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Properties of degraded and reclaimed soils in the area of the abandoned "Jeziórko" sulfur mine (Poland)

Abstract: The aim of the study was to determine some physicochemical and chemical properties of post-mining soils reclaimed in different directions, after completed sulfur exploitation by means of the borehole (Frash) method. The study was conducted in 2013 in the former Sulfur Mine „Jeziórko" located on the Tarnobrzeg Plain between Tarnobrzeg and Stalowa Wola cities (Podkarpackie Voivodeship, south Poland). It covered an area of land reclaimed as the arable or forest land. The most important problems connected with sulfur exploitation was the occurrence of a layer of solid sulfur which was previously removed. During the reclamation process, embankments and excavations were leveled through replenishing large amounts of ground, post-flotation lime, mineral fertilizers, and sewage sludge. Moreover, studies upon degraded and non-reclaimed area (by 2013) were also carried out. Examined land was characterized by granulometric composition of sands, loamy sands, and sandy loams. Re-leveling of degraded land using post-flotation lime contributed to lower levels of acidification of reclaimed soil surface. The highest contents of organic carbon and total nitrogen were found in the surface layers of the soils studied. Content of available potassium ranged from very low to average. The soils were characterized by a high content of available magnesium in the surface layers of the profiles (maximum 71.8 mg·kg^{-1} in soil reclaimed as forest land), while below the Mg content was usually low. Contents of individual exchangeable cations could be lined up in a following decreasing sequence: Ca^{2+}>Na^{+}>K^{+}>Mg^{2+} Referring to the topsoil, reclaimed soils were characterized by more favorable properties (pH close to neutral, lower acidity, higher sorption capacity, higher organic carbon, total nitrogen, and available forms of phosphorus, potassium, and magnesium concentrations) as compared to non-reclaimed soil.

Keywords: post-mining soils, sulfur mine, soil profile, reclamation

INTRODUCTION

Soil plays a variety of ecological functions in the environment, including protective role for ecosystems from excessive influence of undesirable substances. The above-mentioned properties last as long as the biogeochemical balance in their functioning is maintained (Baran 1999). In areas that are intensively used by industry, which can include mining regions, the negative impact of humans on the natural environment and its individual components can be observed. This applies especially to the mining, which significantly transforms the relief of terrain and excludes considerable acreage of agricultural land and forests from the use, degrading the landscape values (Dulewski and Wtorek 2000).

Native sulfur deposits in Poland, located in the Carpathian Foreland, come from the Miocene (Gąsiewicz 2000; Frankiewicz and Pucek 2006), while the most abundant ones can be found near Tarnobrzeg town (Machów, Jeziórko, Grębów, and Piaseczno villages). Sulfur exploitation in the Sulfur Mine „Jeziórko" was conducted between 1967 and 2001 by means of the borehole method (underground melting) which was in that time in Poland a new mining technology with unrecognized effects on the nature. Generally, this method consisted in the supplying a carrier (i.e. water with temperature above 140°C) to the bed, melting the sulfur in the underground, and then its pumping to the surface by means of an air-lift (Warzybok 2000). In general, technology of an underground sulfur melting according to Frash method assumptions, uses low melting point of sulfur (about 120°C), its insolubility in water, not mixing with water, and its density that is almost twice as large as that of water (Hajdo et al. 2007).

Sulfur mining and processing was an economic activity that significantly affected the natural environment, both within the mine and adjacent surroundings (Trafas 1994, Gorylewski and Uberman 1999, Bryk and Kołodziej 2009). The range of soil degradation due to underground sulfur melting is estimated to about 5 through 6000 ha (Helios-Rybicka 1995). The environmental transformations, fundamental and characteristic for the borehole mining technology, were associated with creating of sulfuric acid during the

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sulphur oxidation (Gołda et al. 2005). Sulfur mining caused an acidic soil degradation by destroying its physicochemical, chemical, and biological properties (Kaniuczak 2007). The soil acidity altered from weakly acidic or neutral typical for soils of this region before exploitation, to extremely toxic acidic pH values (2.33–4.46 in H_2O and 2.24–4.42 in 1 M KCl). Studies (Siuta and Lekan 1972, Skawina et al. 1972) have shown that even perfect operation of the borehole caused sulfation of near-surface layers (0–20 cm) to the sulfur contents from 0.5 to 1.0% as a result of sulfur transport with steam during its de-pressing. All other errors during the borehole work, or lesser or greater failure, resulted in the increase in sulfation up to 5–30% (point or spot sulfation). The most drastic were, however, significant failures in the borehole (head breaks) and leakage of underground water containing sulfur (so-called "eruptions") causing uncontrollable pangs of water with molten sulfur and hydrogen sulfide on land surface, leading to saturation of the soil with sulfur and its compounds sufficiently to preclude the plant growth. The extent of these ejections varied widely and ranged from a few to several dozen meters from the place of eruption, wherein as a result of some of them, sulfur cones having a diameter and a height of a few dozen meters formed on the surface of surrounding area (Jońca 2000, Warzybok 2000). Such a state of land surface enforces different directions of reclamation on relatively small area (Baran and Turski 1996).

