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Use of solid mining waste to improve water retention capacity of loamy soils

Viktor Kostenko[1], Olha Bohomaz[1*], Inna Hlushko[1], Nataliia Liashok[1], Tetiana Kostenko[2]

[1]*Donetsk National Technical University, Pokrovsk, Ukraine*
[2]*Cherkasy Institute of Fire Safety named after Chornobyl Heroes of National University of Civil Defence of Ukraine, Cherkasy, Ukraine*
**Corresponding author: e-mail olha.bohomaz@donntu.edu.ua*

Abstract

Purpose. The research explores the possibility of increasing the fertile properties of agricultural soils of loamy type by adding burnt-out dump mass from coal enterprises.

Methods. Laboratory research on parameters of penetration and retention capacity of sorbed and meniscal water for different burnt-out rock fractions. The burnt-out rock was sampled from the mine No. 5/6 waste rock dump in the city of Myrnohrad, Donetsk Oblast, and divided into four fractions from 0.63 to 10 mm. The water penetration coefficient of the soil with the added dump mass is measured by the velocity of water seepage into the test samples. The ability of rock additives to retain film-sorbed and capillary water is assessed by comparing the weight of dry and moistened samples of crushed dump mass.

Findings. The velocity parameters of water penetration into samples of loamy mixtures with burnt-out dump mass with fractions ranging from 10 to 0.63 mm in size have been determined. It has been found that an increase in the percentage of burnt-out rock in the mixture leads to an increase in the water penetration velocity from 1.2 ml/cm^2·min with a rock content of 30% to 30.66 ml/cm^2·min with a rock content of 70%. The highest penetration coefficients are achieved when adding rock with a small fractional composition of 0.63-3 mm, since an increase in grain size leads to a reduction in the coefficient by several times. It has been determined that with an increase in the size of the rock fractions in a loamy mixture, the retention capacity of sorbed and pore water suitable for plant nutrition decreases by approximately 40%.

Originality. For the first time, the parameters of penetration coefficients, as well as the accumulation of sorbed and meniscal water for mine waste in the Selidovo-Pokrovskyi district of Donbas, have been determined.

Practical implications. The results obtained can be used to improve the physical properties of agricultural soils of loamy type by increasing their water retention capacity.

Keywords: *mine rock, waste heap, mining waste, sorbed and meniscal water, water penetration velocity*

1. Introduction

The key to energy security and energy independence of Ukraine is the stable functioning of its own fuel-energy sector, the main component of which is the coal industry [1], [2]. Underground mining of energy resources is characterized not only by difficult mining conditions and technological processes with constant exposure to hazardous factors [3], [4], but also by a significant technogenic burden on the environment, due to the generation of waste of various aggregate states [5].

One of the most important environmental issues in the mining industry is the problem of managing solid waste from the mining industry. According to statistical data, before the start of the full-scale Russian-Ukrainian war, there was a tendency in Ukraine to increase the volumes of solid waste generated at mining industry enterprises. Thus, while in 2015 257.8 million tons of wastes were generated, then in 2020 this figure increased by 1.52 times and amounted to 391.1 million tons [6]. Over the last almost 1.5 years, the volume of solid waste generated has probably decreased due to a reduction in the number of coal-mining enterprises operating in the Donetsk and Luhansk regions.

The low level of utilization and recycling of waste rock (up to 25-30% of the created parameter) [7] results in its significant accumulation on the daylight surface in the form of waste rock dumps. Over the past 50 years, over 25 billion tons of mining waste have been accumulated in the coal-mining regions of Ukraine, occupying thousands of hectares of fertile land [8], [9].

Waste rock dumps are objects of increased danger due to their ability to spontaneous combustion and explosion. The presence of combustible components in the middle of the dump leads to their smoldering, which can last for decades [10], [11]. According to scientists, waste rock dumps in the Donetsk region annually emit more than 120 kilotons per year of greenhouse gases and other toxic substances [12]. Water and air erosion that occurs on the slopes of waste heaps due to climatic factors, leads to an expansion of their

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area and poses a risk of hazardous substances penetrating from the surface of waste rock dumps into ground and surface waters [13]-[17].

