PHYSICAL AND CHEMICAL PROPERTIES OF TOPSOIL USED FOR BIOLOGICAL RESTORATION OF COAL MINE WASTE-BASED STRUCTURES IN THE UPPER SILESIAN COAL BASIN IN POLAND[1]

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Abstract: In the Upper-Silesian Coal Basin in southern Poland large areas of coal mine waste heaps, riverbanks and shoulders of transportation routes built of coal mine waste are biologically restored by the initiation of soil-forming processes. The purpose of this research was to determine, using laboratory research and observation "in situ" (field), some physical and chemical properties of mixtures of topsoil composed in the forming process (coal mine waste and sewage sludge), before placing them on the coal mine waste heaps and riverbanks, and after a period of 1- 3 years, when the layer has been fully penetrated by root mass. Adequate physical properties of topsoil in the process of forming mixtures protect the spoil-banks against erosion. Poor water retention ability should be taken into consideration when selecting the plants for biological restoration. High levels of macro components and increased sorption guarantee long and appropriate supply of nutrients. The application of analysed soil-forming mixtures for biological restoration of coal mine waste heaps and spoil-banks, along with proper selection of plants, assist in maintaining a durable, self-sustaining ecosystem.

Additional Key Words: coal refuse, coal waste, mine reclamation, (angle of shearing resistance, apparent cohesion, water retention, sorption complex)

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Introduction

In the Upper Silesian Coal Basin in southern Poland, coal mine waste (mainly waste remaining after hard coal processing) is used to construct large surfaces and dumping grounds of substantial capacity, river embankments and shoulders of roads. Thereby, non-soil grounds are formed (Patrzałek, 2001). Those grounds are characterised by physical and chemical properties that preclude the growth and development of flora. A durable layer of vegetation cover, which actively prevents erosion, can be obtained by topsoil addition, soil fertilisation, and introduction of appropriately selected topsoil forming plants (Patrzałek et al., 1993).

Soil fertility is achieved by either mineral fertilization or by covering the coal waste with a topsoil layer. The top layer is usually a layer of soil, or a mixture of rock waste with either compost or sludge. The flora introduced on such topsoil should be one characterised by its longevity, resistance to periodic droughts, or with the ability to be supplied with water and nutrients over long periods of time.

The fertilized soil, along with vegetation, initiates the process of topsoil formation on coal mine waste areas. The intensity of the soil formation process is determined by both the content of flora nutrients in the soil, and the flora itself, which ought to have substantial longevity and maintain a good plant density. Such plant communities initiate the establishment of an ecosystem.

That is why the revegetation or reclamation processes of coal mine waste areas should have the objective to provide long-lasting fertility of the initial soil. Such an effect can be achieved by covering a rocky base with a layer of mixed coal mine waste and sludge, and sowing the area with properly selected blend of grass species.

The purpose of the study was to assess the biological durability of the river embankment made of coal mine waste, applying for the assessment of the physical and chemical characteristics of the topsoil layer, as well as on the growth and development of vegetation.

Experimental Conditions

The research was conducted on a river embankment constructed of hard coal mine waste, which was covered with a mixture of such waste with sludge and sowed with a mixture of different types of grass species (Patrzałek and Pozzi, 2003). The properties of the topsoil are given in Table 1.

The topsoil layer, installed some 5 years earlier, was severely eroded. This material consisted of fine stones $\boldsymbol{\Phi}$ <25mm, along with a gravel fraction $\boldsymbol{\Phi}$ 25-1mm. The surface of the ground was loose. The soil reaction or pH was very acidic and the content of readily soluble salts was very low. The exchange capacity, in comparison to that in natural soils, was also very modest, as was also the sum metallic cations with alkali characteristics on the exchange complex. Those properties indicated extremely deficient soil and its low ability to retain nutrients necessary for plant growth. This largely explains why there were no plants on the embankment.

Table 1. Physical and chemical properties of the topsoil layer of the river embankment slope before fertilization

Item determined	Slope away from water
Fraction Φ 25-1 mm [%]	58
fraction Φ 1-0.1 mm [%]	31
fraction Φ < 0.1 mm [%]	11
pH_{KCL}	4.4
pH_{H2O}	5.0
Filtration factor ***k*** [m/sec]	$1.21 * 10^{-7}$
Cohesion c_u [Kpa]	0
Internal friction angle φ	42.9
Water retention	
pF 0	45.5
pF 2	32.5
Electric conductance [μScm^{-1}]	336
$Na^{+}+K^{+}+Ca^{++}+Mg^{++}$ (+)cmol/kg)	4.192
Sorption capacity [Total]	8.467
Base saturation [V_s]	59.51