Reclamation of sulfur post-mining areas (borehole) is a complex and difficult issue, because this type of mining activity invokes a variety of transformations in the natural environment with a very wide range (Gołda 2000, Jońca 2000, Warzybok 2000, Baran 2006). Reclamation works carried out in The Sulfur Mine „Jeziórko" were aimed, among others, at inhibiting the environment degradation by eliminating the soil acidity and the acid-forming potential of accumulated sulfur (Jońca 2000), as well as restoring the biologically active humus horizon.

Applying the post-flotation lime is an effective treatment neutralizing the soil acidity (Jońca 2002). Agricultural character of reclamation of such transformed area has been initially proposed in the studied area. However, after finding the minimum interest of farmers in using the reclaimed areas, the concept was changed and a multi-purpose management was approved – mainly as forest, pasture, and for water (Kołodziej and Słowińska-Jurkiewicz 2004).

The aim of the study was to determine some physicochemical and chemical properties of post-mining area reclaimed in different directions after completed exploitation as compared to the non-reclaimed surface.

MATERIALS AND METHODS

The study was conducted in 2013 in the former Sulfur Mine „Jeziórko" located on the Tarnobrzeg Plain between Tarnobrzeg and Stalowa Wola cities (Podkarpackie Voivodeship, south Poland). Natural soils of the area developed from Pleistocene sands and Holocene alluvia, in terms of bonitation represented mainly poor and very poor (Kołodziej and Słowińska-Jurkiewicz 2004).

Four areas (fields) were selected to studies, on which 6 soil profiles were prepared. It was assumed that the soil profiles studied were representative for the fields described below. These were places where sulfur mining (Fig. 1) was carried out for a period of 35 years followed by reclamation (including the soil neutralization using lime):

a) field No. II (profile No. 1; N50°34'10,6"; E021^{0}46'03,7") – reclaimed in forest direction between 1995 and 1997. Re-leveling of this field, where land subsidence occurred due to the sulfur exploitation, was carried out using post-flotation lime in a dose of 300 $Mg \cdot ha^{-1}$. After treatment, sulfur accumulation layer in the soil was about 0.2–5.0 m. Organic and mineral fertilizers, sometimes soils with good properties and sewage sludges, were also applied for reclamation this field.

b) Field No. II (profile No. 2; N50°34'13,7"; E021^{0}46'03,8") – reclaimed in the meadow direction in 2002. Pollution and acidification of the soil were neutralized by covering the surface of the soil with a lime layer. In order to accelerate the processes of soil formation also used sewage sludge, mineral and organic fertilizers. Alfalfa with a mixture of grasses

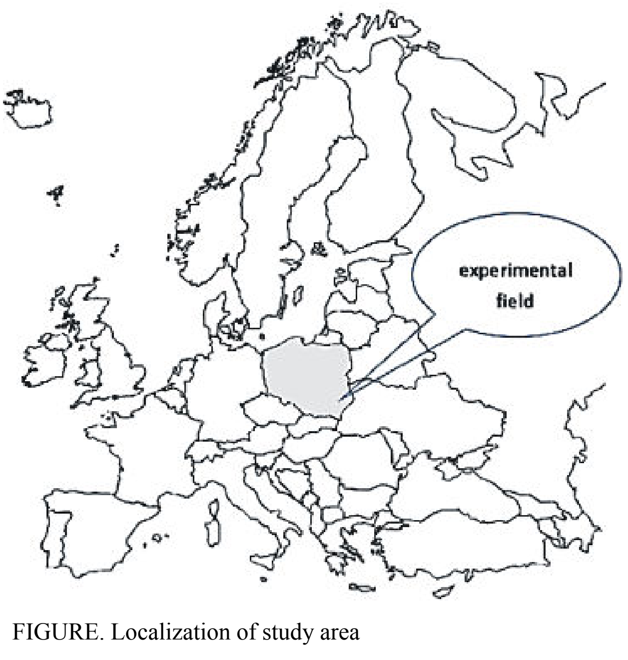

FIGURE. Localization of study area

(fescue, Italian ryegrass, timothy grass) were seeded in ground obtained in this way. Care of the field consisted of complementing alfalfa loss, which in the early days was very much, and mowing of 2 to 3 times during of the year.

c) field No. IX (profile No. 3; N50°32'54,3"; E021^{0}48'13,4") – reclaimed in meadow direction in 2004. Leveling of the reclaimed area above predicted water surface level required supplying large amounts of a ground. Due to its deficit near the post-exploitation fields, re-leveling of the terrain was made using degraded and sulfur-contaminated ground that was supplied from areas owned by The Sulfur Mine "Jeziórko". The re-leveling works were preceded by preparation, i.e. a proper profiling the ground surface and making the insulation-blocking layer using post-flotation lime 0.5 m thick. Then, re-leveling using degraded and sulfur-contaminated ground was performed with subsequent neutralization applying post-flotation lime. At the final phase, the blocking layer made of post-flotation lime of about 15 cm thickness, was made on the surface of newly formed area. The main goal of the biological reclamation phase was complete neutralization of degraded soils using the post-flotation lime, taking into account that neutralization of acidic reaction is a long-term process. The agricultural technology consisted in sowing the grass with legume species mixture onto the area being reclaimed. The procedure was preceded by general reclamation phase including: applying sewage sludge at the rate of 200 Mg·ha^1 DM, twice pre-sowing harrowing, sowing grass with legumes mixture (red fescue, meadow fescue, bird's-foot, orchard grass, tall oat-grass, annual ryegrass, perennial ryegrass), post-sowing harrowing and nursery procedures including mowing and braking of particular cuts with remaining it for green forage.