Under the influence of waste rock dumps, negative geological processes are manifested in various aspects. For example, a rock mass exerts additional pressure on nearby soils, which can affect the change in the filtration characteristics of these soils [18], [19]. In addition, it has been proven that the waste heaps, located directly on the mine's mining allotment, directly affect the stability and condition of underground mine workings [20].

The negative environmental, economic and social impacts of mining industry waste indicate that the industry needs to rethink waste management methods and implement new solutions. One effective option in this direction is to reduce mining waste through the implementation of the advanced coal mining technologies and the use of more powerful equipment, as well as maximizing the use of waste rocks already accumulated in waste rock dumps as raw material for other branches of industry and agriculture.

Thus, reducing the technogenic burden of waste rock dumps on the environment by increasing the level of utilization of solid coal-mining waste is an urgent scientific and technical task.

1.1. Literature review

Many Ukrainian and foreign publications are devoted to studying the issues of using solid mining waste. All of them consider the waste rock from heaps not as waste, but as valuable resource for different industries.

One of the most well-known methods of waste rock utilization is its use for backfilling the mined-out space. This method of using waste rock and beneficiation tailings ensures the stability of mine workings, limits the risks of surface subsidence and the occurrence of underground fires. It is when using this method that the issue of waste-free, environmentally friendly production is resolved [21].

According to I.M. Kuzyk [22], waste rock dumps of Donbas coal mines on average may contain in the tone of the dump mass up to 0.1-85 kg of sulphur, 0.1-20 kg of zinc, 54-343 kg of aluminum, 2-21.4 kg of titanium, 1 kg of molybdenum, as well as a small amounts of nickel, beryllium, barium, cobalt and other compounds. The data presented indicate the feasibility of using accumulated dump masses as technogenic ore deposits for obtaining valuable and rare elements.

It is advisable to use waste mine rock, which has low industrial value, for road construction [23]. The use of burnt-out mine rocks for subgrade in the construction of structural layers of road surfaces is currently relevant and promising [24].

Methods of recycling the waste from the mining industry for the production of construction materials such as slabs, paving stones, wall panels, ceramic bricks are known throughout the world [25]-[27]. In addition, there is a method for extracting residual coal from waste rock and subsequently using the resulting tailings as raw materials for the production of environmentally friendly burnt bricks. The brick produced in this way has improved mechanical properties, namely: increased strength, reduced open porosity and water absorption [28]. However, the use of mining waste in the construction industry is limited by the high variability in the physical-chemical properties of rocks within the same rock dump. Moreover, mine wastes often have poor geotechnical properties in addition to their adverse environmental characteristics.

The presence of a complex of mineral components in solid mining waste, as well as the transformation of burnt-out rock into a poorly soluble state similar to ceramics, opens up the possibility of using this material in agriculture. There is a well-known practice of using solid waste from crushed stone production as a fertilizer for growing energy crops. It has been proven that the addition of crushed stone increases the yield of agricultural crops due to more intensive development of the root system as a result of a change in the structure of peat soil [29].

At present, the soils of Ukraine can be characterized as intensively losing crop yield [30], [31]. Due to the destructured upper layer, their ability to retain and accumulate moisture is reduced, resulting in the suppression of the development of plant root systems. In addition, the structural texture of soils is dominated by clay and silty components, which in turn also worsens the conditions for the full supply of plants with all the elements and minerals necessary for nutrition. Therefore, the possibility of increasing the structural properties of clay and silty soils, as well as improving their water penetration and ability to accumulate moisture is of interest.

There are five main types of water in the composition of soils. These are: hard water – ice; chemically bound water; vaporous water; physically bound (sorbed) water; free water – gravitational and capillary [32].