Scope of study and research methods

The research objectives were to study:

- the properties of topsoil (forming) layer directly after its preparation and installation
- the properties of topsoil (forming) layer after one and four years of use on the embankment, in field experiment
- removal of heavy metals from the 20cm topsoil layer in laboratory experiment

Preparation of topsoil forming layer for study work

Coal mine waste, after six months of seasoning was mixed with sludge, with the volumetric ratio of 3:2. The mixture was prepared by placing the two components onto a pile in thin layers and then mixing with a loader. The prepared mixture was transported to the embankment, where was placed with a dragline excavators on to the surface of the embankment. Such a mixture will be referred to as topsoil forming layer. The material consisting of coal mine waste, together with the topsoil forming mixture will be referred to as the initial soil.

Physical properties of initial soil

Minimum and maximum spatial density was determined by the hydrostatic lift method in kerosene (Polish Norm PN 88/B-04481).

Cohesion and internal friction angle were determined in the box device for direct shearing. The measurements were carried out on material with maximum compaction level achieved, natural moisture content, and devoid of the fraction Φ >10mm.

The water permeability factor was determined applying the variable gradient method in Kamieński tube.

Water-related properties, that is water retention, were determined on the basis of the course of the water retention curve (pF) presenting the dependence between the capillary potential of initial soil, as negative pressure binding water in soil, and its moisture content. The measurements were carried out using laboratory (test-tube) centrifuge, taking advantage of its different speeds. The value of pF 0 was determined by saturation of samples on capillary rise for a few hours. On the basis of the obtained curves, the retention of natural and process water was determined.

The granulometric composition of waste used forming layer was estimated, assuming that stone fraction accounted for some 30%, gravel fraction for some 40 % of its volume, the remaining volume consisted of fractions of sand, dust, and silt.

Chemical and physico-chemical properties of initial soil

All the characteristics were determined for the fraction <1mm:

- Reaction based on the pH measurement in H_2O an pH in 1N of KCl in the ratio 1:2.5, electrometrically;
- Proper conductivity in water solution, in the ratio 1:5, conductometrically;
- Ion composition (Ca^{++} ,Mg^{++}, Na^+ K^+) and exchangeable sorption in 1N (normal) extracts of CH_3COONH_4; Na^+ K^+ Ca^{++} ions by photo-flame method, Mg^{++} by atomic absorption method (ASA); cation exchange capacity obtained by calculation.
- Hydrolytic acidity in accordance with Kappen's method in 1N of $Ca(CH_3COO)_2$ H_2O;
- Organic substance content – by gravimetric method from mass loss after annealing of the sample in the temperature of 550^oC
- Total nitrogen (N-total) by Kjeldahl method, constituting of combustion and titration in 0.05 N of H_2SO_4
- K_2O - absorptive form, acc. to Egner Rhim's method, which consists of turning into calcium lactate and photometric determination
- P_2O_5 - absorptive acc. to Bray-Kurz's method II (in 0.1N HCL and 0.03N NH_4F)
- Heavy metals: Pb, Cd, Cr, Cu, Ni after extraction in 10% HNO_3 in the ratio 10:1 using the method of atomic absorption (ASA)

The laboratory experiment was performed in 3 repetitions on samples collected from the upper, middle, and lower section of the slope. The results have been provided as the average of 3 repetitions.

Laboratory experiment

In the laboratory experiment we determined the levels of salts and heavy metals that water, in the amount equivalent to average annual precipitation in that area (720mm) may leach from a 20 cm topsoil forming layer. The simulation was carried out in Mitcherlich experimental pots, having the capacity of 5.0 and surface of 314cm^2. The pots were filled with material collected from man-made topsoil (topsoil forming layer) 20 cm thick, which then underwent natural compaction over the period of one month. Then, for 2 months, it was watered using cumulative distilled water doses, calculated to equal the total precipitation over that period. In the filtrates obtained, the electrolytic conductivity value was determined, applying conductometric method, and heavy metal content was measured, applying atomic absorption method (ASA).

Productivity of topsoil forming layer

It is the ability to produce floral biomass, adequate to the possibilities of sowed blends/ species of grass and their types, and the abundance of nutritive elements in the soil.

The productivity was determined on the basis of surface cover with plants, vitality of plants, and the floral composition of the plant cover.

The research was carried out in a field experiment, on an embankment slope, covered with a 10cm thick topsoil forming layer. After two months, plots were designated, having the surface of 150 m^2 , which were sowed with 2 different blends of grass containing: *Festuca ovina* Mimi + *Lolium perenne* Niga and *Festuca arundinacea* Wom + *Lolium perenne* Niga. The experiment was ~~repeated~~ replicated three times.

