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Indicators of pedogenesis of Technosols developed in an ash settling pond at the Bełchatów thermal power station (central Poland)

Abstract: Technogenic soils (Technosols) developed in an ash settling pond at the Bełchatów thermal power station, central Poland, were studied in order to identify soil property transformations over 30 years of pedogenesis. Standard pedological methods were applied in order to determine the properties of the studied samples. All investigated soils were classified according to WRB as Spolic Technosols with various supplementary qualifiers (Alcalic/Hypereutric, Arenic/Loamic, Protocalcic, Hyperartefactic, Immisic, Laxic, Ochric, and Protosalic). The studied materials can be arranged into a chronosequence starting from fresh (unweathered) ashes, by young Technosol BE1 (age: several months), up to older Technosols BE2 (about 20 years) and BE3 (about 30 years). The studies showed that weathering and soil-forming processes changed properties of ash in soil environment. Fresh ash was characterized by high pH (11.0 – fly ash, 8.7 – bottom ash), low content of carbonates (1.5% in both samples), variable concentrations of TOC (1.2% – fly ash, 6.9% – bottom ash), and very low total nitrogen content (0.04%). Electrical conductivity (EC_e) was 2.6 and 2.1 $dS \cdot m^{-1}$ in fly ash and bottom ash respectively. Young Technosol BE1 had the pH 9.2–10.0, contents of carbonates were in the range 2.4–3.3%, TOC 1.3–1.7%, and total nitrogen less than 0.03%. EC_e in young Technosol was in the range 2.7–4.0 $dS \cdot m^{-1}$. There was no plant cover present on that soil and no well-developed genetic horizons were distinguished in the profile. Finally, old Technosols BE2 and BE3 had lower pH (from 7.9 up to 9.1), and, in general, higher contents of carbonates (from 1.5 to 7.9%) than fresh ash and young Technosol BE1. Old Technosols contained high concentrations of TOC (up to about 38% in Oi horizon) and total nitrogen (up to 0.9%) in the topsoil, where O and A horizons developed due to accumulation of soil organic matter. EC_e in old Technosols was in the range 0.8–1.5 $dS \cdot m^{-1}$. All studied ashes and soils were characterized by very low or even absence of total potential acidity. Base cations predominated in the sorption complex of the investigated ash and soils and can be arranged in the following order according to the abundance: Ca>Mg>K>Na. Base saturation (BS) of fresh ashes and Technosols was nearly 100%. The study shows that the first indicators of pedogenesis of the studied technogenic soils within the first 30 years of formation are: (1) changes of consistence of ash material from firm to friable/very friable due to root action, (2) accumulation of soil organic matter in the topsoil and formation of O and A horizons, (3) decrease of pH, (4) formation of pedogenic carbonates in soils and (5) decrease in soil salinity.

Key words: Technosols, fly ash, bottom ash, pedogenesis, WRB soil classification

INTRODUCTION

Thermal power stations (TPSs) produce large quantities of solid wastes from which fly ash and bottom ash predominate. They are the products of fuel (coal or lignite) combustion for the generation of electric power. The wastes originate because coals and lignites contain non-combustible admixtures such as quartz, clay minerals, carbonates, sulphides, and others (Vassilev and Vassileva 1996) therefore variable quantities of mineral residues have always been formed as an effect of fuel combustion. Fly ash and bottom ash are often reused (Ahmaruzzaman 2010). However, the waste not reused is deposited on land surface in settling ponds or dry landfills where they are subject to weathering (Adriano et al. 1980, Carlson and Adriano 1993). After cessation of ash deposition, the disposal sites are reclaimed or overgrow due to spontaneous plant succession. The appearance of plant cover initiates soil formation in the superficial parts of disposal sites (Tomaszewicz et al. 2017).

Soil properties and processes of soil formation on ash disposal sites have been studied by Maciak et al. (1976), Zikeli et al. (2002, 2004, 2005), Chudecka and Tomaszewicz (2009), Weber et al. (2015), Uzarowicz and Zagórski (2015), Tomaszewicz and Chudecka (2016), Uzarowicz et al. (2017, 2018), and Kostić et al. (2018). All these studies show that pedogenic processes initiated by natural plant succession or reclamation by human lead to the following transformations in the upper layer (from several to several dozen cm) of soils developed on ash disposal sites: (1) change of morphology of soil, (2) accumulation of organic matter, (3) increase in cellulose decomposition constituting an indicator of

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biological soil activity, (4) decrease in ash alkalinity and (5) increase in carbonate contents.