d) field No. X (profile No. 5; N50°34'16,7"; E021^{0}47'58,5" and 6; N50^{0}34'01,0"; E021^{0}48'12,9") – reclaimed in forest direction in 2002. Solid sulfur contamination was removed, excavations made during sulfur exploitation were leveled by bringing large amounts of ground and post-flotation lime along with mineral fertilizers were applied. This area was planted by birch and black locust.

e) field No. XXI (profile No. 6; N50°31'94,8"; E021^{0}50'89,2") – degraded area non-reclaimed by 2013. It was classified as strongly degraded area with visible solid sulfur spots. The area included pipelines transporting the steam for underground sulfur melting. Numerous failures of transport lines resulted presence of sulfur in solid form on the surface.

In each soil profile, uniform morphological layers were designated, from where soil samples were collected. After drying and separating the soil skeleton, samples were subject to laboratory analyses applying following methods (Ostrowska et al. 1991, Karczewska and Kabała 2008):

- granulometric composition by means of aerometric-sieve Bouyoucos method with modifications by Casagrande and Prószyński according to the norm PN 04032 (1998),
- pH in H_2O (pH_{H2O}) and in 1 mol·dm^{-3} KCl (pH_{KCl}) by means of potentiometry maintain the soil to solution ratio of 1:2.5,
- hydrolytic acidity (H_h) by means of Kappen method,
- exchangeable acidity (H_{ex}) and exchangeable aluminum (Al_{ex}) – Sokolov's method,
- organic carbon content (Corg) – Tiurin's method,
- total nitrogen (N_t) – Kjeldahl's method,
- available forms of phosphorus and potassium – by means of Egner-Riehm method,
- available magnesium – Schachtschabel's method,
- exchangeable base cations: Ca^{2+}, Mg^{2+}, K^+, Na^+ – Pallmann method.

The following characteristics were also determined:

- cation exchange capacity (CEC) – calculated as a sum of exchangeable base cations (BEC) and hydrolytic acidity (CEC= BEC + H_h),
- base saturation (BS).

Analyses were performed in three replicates and presented as mean values along with the variability ranges.

RESULTS AND DISCUSSION

Grain size distribution – often determining the productivity of the soil – showed some diversity within the sands, loamy sands, and sandy loams in various layers of soil profiles (Table 1). Profiles of fields IX, X and II (meadow use) developed from sandy formations, field XXI was located on clay formations, like the upper layers (up to 70 cm) of field II (forest use).

One of the most important characteristics of soils derived from post-mining grounds is their pH. The role of parent material reaction, is considered an important factor shaping their productivity, because it directly affects the development of microorganisms and higher plants (Szafrański and Stachowski 2000). The pH of the soil is closely related to the type of parent rock, and in the case of post-mining grounds, the type of dump groundworks. In the case of sulfur deposits exploitation, possibility of oxidation of sulfur to sulfuric acid is additional factor, that can cause a decrease in the soil pH to a value even near 1 (Helios-Rybicka 1995). The pH values in the soil profile that was reclaimed at the earliest in the forest direction

TABLE 1. The pH value, exchangeable acidity, hydrolytic acidity, and exchangeable aluminum in the different layers of soil profiles in post-mining land

Soil profile	Depth [cm]	Soil texture (SGP5/USDA)	pH_{H2O}	pH_{KCl}	H_h	H_{ex}	Al_{ex}
					$cmol_{(+)} \cdot kg^{-1}$		
Profile No.1	0–50	gp/SL	6.7	6.2	2.68	0.13	0.05
field No. II	50–68	pyg/SiL	7.6	7.5	0.60	0.00	0.00
mixed forest	68–70	gl/SL	7.4	7.2	0.84	0.00	0.00
	70–80	pl/S	2.3	2.2	4.92	4.09	1.80
	80–92	pl/S	3.3	3.2	1.12	0.51	0.40
	92–132	pl/S	3.2	3.0	2.90	1.00	0.80
Profile No. 2	0–7	pg/LS	6.7	6.0	1.36	0.07	0.05
field No. II	7–11	gp/SL	6.9	6.3	0.98	0.04	0.02
meadow	11–32	pg/LS	7.5	7.1	0.70	0.00	0.00
	32–58	pg/LS	7.7	7.3	0.56	0.05	0.01
	58–83	gp/SL	7.8	7.4	0.58	0.08	0.04
	>83	pg/LS	7.8	7.5	0.30	0.03	0.02
Profile No. 3	0–5	pl/S	7.2	6.7	0.64	0.02	0.00
field No. IX	5–20	pl/S	7.3	7.1	0.50	0.00	0.00
meadow	20–35	pl/S	7.2	7.2	0.82	0.03	0.02
	35–95	pl/S	7.1	7.0	0.94	0.03	0.02
Profile No. 4	0–2	pg/LS	6.7	6.3	1.90	0.10	0.05
field No. X	2–32	pg/LS	6.9	6.5	0.72	0.00	0.00
birch forest	32–56	pl/S	5.6	4.4	1.20	0.25	0.19
	56–110	pl/S	4.6	3.8	1.86	0.88	0.05
	>110	pl/S	4.5	3.8	1.86	0.98	0.90
Profile No. 5	0–6	ps/S	6.5	6.1	0.82	0.05	0.01
field No. X	6–25	ps/S	6.8	6.7	0.54	0.06	0.02
mixed forest	25–63	pl/S	7.1	6.6	1.48	0.05	0.01
	>63	pl/S	6.8	4.9	1.18	0.12	0.02
Profile No. 6	0–2	pg/LS	4.8	4.2	4.12	0.32	0.23
field No. XXI	2–35	gp/SL	4.5	4.1	2.80	0.62	0.56
non-reclaimed	35–44	gp/SL	5.1	4.3	2.56	0.14	0.08
land	44–110	gp/SL	5.9	5.3	1.04	0.05	0.01