Solid water is a frozen state of other forms, chemically bound (crystalline hydrate, etc.) is not an independent physical body and does not have solvent properties, vaporous water is dependent on the thermobaric conditions of the air and the presence of other types of water. It is important to note that for clay and loamy soils, there is another type of water associated with the aggregation process of diffuse water-rich organic particles, which can lead to the formation of hydrogels in which water acts as a dispersion medium. An example is the process of soaking clay for at least a week to produce a homogeneous sand-clay-water solution when constructing heating furnaces from bricks.

Physically bound water is represented by a film formed around the surface of solid particles. When particles touch water molecules, the latter are attracted by these particles, and the retention of water molecules occurs by sorption forces. The water film thickness can reach several tens or even hundreds of molecule diameters. In terms of its physical state, film water is very heterogeneous, which is conditioned by the different bond strength between molecules of different layers. On average, for most soils, it is 7-15% of the mass, and sometimes it reaches 30-35% in clay soils.

In rocks, free water is present in capillary and gravitational forms. Capillary water is retained in small-diameter cavities – fractures, pores, capillaries, under the action of meniscal forces. Gravitational water is characterized by the presence of large-sized cavities in which water can freely settle and move.

An assessment of the ability of solid mine waste to influence the filtration and retention of sorbed capillary water is important for the possibility of using burnt-out rock to improve the moisture saturation parameters of degraded loamy soils.

The research purpose is to explore the possibility of using the burnt-out mass from coal mine rock dumps to improve the physical properties of agricultural soils of loamy type, thereby increasing their fertility.

2. Methods

2.1. Determining the ability of burnt-out dump mass to retain sorbed and capillary water

The dump mass was sampled from the mine No. 5/6 waste rock dump in the city of Myrnohrad, Donetsk Oblast The mining-geological conditions for mining mine layers are quite typical for the Selidovo-Pokrovskyi district of Donbas. The rock was sampled at five points from a depth of up to 10 cm using the "envelope" method. The waste rock dump mass is burnt-out and has been exposed to climatic factors for a long time. The dry rock is crushed and sifted with laboratory sieves into three fractions, mm: 1.25-3; 3-5; 5-10. Each fraction in each sieve is thoroughly washed with running water to remove fine residues.

Laboratory beakers with a volume of 300 ml are pre-weighed on a laboratory analytical balance of the Radwag AS 220.R2 type with an accuracy of one hundredth of a gram. The weight of each empty container is recorded (m_1). The sifted rock samples are poured in laboratory beakers to the approximately 250 ml mark and heated in a drying cabinet at a temperature of 110°C until a constant mass is achieved. The mass of beakers with dried rock (m_2) is recorded.

To determine the ability to retain film-sorbed water, distilled water is poured into filled beakers until the rock surface is covered. After this, the rock is covered with a fine metal mesh and turned over, allowing the gravitational water to drain completely. The beakers without a mesh with rock covered with a water film are weighed (m_3).

The ability of the rock to simultaneously retain film-sorbed and pore water was determined at a preliminary stage, but beakers filled with distilled water are held for a day, which ensures the penetration of water into fractures, pores and capillaries. After that, the water is drained and weighing is performed without a mesh (m_4).

The content of film-sorbed together with pore water (% to the dry rock mass) is calculated according to the formula:

$$W_{PC} = \frac{m_4 - m_2 - m_1}{m_2} \cdot 100, \tag{1}$$

where:

m_1 – weight of an empty laboratory beaker, g;

m_2 – weight of a laboratory beaker with dried rock, g;

m_4 – weight of a laboratory beaker with rock containing film-sorbed and pore water, g.

Accordingly, the content of predominantly film water (% to the dry rock mass) is:

$$W_P = \frac{m_3 - m_2 - m_1}{m_2} \cdot 100, \tag{2}$$

where:

m_3 – weight of a laboratory beaker without a mesh with rock covered with a water film, g.