Despite the growing knowledge about Technosol pedogenesis developed from TPS ashes further investigations are still needed. This is because TPSs use different kind of fuels containing diverse contents of mineral admixtures. Therefore ashes produced in TPSs are very heterogeneous materials and their properties can differ from one TPS to another. Ash properties influence the properties of technogenic soil developed from ash deposits. Studies in Poland (Maciak et al. 1976, Uzarowicz and Zagórski 2015, Uzarowicz et al. 2017, 2018) have shown that there are considerable differences between properties of Technosol developed from ash after combustion of Carboniferous bituminous coal coming from Upper Silesia Coal Basin (southern Poland) and soil properties developed from ash after combustion of Miocene lignite in the vicinity of the town of Konin (central Poland). These differences are exhibited among others by different mineral composition, variable contents of CaO in the material, as well as by variable pH of ash and soils developed from them (Uzarowicz and Zagórski 2015). However, lignites in Poland are mined not only in Konin region but also in a few other places (Widera et al. 2016). One of them is the region of the town of Bełchatów (central Poland), where there is a huge open-pit lignite mine. This is the greatest open-pit mine in Europe (12 km long, 3 km wide, and about 200 m deep at the deepest point). Lignite excavated in the mine constitutes a fuel for the Bełchatów TPS located adjacent to the mine. It is the world's largest lignite combusting TPS with a total maximum power of ~5.47 GW. Ashes generated in the TPS are deposited in settling ponds situated in the close vicinity of the TPS.

Previous studies conducted on ash settling ponds in the vicinity of Bełchatów TPS focused mainly on land reclamation and its effect on plants and soil properties (Strączyńska and Strączyński 2007, 2008; Strączyńska et al. 2009, Pietrzykowski et al. 2010a, 2010b, 2013, 2015, 2018). However, the development of soils based on soil chronosequence has not been studied until now. The aim of the present study is to characterize the transformations of technogenic soil (Technosol) properties developed on settling ponds receiving fly ash and bottom ash from the lignite-firing Bełchatów TPS within 30 years of pedogenesis. Morphological, physical, and chemical indicators of studied soil pedogenesis are discussed on the basis of the obtained results. The results permitted soil classification according to WRB soil system (IUSS Working Group WRB 2015).

MATERIALS AND METHODS

Study area and object

The objects of the study were fresh (unweathered) fly ash and bottom ash as well as three soil profiles developed from ash mixtures. The ashes were taken from the Bełchatów TPS (central Poland) combusting Miocene lignite immediately after generation. Ashes were deposited in the settling pond in slurry form, i.e. they were mixed with water, transported through a pipe and sluiced in a pond. Studied soil profiles (Fig. 1) were located on the embankment of the