*pl/S – piasek luźny/sand, pg/LS – piasek gliniasty/loamy sand, pyg/SiL – pył gliniasty/silt loam, gl/SL – glina zwykła/sandy loam, gp/SL – glina piaszczysta/sandy loam, ps/S – piasek słabo gliniasty/sand.

(field No. II), were from 6.7 to 7.6 in H_2O and 6.2–7.5 in 1 mol·dm^{-3} KCl suspension in the surface layers to a depth of 70 cm. The deeper layers were very strongly acidified (pH_{H2O} from 2.3 to 3.3, as well as pH_{KCl} within 2.2–3.2). Similarly, low pH values in soils reclaimed after sulfur mining in the Lusatia (Germany) were found by Katzur and Haubold-Rosar (1996). High pH of the upper part of the profile may be due to residual flotation lime used at a depth of 0–70 cm for re-leveling of this field. A similar relationship was observed in the soils reclaimed later (2004) in the forest direction (field No. X). It was reported that the pH value of degraded soil (field No. XXI) increased with depth of the soil profile (Table 1). Unlike other ones, the pH of soil reclaimed in the meadow direction (field No. II and IX) within the whole profile was high (from 6.7 to 7.8 in H_2O and 6.0–7.5 in 1 mol·dm^{-3} KCl).

The highest values of hydrolytic acidity, exchangeable acidity, and exchangeable aluminum (4.92, 4.09, and 1.80 $cmol_{(+)} \cdot kg^{-1}$, respectively) were recorded in layer 70–80 cm in the soil reclaimed in forest direction (1995–1997), field No. II, profile No. 1 (Table 1). Considerable sulfur accumulation was observed in that layer during the field study. In degraded soil (field No. XXI, profile No. 6), the highest levels of hydrolytic acidity, exchangeable acidity, and exchangeable aluminum were reported in topsoil, which was also the effect of sulfur presence (Table 1). The sulfur compounds oxidation process is very slow. They are not completely oxidized even after dozens of years (Krzaklewski and Wójcik 2000), which is often the reason of secondary acidification of reclaimed soils. Soil in the field No. IX had the best parameters with respect to hydrolytic acidity, exchangeable acidity, and exchangeable aluminum.

In the studied soils, Corg was subject to accumulation in surface layers and its content decreased deep in the soil profile. It was also found that the average value of Corg in surface levels of studied soil profiles was highest in the field No. II, profile No. 1 and the lowest in the field No. XXI, profile No. 6 (Table 2). Sewage sludge used for the reclamation (fields No. II and IX) could contribute to the increase in carbon content, as indicated by previous studies (Flis-Bujak et al. 1986, Turski et al. 1992, Baran et al. 1993). The sewage sludge may contain many compounds harmful for the environment, but it also contains a lot of valuable agricultural nutrients and organic substances. Therefore, it is believed that the use of sewage sludge as organic fertilizer is the right way of its management, and their impact on improving the balance of organic matter in soil is additional virtue of agricultural use of the sludge (Baran et al. 1993, Mazur 1996, Żukowska et al. 2002, Krutysz-Hus and Chmura 2008). Municipal sewage sludge at doses for soil recovery also enriched the post-mining ground in macro-elements, micronutrients, and trace elements (Baran 2005).