The share of film water relative to the total retained C_c is calculated as a ratio:

$$C_c = \frac{W_P}{W_{PC}}, \tag{3}$$

where:

W_P – the content of film water (% to the dry rock mass);

W_{PC} – the content of film-sorbed together with pore water (% to the dry rock mass), %.

2.2. Assessing the water penetration velocity of soils with impurities of dump mass

As in the previous experiment, the burnt-out dump mass was sampled using the "envelope" method from the mine No. 5/6 waste rock dump in the city of Myrnohrad. The rock is crushed and sifted with laboratory sieves into four fractions, mm: 0.63-1.25;1.25-3; 3-5; 5-10.

In the field, soil samples are selected, namely degraded loamy chernozem. In the laboratory, the samples are dried and cleaned of excess impurities, such as leaves, sticks, and others, which could potentially affect the study of filtration parameters.

Mixtures of soil and rock are prepared by weighing using a Radwag AS 220.R2 analytical balance. From N = 30% (by mass) to 70% of each rock fraction is added to the soil, with a step of 10%. In this way, 20 samples have been obtained, which are used to fill laboratory beakers. The mixtures are compacted by intensive shaking, and the surfaces are leveled.

In each beaker, a metal fine-celled stainless steel mesh measuring 0.056×0.04 (AISI 304 08X18XH10) is placed on the surface of the mixture. The beaker is turned over while holding the mesh. A 100-ml measuring vessel filled with water, with a scale of one ml marked on the wall and an internal radius (R) of two centimeters is placed on the mesh. The beaker with the installed measuring vessel is returned to its original state, and the duration of air portion seepage into the vessel and, accordingly, filtering of the same volume of water into the soil is recorded.

The time (T, min) during which the flow rate (Q, ml) of 30 ml of water flowing into the beaker is fixed with the help of an electronic stopwatch. Velocity parameter (V) of water seepage into soil-rock mixture is calculated for a certain fraction (N) by the formula:

$$V_N = \frac{Q}{\pi R^2 T}, \tag{4}$$

where:

Q – flow rate of the water flowing into the beaker, ml;

R – radius of the laboratory beaker, cm;

T – time, min.

3. Results and discussion

The results of experiments to assess the ability of a burnt-out dump mass to retain sorbed and capillary water are given in Table 1. The parameters obtained as a result of the experiment make it possible for the first time to determine the retention capacity parameters of sorbed and pore water suitable for plant nutrition for burnt-out rocks of Selidovo-Pokrovskyi district of Donbas.

Parameter W_{PC} ranges from 8.08 to 13.6% of the dry rock mass. The larger particle size fraction (5-10 mm) has a low value, which can be explained by the smaller total sorbing surface plane of large-sized particles with the same mass of test samples.

For a fraction that is approximately three to four times smaller (1.25-3 mm), the W_{PC} value is approximately 40% higher.

It has been found that the ratio of sorbed and pore water types depends on the size of the rock particles. In relatively large rock grains, the surface is more developed and has more microfractures, pores and capillaries – reservoirs with meniscal water, so C_c = 0.86. Smaller grains have a smoother surface, therefore the ratio is reduced to 0.95.

Table 1. Film sorbed and pore water retention capacity for fractions

Fraction, mm	m_1, g	m_2, g	m_3, g	m_4, g	W_{PC}, %	W_P, %	C_c, share
5-10	100.8	268.77	388.30	391.30	8.08	6.96	0.86
3-5	104.9	258.30	392.55	395.70	12.58	11.36	0.90
1.25-3	101.4	288.25	427.97	428.88	13.60	12.96	0.95

In the process of burnout and oxidation, dump rocks become similar in properties to ceramics, as they do not increase in volume when wet and prevent the formation of a water-impermeable layer and crust on the earth's surface when drying.

In general, it can be stated that the studied water retention capacity of burnt-out rocks is less than that of loamy soils, reaching up to 30%, but close to those of sandy soils – 10-13%.