Ground cover was determined by means of the method of squares (as average percentage of visual assessment of 100 squares, dimensions 10x10cm each). The determination was replicated four times, and presented as average.

Plant vitality was determined in the visual manner, on the basis of the ratio of green mass to dry mass on the above surfaces.

The floral composition of plant cover was determined on the basis of floral lists prepared for each plot.

Results

Bulk density of the topsoil forming layer immediately after its preparation oscillated around average values for soils. After one year the soil loosened. Bulk density value dropped as a result of penetration of abundant rooting of grass.

Internal friction angle of the river bank ground was slightly lower than that of the overlying mixture. During the following years this value in the initial soil was slowly decreasing but should still be considered high (Tables 1 and 2.).

Table 2. Physical characteristics of topsoil forming layer introduced on coal mine waste-based ground

Entity determined		Unit	Waste + Sludge (3:2) After mixing	After 1 year	After 4 years
Bulk density with loose arrangement of grains	(ρ_{dmin})	$10^3 kgm^{-3}$	1.93	1.78	-
Bulk density with condensed (compacted) loose arrangement of grains	($\rho dmax$)	$10^3 kgm^{-3}$	2.11	2.04	-
Filtration coefficient	k	(m/s)	$2.73*10^{-8}$	$1.73*10^{-8}$	
Internal friction angle (In natural moisture content)	Φ	$(^0)$	46.2	37.7	35.8
Cohesion (in natural moisture content)	c_u	(kPa)	8.1	3.47	3.2
Reaction		pH_{KCL}	7.3	7.3	5.8
Electrolytic conductivity		(μScm^{-1})	1115	232	215
Water retention	pF 0	(vol. %)	22.0	-	-
	pF 2		21.9	22.5	-
	pF 4.2		2.9	8.3	17.2

Cohesion – the value of that parameter decreased in the topsoil prepared, in comparison with (natural) initial soil. That was a result of decomposition of bio-gels (hydro-gels), which were added to sludge for stabilisation, as well as due to root mass penetration.

Water is the ingredient allowing the growth and development of flora and shaping physical and mechanical properties of soil. Therefore it was important to determine the ability of retention, circulation and availability of water in topsoil forming layer.

Total water retention capacity of the soil on the embankment averaged 45.5%. Field water capacity was significantly lower and amounted to 32.5%. The topsoil forming layer's total retention capacity was almost twice as small and it was mainly field water capacity. The retention of water usable to plants, in the range of pF 2 – 4.2 was low in the introduced topsoil forming layer (2.9%), due to excess water combining with water-absorptive gel (hydro-gel) in sludge. Over the period of intense floral growth and development on the embankment, usable water level retention increased to 17.2 %. That water was made available to plants as changes in the topsoil progressed. Despite seasonal droughts, which occurred in the area of field research conducted, no signs of plant withering were noted. The flora seemed very vital throughout the vegetation period.

Water permeability is a quality shaping the topsoil forming process. The mixture indicated very low permeability compared to natural soils. This value tended to decrease in time (Table 1, 2).

High water demand in the vegetation layer influenced the water economy on the river bank. During the conducted research and in the following periods of time, there was no sign of erosion gullies or of moving of the fine-grain fraction towards the base of the bank. At the same time, on the areas of embankment lacking flora, deep erosion drains were observed.

The topsoil forming layer, immediately after the application, had a slightly acidic pH, and the quantity of salts exceeded the values tolerated by cultivated grass. In initial soil the pH remained in the same range, while precipitation as well as floral layer contributed to a drop in salinity.

Table 3. Chemical and physico-chemical characteristics of topsoil forming layer on coal mine waste-based ground

Entity determined	Unit	Soil-forming layer	
		After composition	After 1 year
Reaction	pH in H_2O	6.0	6.4
	pH in KCl	5.9	6.3
Conductivity	μScm^{-1}	2440	441
S	(+)cmol/kg	16.66	14.76
T	(+)cmol/kg	21.16	19.22
V_s	(%)	78.73	76.80
Total organic matter *TOM*	(%)	32.72	34.65
N_T	(%)	0.76	0.88
$N\text{-}NH_4$	mmol./100g	1.11	0.56
MgO	mg/100g	47.21	38.0
K_2O	mg/100g	69.80	54.5
P_2O_5 acc. to Bray-Kurz 2	mg/100g	159.9	134.5

S- Sum of cations having basic character
T- Sorptive capacity
V_s- Degree of saturation with cations of basic character
N-general (total)

The quantity of organic matter in topsoil forming layer was high. It consisted of organic matter originating from sludge and carbon from coal mine waste. The total nitrogen content and content of $N\text{-}NH_4$ forms in the topsoil was at the level encountered in humus soils. In the initial soil the organic matter quantity was found to rise as a result of floral growth and development. The total nitrogen content increased simultaneously with the drop in the quantity of NH_4 ions. That was a result of changes taking place in the initial soil, as well as utilisation of oxygen by the flora for bio-mass production.