Total nitrogen was subject to accumulation in surface horizons of post-mining soils. Its average content in these layers ranged from 1.0 to 5.7 $g{\cdot}kg^{-1}$ (Table 2). The lowest nitrogen quantity was recorded in degraded non-reclaimed ground (field No. XXI) (0.1 – 1.0 $g{\cdot}kg^{-1}$). Reclamation of post-mining land in the forest and meadow directions increased the content of total nitrogen (Kaniuczak 2007). Among the reclaimed soil types, the highest amounts of total N were observed in the soil developed on area reclaimed in the meadow direction (field No. II, profile No. 2) – average 5.7 $g{\cdot}kg^{-1}$ at a depth of 0–7 cm and forest direction (mixed forest, field No. II, profile No. 1) – average of 2.6 $g{\cdot}kg^{-1}$ at a depth of 0–50 cm. It should be underlined that C/N ratio was found in examined profiles amounting up to 28 (except for layers: 70–80 cm depth of field No. II, profile No. 1, 35–95 cm of profile No. 3, 32–110 cm profile No.4 and >63 cm of profile No. 5) and in the superficial layers – below 17. It can positively affect the nitrogen availability for plants (Pałosz 2009).

One of the factors hindering the growth of plants in areas degraded geo-mechanically may be the low abundance of available forms of nutrients. Katzur and Haubold-Rosar (1996) determined the content of available forms of P, K, and Mg in soils after sulfur mining in Lusatia for below 1 $mg{\cdot}kg^{-1}$. The content of available phosphorus forms varied in different layers of the soil profiles and tended to decrease with depth. Determined contents testified high and very high abundance of phosphorus in soils from the surface fragments of reclaimed soil profiles (field No. II, profile No. 1 to 68 cm, field No. II, profile No. 2 to 11 cm, field No. IX, profile No. 3 – to 35 cm, field No. X, profile No. 4 – to 32 cm and field No. X, profile No. 5 to 25 cm). The topsoil (0–5 cm) from field No. IX, profile No. 3 was particularly abundant; it contained up to 744 mg $P{\cdot}kg^{-1}$ of soil. Samples obtained from the profile of the profile No. 6, field XXI (non-reclaimed), as well as from deeper soil layers of reclaimed area were usually characterized by low or very low content of available phosphorus.

Contents of available potassium was usually below the average abundance (with the exception of fields X, profile No. 4 and XXI, profile No. 6) and was the highest in surface layers (Table 2). Very large diversity of abundance in available potassium in non-reclaimed soil (field No. XXI) should be stressed: from very low (minimum 15.2 mg $K{\cdot}kg^{-1}$ of soil from 0–2 cm depth) to very high (maximum 145 mg $K{\cdot}kg^{-1}$ of soil from 2–35 cm depth).

The high content of available magnesium was reported in the surface layers of the studied soils; the surface level of the forest soil that was reclaimed at the earliest (field No. II, profile No. 1), available magnesium content was as high as 71.8 $mg{\cdot}kg^{-1}$. The deeper layers showed general low abundance of bioavailable magnesium. Some authors (Baran et al. 2004) pay attention to the increase in available forms of these elements in soils reclaimed after the sulfur mining, as a result of the use of sewage sludge with sawdust compost.

The abundance of soil is particularly related to its ability to retain (adsorb) various components on the surface: water, vapors, gases, etc. An important feature of soils is their sorption capacity. It determines the soil resistance towards degrading factors (Wang and Qin 2007). Sorption properties of soils are mainly associated with the content of mineral colloids and humic compounds, but also depend on the grain size and mineral composition, as well as acidity (Dąbkowska-Naskręt et al. 2001, Krasowicz et al. 2011). The sorption capacity in the soils studied varied. The highest average BEC and CEC values (34.8 and 36.2 $cmol_{(+)}{\cdot}kg^{-1}$, respectively) were recorded in the topsoil of the profile No. 2 of the field No. II, whereas the largest degree of base saturation (98.1%) was observed in layer 5–20 cm of the profile No. 3, field No. IX. The lowest BEC and CEC values were found in layer >83 cm of the profile No. 3 from the field No. IX: 0.36 and 0.66 $cmol_{(+)}{\cdot}kg^{-1}$, respectively. It can be supposed that the main sorbent determining the sorption capacity of tested soils, under conditions of restoring humus horizon, were clay minerals. Uzarowicz and Skiba (2011) noticed that intensive conversion of silicates leading to formation of swelling clay minerals

TABLE 2. The content of organic carbon, total nitrogen, available phosphorus, potassium and magnesium in the soil profiles of individual layers of post-mining land