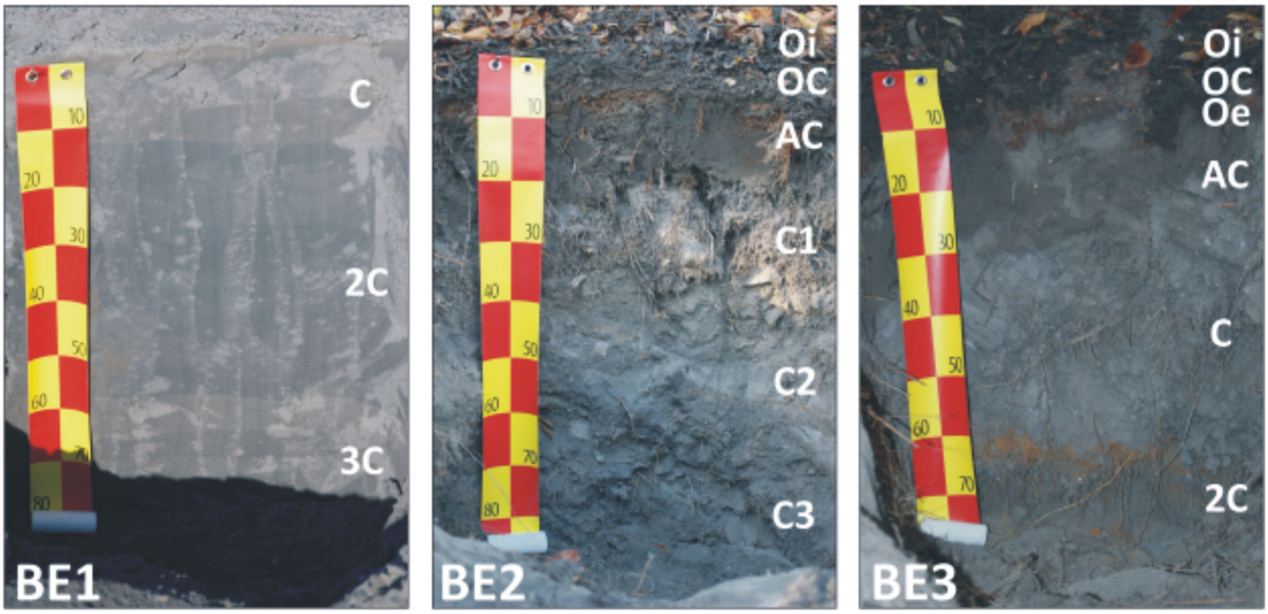

FIGURE 1. Soil profiles subject to study

TABLE 1. Morphology and WRB classification of the investigated soils

Profile	Horizon	Depth (cm)	Soil colour in the field	Moisture status	Consistence of soil mass	Soil structure	Abundance of roots	Boundary with the underlying horizon	Other characteristic features
BE1	*Spolic Technosol (Alcalic, Hyperartefactic, Laxic, Loamic, Epiprotosalic)*								
	C	0–12	GLEY1 4/N	Slightly moist	Firm	Angular blocky (weakly platy)	None	Abrupt	–
	2C	12–58	GLEY1 3/N	Slightly moist	Firm	Angular blocky	None	Abrupt	–
	3C	58–80	GLEY1 4/N	Slightly moist	Firm	Angular blocky	None	–	–
BE2	*Spolic Technosol (Arenic, Hypereutric, Hyperartefactic, Epiimmisic, Laxic, Ochric)*								
	Oi	0–1	Weakly decomposed leaf litter						
	OC	1–5	GLEY1 3/N	Slightly moist	Very friable	None	Few	Clear	Silty and sandy material blown away from ash settling ponds, deposited on the surface of soil, and mixed with organic soil material
	AC	5–15	10YR 3/1	Slightly moist	Very friable	Weak blocky	Common	Gradual	–
	C1	15–35	10YR 5/1	Dry	Loose	Single grain with dispersed little angular blocks	Many	Gradual	–
	C2	35–60	10YR 5/3 and 4/1	Dry	Loose	Single grain with dispersed little angular blocks	Common	Gradual	–
	C3	60–90	10YR 5/3 and 4/1	Dry	Loose	Single grain with dispersed little angular blocks	Many	–	–
BE3	*Spolic Technosol (Protocalcic, Hypereutric, Hyperartefactic, Epiimmisic, Laxic, Loamic, Ochric, Endoprotosalic)*								
	Oi	0–1	Weakly decomposed leaf litter						
	OC	1–3	GLEY1 3/N	Slightly moist	Very friable	None	None	Clear	Silty and sandy material blown away from ash settling ponds, deposited on the surface of soil, and mixed with organic soil material
	Oe	3–10	10YR 3/2	Slightly moist	Very friable	Fibre	Very common	Clear	Moderately decomposed organic material buried by the material from OC horizon
	AC	10–25	10YR 3/1	Slightly moist	Friable	Weak subangular blocky	Common	Gradual	–
	C	25–60	10YR 5/1	Dry	Very friable	Single grain with dispersed little angular blocks	Very common	Clear	Common whitish carbonate coatings on aggregates
	2C	60–70	10YR 5/4	Dry	Loose	Single grain	Very common	–	Autochthonous sandy material from the basement of the settling pond

Bagno-Lubień settling pond adjacent to the Bełchatów TPS.

The embankment of the Bagno-Lubień settling pond consists of a system of levels in the form of successive escarpments and flat shelves (Strączyńska et al. 2004). The embankment creates eight 4 m wide shelves. The escarpments between the shelves are about 3.5 m high. The lowest level (the basement of the embankment) was created in 1980 and is composed of sandy deposits (autochthonous material occurring in the basement of the settling pond) mixed up in the construction process. In the second construction phase (1985–1989), five levels were formed, and in the third phase (1993–1995) two more were created. Starting from 1985, escarpments and shelves were formed from ash and furnace slag obtained from internal parts of the settling pond. In order to protect the settling pond and its embankment against erosion, shelves and escarpments were planted with various species of trees and shrubs between which grass mixtures were sown. Plantings occurred successively between 1986–1998 (Strączyńska et al. 2004).

The investigated profiles can be arranged into a chronosequence as follows (from the youngest to the oldest) BE1<BE2<BE3. The soil age was estimated based on the date of ash material deposition on land surface. Young Technosol BE1 was developed in the top of the "Bagno-Lubień" settling pond from recently deposited ash and its age was several months. The site where BE1 profile was taken has not been reclaimed so was not covered by plants. Profiles BE2 and BE3 were developed on the embankment in southern part of the settling pond. Profile BE2 was located in the middle part of the slope. The embankment was constructed there in the beginning of 1990s, therefore profile BE2 was about 20 years old. The oldest Technosol BE3 was situated in the lower part of the slope, which was formed in the middle of 1980s so profile BE3 was about 30 years old. Profiles BE2 and BE3 were covered by forest with a domination of black locust (*Robinia pseudoacacia*) and ash (*Fraxinus* sp.).