When experimentally assessing the water penetration velocity of the artificial soil, into which dump mass is added, the following results have been obtained (Table 2). A matrix has been obtained indicating the velocity of the water seepage into the soil-rock mixture (V, ml/cm^2·min). By its nature, this parameter is similar to the filtration coefficient, but the non-conformity of the experimental equipment to the regulatory requirements [33] allows in the future to operate only with qualitative comparisons.

Table 2. Velocity of the water seepage into the soil-rock mixture, V, ml/cm²·min

Rock grain size, mm	Rock content in the mixture, N, %				
	30	40	50	60	70
5-10	1.2	0.92	1.74*	4.36	9.7*
3-5	0.94	1.08	1.14	6.2*	9.04
1.25-3	1.7	4.42	6.4	10.18	13.48
0.63-1.25	2.66	22.66	22.6	27.7	30.66

It should be noted that due to imperfect sample preparation methods, namely insufficient compaction by shaking, data reproducibility is unstable. In several cases, the Y-error is excessive, so Table 2 gives the minimum results, marked with an asterisk. Such results are typical for experiments conducted with large-sized fractions (over 5 mm). This can be explained by the fact that there are cavities between the large grains, and a medium of soil, rock, and air is formed. The presence of cavities facilitates the accelerated filling of the mixture with water.

From Table 2 it is clear that the highest values of V parameter, ten or more times higher than the lowest, are obtained by adding small-sized rock grains (less than 3 mm) to the loam in proportions of over 40-50% (such values are highlighted in color in Table 2).

The tendencies of water penetration velocity V at different amounts (N, %) of rock impurities indicate a logarithmic dependence when adding a fraction of less than 3 mm (V_A, V_B, Fig. 1). When using larger-sized grains, the nature of the dependences changes to exponential and they almost coincide (see V_C, V_D, Fig. 1). Such a phenomenon can be explained by an increase in the presence of free macropores with increasing content of large rock grains.

Attention should be paid to the need to add a significant amount of rock (over 50%) to the loam to obtain high V values, which is not always appropriate. Significantly lower doses of impurities also provide a qualitative improvement in penetration, so that a 30% addition of rock provides penetration of 1-2.5 ml of water per minute. In this case, increasing the duration of irrigation also makes it possible to increase the accumulation of moisture in the soil layers deeper from the surface.

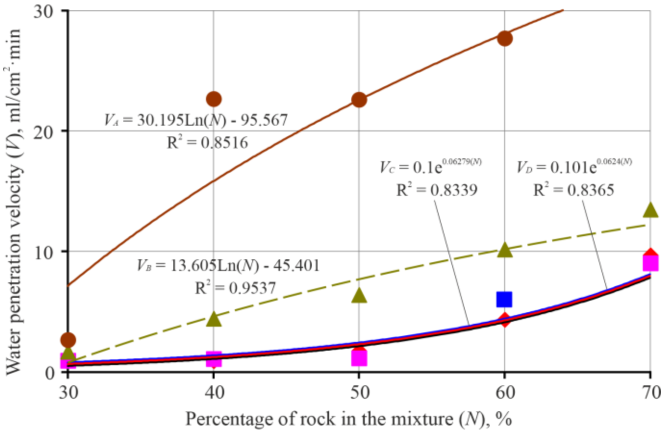

Figure 1. Influence of the amount (N, %) of rocks added to the loam on the velocity parameter (V, ml/cm²·min) of water penetration into the sample: V_A, V_B, V_C, V_D – according to the factions, mm: 0.63-1.5; 1.5-3; 3-5; 5-10

From a practical point of view, the quality of preparation of the rock impurity, namely its fractional composition, is of great importance. The experimental results indicate the feasibility of using small-sized grains (Fig. 2). But for the smallest fraction (0.63-1.5 mm) at $N \geq 40\%$, the parameters of water penetration velocity have quite close values. This means that the spotty use of large concentrations of different varieties of rock (less than 10 mm) for application to the soil provides a sufficient water accumulation velocity.