The content of P_2O_5 forms, which plants can assimilate easily, as well as K_2O, also of the same nature, was very high. Such amounts are not encountered even in most cultivated soils. The level of easily assimilated forms of magnesium also was very high. The depletion of toxic elements from initial soil formed at river embankment is an extremely slow process.

The quantity of heavy metals in the sewage sludge that we used did not exceed the Polish Norms, therefore they were allowed to be used for reclamation of grounds (Table 4.).

Table 4. Heavy metals in topsoil forming layer and its components in 10% HNO_3 extract [$mgkg^{-1}$ d.m.]

Material	Pb	Cd	Cr	Cu	Ni	Zn
Coal mine waste	6.51	0.08	3.70	10.49	13.18	5.62
Sewage sludge	69.50	2.60	69.09	97.13	16.14	1703.33
Soil-forming mixture	26.97	0.77	11.41	31.74	15.57	479.23
Allowable quantity of heavy metals in sewage sludge used for ground reclamation for non-agricultural purposes, according to Polish Norm	1000	25	10	200	3500	1000

Heavy metals and other salts contained in the soil mixture applied on the river embankment could be leached to adjoining water body, that is why the attempt at their determination (Table 5.).

Table 5. Dynamics of saline drainage from mixtures forming topsoil layer

Precipitation [mm]	16	80	160	240	320	400	480	560	640	720
Electrolytic conductivity [μScm^{-1}]	3497	3290	2297	1323	999	765	691	628	585	576

The level of electrolytic conductivity in the initially leached water was very high. Not until the material was washed with a quantity of water corresponding to the level of 400mm precipitation did the salinity level drop to the value of $765\mu Scm^{-1}$. Annual precipitation caused the electrolytic conductivity level to drop to 576 μScm^{-1}. This research confirms a high level of salinity leaches from such material in the initial period after application.

This fact is important when starting agronomic activities on areas covered with similar topsoil forming layers. The concentration of heavy metals, such as Cd, Zn, Pb, Fe, that leached to water extracts did not exceed levels permissible according to Polish norm (Table 6.).

Table 6. Heavy metals in water extract from topsoil forming mixture [mg/l]

Material	Pb	Cd	Zn	Fe
Soil-forming mixture	0.021 – 0.032	0.003-0.004	0.115-0.200	0.099-0.0187
Allowed level according to Polish Norm	0.5	0.1	2.0	10.0

The floral layer on the river embankment was balanced even at the onset of grass growth and of substantial vitality. The floral composition was different between the first year and subsequent years. The undergrowth grown from the mixture containing *Festuca ovina* had a scarce vegetative composition, only single heliophylic low-biomass plants grew there. These were totally eliminated in the following year from the undergrowth after recession of *Lolium perenne*. As early as in the first year, the plants formed a compact cover of the embankment. In the third year, balanced single-type undergrowth covering the soil was obtained, composed only by the sown *Festuca ovina* variety.

The undergrowth formed from the sown *Festuca arundinacea* and *Lolium perenne* developed in a different way. Part of the plants of *Festuca arundinacea* froze out during winter, allowing large amounts of volunteer tall nitrophylic and heliophylic wild species to grow and develop in the undergrowth. Those plants followed a full cycle of development, producing seeds and regenerating by self-seeding for a few years. Their abundant growth resulted in high above-ground bio-mass production Absence of its reception suppressed the growth of grass. Despite the fact that adjacent fields contained such plants, they did not develop on the fields with *Festuca ovina* variety. That was due to allelopathic properties of the latter specie.

Conclusion

Physical properties of the topsoil forming mixture made of hard coal mine waste with sludge can prevent the erosion of embankments of structures. Modest water retention ability in mixtures should be taken into consideration when selecting plants to be introduced as biological layer. High content of trophic macro-components and a high value of sorption complex guarantee a proper and long-lasting nutrition base for vegetation.

Applying topsoil forming layers made of mixtures of hard coal waste and sludge to river embankments there was no danger of introducing large amounts of heavy metals to water.

The application of analysed soil-forming mixtures to create plant- supporting topsoil layer on ground structures made of coal mine waste, together with proper selection of plants, results in guaranteed durability of that layer over long periods of time.

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