Soil profile	Depth [cm]	Corg	N_t	C:N	Available forms		
					H_{ex}	K	Mg
		g·kg^{-1}			mg·kg^{-1}		
Profile No.1	0–50	39.9*	2.6	15	85.1	27.4	71.8
field No. II		39.8–40.0	2.6–2.7		84.2–86.0	24.4–30.4	68.7–74.9
mixed forest	50–68	2.3	0.2	12	74.3	4.2	21.0
		2.2–2.5	0.2–0.2		74.2–74.4	4.0–4.5	17.2–24.8
	68–70	2.8	0.1	28	13.6	12.7	27.6
		2.5–3.1	0.1–0.1		13.2–13.9	10.7–14.9	22.3–33.0
	70–80	5.8	0.0	0	10.9	35.4	20.0
		5.6–6.0	0.0–0.0		10.0–11.8	31.5–39.2	18.8–21.1
	80–92	1.8	0.1	18	15.5	14.3	16.8
		1.5–2.1	0.1–0.1		14.8–16.2	11.2–17.4	16.3–17.3
	92–132	2.3	0.1	23	4.0	20.3	24.7
		1.5–3.1	0.1–0.2		3.6–4.4	18.3–22.4	20.4–29.0
Profile No. 2	0–7	27.7	5.7	5	241.0	15.0	30.7
field No. II		21.3–34.0	5.6–5.7		206.8–275.1	13.4–16.6	29.4–32.0
meadow	7–11	9.5	1.6	6	98.8	0.0	16.1
		9.2–9.7	1.5–1.6		90.6–107.0	0.0–0.0	15.7–16.4
	11–32	0.5	0.2	3	5.6	0.0	12.4
		0.2–0.8	0.1–0.2		3.9–7.3	0.0–0.0	10.5–14.2
	32–58	0.1	0.1	1	1.1	6.2	14.0
		0.0–0.02	0.1–0.1		0.4–1.8	5.6–6.7	10.9–17.0
	58–83	0.1	0.1	1	4.8	11.0	10.2
		0.0–0.2	0.1–0.1		3.2–6.4	9.0–12.9	8.3–12.1
	>83	1.5	0.1	15	3.5	23.4	28.1
		1.0–2.0	0.1–0.1		2.7–4.4	17.1–29.6	27.8–28.4
Profile No. 3	0–5	27.5	1.6	17	744	52.7	45.0
field No. IX		26.6–28.4	1.6–1.7		722–765	52.3–53.1	44.7–45.3
meadow	5–20	16.1	1.0	16	242	3.4	17.6
		15.6–16.5	1.0–1.0		234–250	2.9–3.9	17.3–17.8
	20–35	0.9	0.1	9	110	28.8	14.7
		0.8–0.9	0.1–0.1		107–114	27.8–29.8	13.8–15.5
	35–95	1.2	0.0	0	43.4	16.2	10.6
		1.1–1.3	0.0–0.0		42.6–44.3	16.1–16.3	10.3–10.9
Profile No. 4	0–2	18.5	1.4	13	131	86.3	48.9
field No. X		16.5–20.6	1.2–1.6		130–133	85.5–87.2	46.2–51.6
birch forest	2–32	15.4	0.9	17	108	59.3	27.0
		14.9–15.8	0.8–0.9		108–109	59.1–59.4	25.3–28.7
	32–56	0.6	0.0	0	2.1	9.9	16.4
		0.0–0.1	0.0–0.0		2.1–2.0	9.3–10.5	15.8–16.9
	56–110	0.1	0.0	0	2.1	16.1	21.1
		0.1–0.2	0.0–0.0		2.0–2.2	15.3–17.0	20.1–22.1
	>110	0.0	0.0	0	4.5	21.6	18.4
		0.0–0.0	0.0–0.1		3.3–5.7	20.8–22.3	18.1–18.7
Profile No. 5	0–6	18.6	1.3	14	51.1	34.5	32.5
field No. X		16.4–20.7	1.3–1.3		48.8–53.5	33.8–35.1	32.1–32.9
mixed forest	6–25	13.9	0.8	17	47.6	40.8	12.2
		13.7–14.1	0.7–0.8		39.9–55.2	36.6–44.8	8.8–15.6
	25–63	1.6	0.2	8	7.5	16.0	8.2
		1.4–1.7	0.1–0.2		6.5–8.5	15.5–16.4	6.8–9.5
	>63	0.0	0.0	0	1.3	1.7	8.9
		0.0–0.0	0.0–0.0		1.0–1.6	1.6–1.7	8.2–9.5
Profile No. 6	0–2	13.1	1.0	13	7.2	15.2	34.4
field No. XXI		12.3–13.9	1.0–1.1		6.8–7.5	14.8–15.6	34.1–34.7
non-reclaimed	2–35	3.7	0.3	12	5.8	145	29.7
land		3.4–3.9	0.3–0.3		5.7–5.9	138–151	29.3–30.1
	35–44	7.2	0.7	10	14.2	58.9	34.0
		7.1–7.3	0.7–0.7		13.1–15.3	57.1–60.6	30.7–37.2
	44–110	0.3	0.1	3	7.5	42.0	65.4
		0.2–0.4	0.1–0.1		7.0–7.9	41.8–42.2	65.2–65.7

* average/range

TABLE 3. The content of Ca^{+2}, Mg^{+2}, K^{+}, Na^{+} and parameters of the sorption complex in the soil profiles of individual layers of post-mining land