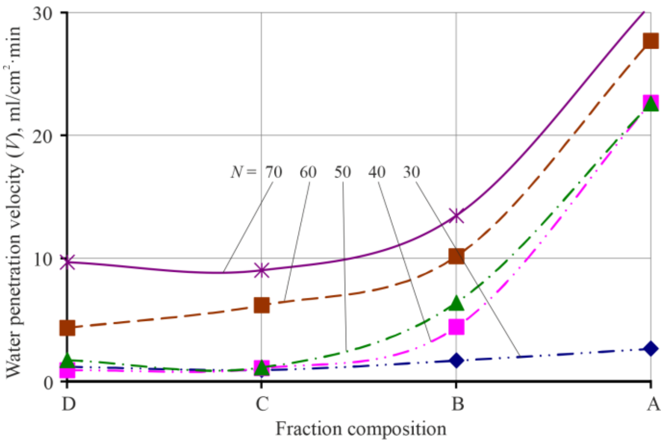

Figure 2. The influence of the fractional composition of rocks added to loam on the parameter of water penetration velocity (V, ml/cm²·min): V_A, V_B, V_C, V_D – according to the factions, mm: 0.63-1.5; 1.5-3; 3-5; 5-10

The structural texture of most soils of Donbas and other regions of Ukraine is currently dominated by clay and silty components. Such soils are characterized by increased density and viscosity, as a result of which water does not pass through well and plants do not receive the amount of moisture necessary for nutrition. When dry, such soils become covered with a dense crust, preventing the flow of moisture, air and light to the plant root system. After the crust dries, wide fractures form in it, which, on the contrary, contribute to the removal of moisture from the lower layers of the soil.

Visual observations make it possible to specify the mechanisms of water saturation of different types of soil. So, as for loams, when first watered, water quickly penetrates into folds, fractures, and macropores, moistening a rather significant surface space. The wetted organic component particles of the soil medium begin to absorb water by their mass, increa-sing significantly in volume. With a sufficient amount of moisture, aggregation of particles is observed to form a hydrogel. A layer of fairly stable medium unsuitable for water filtration is formed. Water reaches the lower soil layers in a mode close to diffuse, and the velocity of such water front movement is orders of magnitude less than during filtration.

Sandy soils with limited organic constituents are not prone to significant water absorption by their mass, that is, water penetrates to the surface, but there is almost no increase in the volume of wetted particles. The particle surface is wetted with so-called film sorbed water, the capillaries and micropores are also gradually filled with meniscal water. The movement of water in depth occurs through macropores and cavities. Between parts of sandy soil, gravitational water moves in a filtration mode.

Laboratory experiments have confirmed a several-fold increase in water penetration when adding fine-grained material less than 5 mm in size to loam. Changing the soil structure by adding granular media can increase water penetration and prevent the surface crust formation.

To ensure the highest water penetration parameters, it is advisable to add at least 50% of solid mining waste. In terms of the availability of such a resource in Donbas, there are no restrictions, but in terms of logistics, as well as financial and labor costs, there is a problem.

We have conducted preliminary research on the possibility of using burnt-out dump mass as a fertilizer additive. Solid mine waste in iself is not a nutrient medium. Therefore, it was used to prepare a three-component nutrient mixture consisting of 25% burnt-out mine rock, 25% river silt and 50% degraded loamy chernozem treated with California red worms, on which tomato seeds were later planted. In the course of conducting laboratory research, it has been revealed that the highest germination rate – 100% – was in samples grown on a substrate with the addition of burnt-out mine rock. While the germination percentage of samples grown on the other two substrates (1 – reference, degraded loamy chernozem; 2 – a mixture of reference chernozem and treated with earthworms, in a proportion of 50 to 50%) was only 40% [34]. This makes it possible to confirm the hypothesis of the possibility of using burnt-out mine rock not only to improve moisture capacity, but as components of nutrient additives to degraded soils [35]. The results obtained are new, since no previous research has been conducted on the use of burnt-out dump mass from coal mining enterprises as a soil former and fertilizer component.

