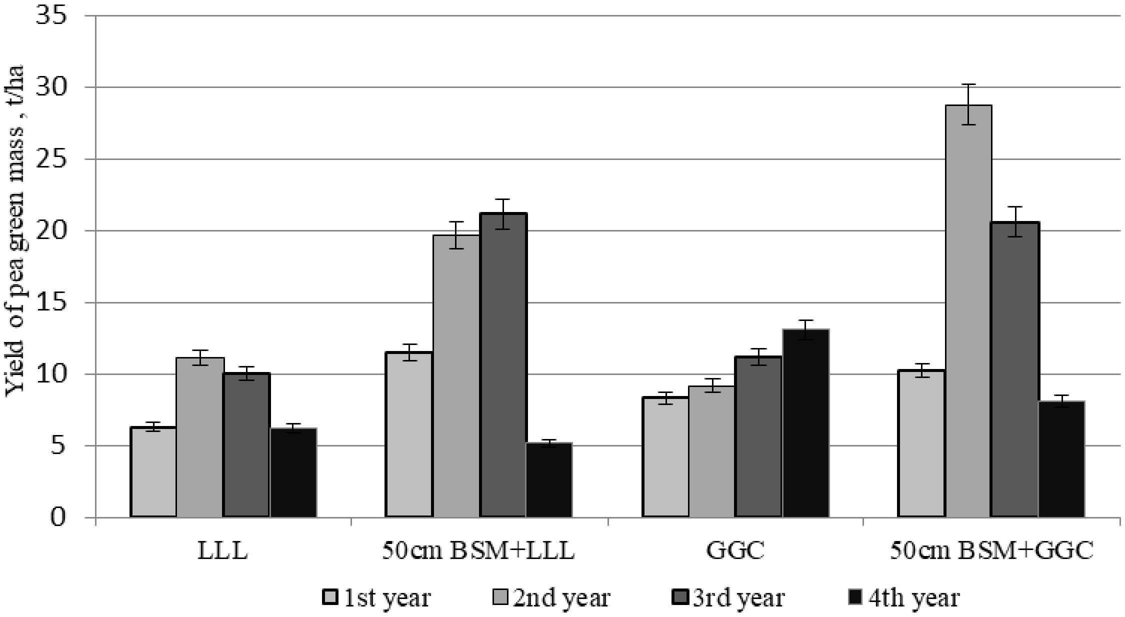

Fig. 4. Yield of green mass of peas in artificial soil profiles, t / ha

Grey-green clay turned out to be the most favorable rock and underlying base for the bulk soil layer. In average the increase in pea yield in comparison with loess-like loam was 2.54 tons/ha or 17.7 %.

The aeration porosity rate of the basic models of technosoils, underlain by smoldering potential-producing overburden rocks, was on average 25–32 %, which generally accounts for 50–60 % of the total porosity. It was established that the porosity of aeration is in direct dependence on the amount of field moisture of soils (Sadovski and Ivanova, 2020). Soil moisture supply depends on the amount of water that the soil mass is able to accumulate and retain (Rode, 1965). Moisture availability limits correspond to important hydrological constants, including soil moisture resistance. Some underlying rocks in our model experiments have both increased maximum hygroscopicity and low. This is due to the different texture, compaction and features of their micro – aggregate composition (Asano and Wagai, 2014). Soil micro-aggregates are considered as the smallest functioning units, stable composite structures that can be grouped into different size classes (Chenu and Plante, 2006; Totsche et al., 2018). The polymineralITY and polydispersity of the overburdened rocks give them more favourable physical and chemical properties. An optimal ratio of clay minerals provides rather high capacity of grey-green clay for water absorption. It makes it possible to consider this mining rock as a potential waterproofing while constructing an artificial soil-ecological profile (Kharytonov et al., 2013). Thus, using grey-green clay as artificial waterproof in arid conditions can be considered as cost-effective water – saving technology.

Conclusion

The suitability of the disturbed rocks extracted to the surface in the process of open-pit mining for biological land reclamation is determined by their physical, physico-chemical and biological properties. The study of the composition and properties of disturbed soils and rocks makes it possible to establish the parameters of the natural fertility of the studied substrates, to detect limiting factors, and to determine a set of restoration measures. Loess-like loam and grey-green clay of the Kerch iron ore deposit are distinguished by a higher bulk density, but lower porosity and wilting moisture compared to samples from the Nikopol manganese ore basin. It was found that after dry sieving of loess-like loam samples the sum of aggregates from 0.25 to 10 mm was 66.2 %, grey-green clay – 55.9 %. According to the results of wet sieving, the model of technosoil from grey-green clay stands out, where the sum of water-resistant units was 78.2 %. The use of the rotor complex leads to mechanical destruction and an increase in the content of small particles of rocks. Microaggregate structure breaks down as successive layers of soil and rocks are removed and stockpiled. Self-compacting processes occur to a large extent in multilayer structures. This pattern is observed at the boundary of the backfill differentiated in texture layers of technosoils. This indicates the existence of a barrier that prevents the relationship of edaphic properties between substrata strata. The model of technosoil composed of grey-green clay differs in a larger number of water-resistant micro-aggregates. The best conditions for land reclamation are connected with including grey-green clay in two- and three-layer constructions of techno-soils, providing a waterproofing effect.

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