Soil profile	Depth [cm]	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	BEC	CEC	BS
		cmol(+)·kg^{-1}						%
Profile No.1 field No. II mixed forest	0–50	24.52 24.20–24.84	0.90 0.81–0.99	0.44 0.42–0.46	1.06 0.93–1.19	26.92	29.60	91
	50–68	182.73 175.50–189.95	0.33 0.31–0.34	0.35 0.33–0.37	0.88 0.76–1.00	n.d.	n.d.	n.d.
	68–70	272.81 263.78–281.83	0.26 0.25–0.26	0.31 0.29–0.33	0.81 0.70–0.92	n.d	n.d	n.d.
	70–80	5.28 4.96–5.60	0.24 0.14–0.33	2.75 0.49–0.50	0.65 0.45–0.85	8.92	13.84	64
	80–92	4.10 3.76–4.44	0.12 0.09–0.14	0.36 0.35–0.37	0.67 0.50–0.83	5.25	6.37	82
	92–132	1.77 1.08–2.46	0.25 0.14–0.35	0.36 0.33–0.38	0.59 0.44–0.74	2.97	5.87	51
Profile No. 2 field No. II meadow	0–7	32.46 31.31–33.61	0.58 0.51–0.64	0.63 0.61–0.64	1.18 0.17–1.19	34.85	36.23	96
	7–11	174.25 172.14–176.35	0.18 0.18–0.18	0.35 0.34–0.35	0.99 0.89–1.09	n.d.	n.d.	n.d.
	11–32	198.22 187.25–209.18	0.21 0.13–0.28	0.32 0.31–0.33	0.99 0.98–0.99	n.d.	n.d.	n.d.
	32–58	181.94 173.74–190.13	0.21 0.20–0.22	0.32 0.31–0.33	0.96 0.85–106	n.d.	n.d.	n.d.
	58–83	180.71 175.16–186.25	0.31 0.25–0.37	0.32 0.30–0.34	0.91 0.88–0.94	n.d.	n.d.	n.d.
	>83	0.13 0.11–0.14	0.01 0.00–0.02	0.02 0.01–0.03	0.20 0.18–0.22	0.36	0.66	55
Profile No. 3 field No. IX meadow	0–5	22.63 21.79–23.47	0.59 0.52–0.65	0.43 0.41–0.44	0.88 0.82–0.93	24.53	25.17	97
	5–20	24.41 24.09–24.72	0.39 0.36–0.41	0.38 0.37–0.39	0.80 0.79–0.81	25.98	26.48	98
	20–35	4.10 4.01–4.18	0.17 0.12–0.21	0.37 0.37–0.37	0.80 0.77–0.82	5.44	6.26	87
	35–95	2.60 2.52–2.68	0.24 0.17–0.30	0.42 0.36–0.48	0.85 0.82–0.88	4.11	5.05	81
Profile No. 4 field No. X birch forest	0–2	15.43 14.96–15.90	0.50 0.47–0.52	0.50 0.48–0.52	1.27 1.26–1.28	17.70	19.60	90
	2–32	8.71 18.03–19.38	0.33 0.29–0.37	0.46 0.45–0.46	1.28 1.25–1.31	10.78	11.50	94
	32–56	0.45 0.41–0.49	0.13 0.12–0.14	0.35 0.33–0.37	1.19 1.18–1.19	2.12	3.32	64
	56–110	1.19 0.99–1.38	0.12 0.10–0.13	0.38 0.36–0.39	1.25 1.21–1.29	2.94	4.80	61
	>110	2.57 2.40–2.73	0.20 0.19-0.20	0.38 0.35–0.40	1.25 1.24–1.25	4.40	6.26	70
Profile No. 5 field No. X mixed forest	0–6	25.35 23.34–27.35	0.45 0.44–0.46	0.43 0.41–0.44	0.89 0.72–1.06	27.12	27.94	97
	6–25	18.57 18.22–18.92	0.24 0.18–0.29	0.36 0.35–0.37	0.80 0.71–0.88	19.97	20.51	97
	25–63	3.62 3.57–3.67	0.12 0.11–0.13	0.35 0.34–0.35	0.69 0.52–0.86	4.78	6.26	76
	>63	0.86 0.71–1.01	0.19 0.10–0.28	0.34 0.33–0.35	0.74 0.54–0.93	2.13	3.31	64
Profile No. 6 field No. XXI non-reclaimed l and	0–2	4.60 4.45–4.74	0.37 0.33–0.41	0.62 0.61–0.62	0.80 0.69–0.90	6.39	10.51	61
	2–35	11.89 11.49–12.29	0.28 0.27–0.29	0.47 0.45–0.48	0.74 0.66–0.81	13.38	16.18	83
	35–44	12.07 11.81–12.33	0.36 0.30–0.42	0.43 0.41–0.44	0.83 0.65–1.01	13.69	16.25	84
	44–110	9.19 8.74–9.63	0.56 0.42–0.69	0.42 0.41–0.43	0.87 0.76–0.98	11.04	12.08	91

* average/range. n.d. – not determined, because calcium ions could origin not only from the sorption complex of soil characterized by relatively low content of organic matter and silty minerals, but from e.g. lime applied for soil melioration.

occurs in strongly acidified technogenic soils due to sulfide minerals transformation. The lowest level of alkaline cations saturation (BS=51%) was recorded in the layer 92–132 cm soil of degraded ground from profile No. 1, reclaimed in forest direction in 1995–1997 (Table 3). It should be emphasized that as for post-mining ground after sulfur exploitation, it was relatively high value, because Katzur and Haubold-Rosar (1996) determined the alkaline cations saturation of soils after sulfur excavation in Lusatia for less than 25%. The degree of sorption complex saturation with alkaline cations was higher in top layers, which confirms the association with applied reclamation liming. Sum of exchangeable base cations (BEC), cation exchange capacity (CEC), and base saturation (BS) were not calculated for layer 50–70 cm of the profile of field No. II due to the fact that calcium ions could origin not from the sorption complex of the soil that was characterized by relatively low content of organic matter and clay minerals (Table 3). Elements from layer to 70 cm (profile No. 1, field No. II) to a lesser extent were migrated deep into the soil profile, which can result from hard layer deposited at 50–70 cm depth.