The widespread use of solid mining waste in agriculture requires research not only into changes in the water-permeable properties of soils when adding burnt-out rock to them, but also other agrochemical properties. Therefore, in the future, it is necessary to assess the minimum amounts of rock addition to specific types of agricultural land and ways of doing so. The issue of safe stripping of dumps and cost-effective obtaining of the necessary fractions of burnt-out rock also remains relevant.

4. Conclusions

Under laboratory conditions, a research has been conducted on the penetration parameters and retention capacity of sorbed and meniscal water for fractions of burnt-out rock with a size from 0.63 to 10 mm. For the first time, the parameters of penetration velocity, as well as the accumulation of sorbed and meniscal water for mine waste, typical of the Selidovo-Pokrovskyi district of Donbas, have been determined.

The velocity parameters of water penetration into samples of loamy mixtures with burnt-out dump mass have been determined. When adding 30% of the rock, the velocity parameter is 1.2-2.66 $ml/cm^2 \cdot min$, with an increase in the addition of rock to 70% – 7.9-30.66 $ml/cm^2 \cdot min$.

The highest penetration parameters are typical for adding a small fractional composition of 0.63-3 mm, and an increase in grain size leads to a reduction in the parameter several times.

The retention capacity of sorbed and pore water suitable for plant nutrition ranges from 8.08 to 13.6% of the dry rock mass. The larger-sized particle fraction (5-10 mm) has a lower parameter, while for a fraction that is approximately three to four times smaller (1.25-3 mm), the parameter is approximately 40% higher.

The conducted research has proven the possibility of using mining waste in the form of burnt-out dump mass from waste heaps to improve the physical properties of loamy soils.

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Використання твердих відходів гірництва для покращення водомісткості суглинкових ґрунтів

В. Костенко, О. Богомаз, І. Глушко, Н. Ляшок, Т. Костенко

Мета. Досліджено можливість підвищення родючих властивостей сільськогосподарських ґрунтів суглинкового типу шляхом додавання перегорілої відвальної маси з вугільних підприємств.

Методика. Лабораторні дослідження параметрів проникливості та місткості сорбованої і меніскової води для різних фракцій перегорілої породи. Перегорілу породу було відібрано з породного відвалу шахти №5/6 міста Мирнограду Донецької області та поділено на чотири фракції від 0.63 до 10 мм. Вимір показника водопроникності ґрунту з доданою відвальною масою визначали по швидкості просочування води до експериментальних зразків. Оцінку здатності породних добавок утримувати сорбовану плівкову та капілярну воду проводили шляхом порівняння ваги сухих і зволожених зразків подрібненої відвальної маси.

Результати. Визначено показники швидкості проникливості води до зразків сумішей суглинку з перегорілою відвальною масою з розміром фракцій від 10 до 0.63 мм. Встановлено, що збільшення відсотку перегорілої породи у суміші призводить до збільшення показника швидкості проникливості води від 1.2 мл/см^2·хв при вмісті породи 30%, а до 30.66 мл/см^2 хв – при вмісті породи 70%. Найбільші показники проникливості притаманні при додаванні породи малого фракційного складу 0.63-3 мм, збільшення розміру зерен призводить до скорочення показника в кілька разів. Визначено, що зі збільшенням розміру фракцій породи у суглинковій суміші зменшується приблизно на 40% показник утримання придатної для живлення рослин сорбованої та порової води.

Наукова новизна. Вперше встановлено параметри показників проникливості, а також накопичення сорбованої та меніскової води для шахтних відходів Селідовсько-Покровського району Донбасу.

Практична значимість. Отримані результати можуть застосовуватися для покращення фізичних властивостей сільськогосподарських ґрунтів суглинкового типу за рахунок підвищення їх здатності до утримання води.

Ключові слова: *шахтна порода, терикон, відходи гірництва, сорбована та меніскова вода, швидкість просочування води*