In studied grounds, contents of particular exchangeable alkaline cations could be lined up in the following decreasing sequence: Ca^{2+}>Na^{+}>K^{+} >Mg^{2+}. This sequence had slightly different form: Na^{+}>Ca^{2+} >K^{+}> Mg^{2+}at the depth of 56–110 cm of profile No. 4. The highest quantities of exchangeable calcium were recorded in profile No. 1 of the field No. II at depths 50–68 cm and 68–70 cm: 253 and 335 $cmol_{(+)}·kg^{–1}$, respectively. Large amounts of exchangeable Ca^{2+} (above 170 $cmol_{(+)}·kg^{–1}$) have been found also in the profile No. 2 of the same field in ground from a depth of 7–83 cm. It could result from the post-flotation lime applied for re-leveling.

CONCLUSIONS

1. Reclaimed and non-reclaimed soils in the area of the former Sulfur Mine "Jeziórko" were characterized by granulometric composition of sands, loamy sands, and sandy loams.
2. Presence of sulfur on the surface and in deeper layers of the soil profiles had considerable impact on acidification of post-mining grounds. Re-leveling of degraded area using post-flotation lime caused the decrease in acidification of the surface layers of reclaimed soils.
3. Contents of organic carbon and total nitrogen were the highest in the topsoil of examined soils. The C:N ratio reached usually relatively low values in superficial layers of studied soils (below 17:1).
4. Contents of available forms of phosphorus, potassium, and magnesium were very diverse in particular layers of the post-mining soils (from very low to high or very high abundance). The topsoil revealed a trend to increase in these elements contents, in particular in reclaimed soils.
5. Cation exchangeable capacity and sum of exchangeable base cations varied in individual layers of the soil profiles (0.66–36.2 and 0.36–34.8 $cmol_{(+)}·kg^{-1}$, respectively); usually higher values of these parameters were recorded in upper layers of soils. The base cations can be lined up in the following sequence: Ca^{2+}>Na^{+}>K^{+}>Mg^{2+}.
6. In the topsoil, reclaimed soils were characterized by more favorable properties (pH close to neutral, lower acidity, better sorption capacity, higher contents of organic carbon and total nitrogen, as well as available forms of phosphorus, potassium, and magnesium) as compared to non-reclaimed one.

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Właściwości wybranych gruntów zdegradowanych i zrekultywowanych po Kopalni Siarki „Jeziórko”

Streszczenie: Celem przeprowadzonych badań było określenie wybranych właściwości fizykochemicznych i chemicznych gruntów pogórniczych zrekultywowanych w różnych kierunkach, po zakończonej eksploatacji siarki metodą otworową. Badania przeprowadzono w 2013 roku na terenie byłej Kopalni Siarki „Jeziórko”. Obejmowały one obszar gruntów zrekultywowanych w kierunku leśnym i łąkowym, na których uprzednio usunięto zanieczyszczenia siarką w formie stałej, wyrównano nasypy i wykopy przez nawiezienie dużych ilości mas ziemnych, wapna poflotacyjnego, nawozów mineralnych oraz osadów ściekowych. Równolegle przeprowadzono badania na obszarze zdegradowanym, niezrekultywowanym (do 2013 roku). Badane grunty charakteryzowały się składem granulometrycznym: piasków luźnych, gliniastych i glin piaszczystych. Reniwelacja zdegradowanych terenów wapnem poflotacyjnym wpłynęła na obniżenie zakwaszenia powierzchniowych poziomów gleb zrekultywowanych. Największą zawartość węgla organicznego, azotu ogólnego stwierdzono w poziomach powierzchniowych badanych gruntów. Zawartość przyswajalnego potasu kształtowała się od bardzo niskiej do średniej (0–145 $mg \cdot kg^{-1}$). Badane grunty cechowały się wysoką zawartością przyswajalnego magnezu w powierzchniowych warstwach profili (maksymalnie 71,8 $mg \cdot kg^{-1}$ w glebie zrekultywowanej w kierunku leśnym), a niżej w profilu zazwyczaj niską. Zawartość poszczególnych kationów wymiennych zasadowych układała się najczęściej według następującego szeregu: Ca^{2+}>Na^{+}>K^{+}>Mg^{2+}. Gleby rekultywowane w poziomach powierzchniowych cechowały się korzystniejszymi właściwościami (pH zbliżonym do obojętnego, niższą kwasowością, wyższymi zdolnościami sorpcyjnymi, wyższą zawartością węgla organicznego i azotu ogólnego oraz przyswajalnych form fosforu, potasu i magnezu) w porównaniu z glebą nierekultywowaną.

Słowa kluczowe: grunty pogórnicze, kopalnia siarki, profil glebowy, rekultywacja gleb