Analytical methods

The soil profiles were described during field works in 2015 according to the Guidelines for soil description (2006). Soil samples were taken from each soil horizon (layer) distinguished in the field. Fresh (unweathered) fly and bottom ashes were taken from the TPS immediately after generation. Soil and fresh ash samples were air dried and sieved (< 2 mm). The properties of fine earth (< 2 mm) of the samples were determined by means of common pedological methods (Pansu and Gautheyrou 2006).

A content of rock fragments (>2 mm) was determined by dry-sieving. Particle size distribution was determined by means of the Bouyoucos and Casagrande areometric method in the Prószyński modification using calgon and gum arabic as dispersing agents. Soil textural classes were defined according to the U.S.D.A. classification (Soil Survey Division Staff 1993). Soil bulk density was examined by collecting 100 cm^3 of undisturbed soil samples by means of metal cores and weighting the sample after drying in 105°C. Particle density was measured by means of pycnometer method. Total porosity was calculated based on bulk and particle density values.

The pH was analysed potentiometrically in H_2O and 1 $mol \cdot dm^{-3}$ KCl based on air-dry fine earth samples using a soil/solution ratio of 1:2.5. Carbonate contents were determined by means of the Scheibler volumetric method (reagent: 10% w/w HCl). Total organic carbon (TOC) contents were determined by the 680°C combustion catalytic oxidation method using a Shimadzu 5000A TOC analyser. Carbonates were removed from the samples prior to TOC analyses using 10% w/w HCl. Total nitrogen (TN) was determined by means of the Kjeldahl method. C:N ratios were calculated based on TOC and TN contents.

The salinity of ashes and soils was assessed by determining the electrical conductivity (EC_e) of saturated paste extracts (van Reeuwijk 2002). The EC_e values in $dS \cdot m^{-1}$ were compared with the following scale (Jackson 1958) in order to obtain the degree of soil salinity: 0–2 $dS \cdot m^{-1}$ – non saline, 2–4 $dS \cdot m^{-1}$ – slightly saline, 4–8 $dS \cdot m^{-1}$ – moderately saline, 8–16 $dS \cdot m^{-1}$ – strongly saline, >16 $dS \cdot m^{-1}$ – very strongly saline.

Total potential acidity (PA) was determined by means of the Kappen method (extraction using 1 $mol \cdot dm^{-3}$ calcium acetate and titration using 0.1 $mol \cdot dm^{-3}$ NaOH). Exchangeable bases (EB) (i.e. Ca, Mg, K, and Na) were extracted from ashes and soils using 1 $mol \cdot dm^{-3}$ ammonium chloride at pH 8.2. The samples were washed once using deionised water prior to exchangeable base extractions in order to remove water-soluble salts. Base contents in extracts were measured using flame atomic absorption spectrometry (Ca and Mg) and flame emission spectroscopy (K and Na). Sum of EB was calculated as a sum of exchangeable Ca, Mg, K, and Na. Cation exchange capacity (CEC) was calculated as a sum of PA and EB. Base saturation (BS) was calculated as a percentage of EB in CEC.

RESULTS

Morphology and classification of studied soils

Profile BE1 (age: several months) was developed from ashes recently deposited on the surface of a settling pond. The material in the profile has no developed genetic soil horizon (Table 1, Fig. 1). Layers of different portions of ashes (labelled as C1, C2, and C3) could be distinguished by slight change of colours in the profile. Soil material was massive and uniform and had firm consistence.

The morphology of profiles BE2 and BE3 (age: ~20 and ~30 years respectively) was apparently transformed by pedogenesis. Soil material was loosened in these profiles by thick net of roots (Fig. 1). Moreover, O and A horizons occurred in the topsoil. The typical feature of both profiles was the occurrence of silty and sandy material that was blown away from ash settling ponds, deposited on the surface of soil and mixed with organic soil material. Furthermore, whitish carbonate coatings on aggregates were very common in C horizon of profile BE3 (Table 1).

All studied soils were classified as Spolic Technosols (IUSS Working Group WRB 2015) with various supplementary qualifiers (Table 1) such as Alcalic/Hypereutric, Arenic/Loamic, Protocalcic, Hyperartefactic, Immisic, Laxic, Ochric, and Protosalic. Tephric or Vitric qualifiers expected for studied soils (Zikeli et al. 2005, Uzarowicz et al. 2017) were not used because oxalate forms of Al and Fe, as well as phosphate retention, were not determined during the present study.

Physical properties of ash and soils

The studied fresh fly ash had a texture of silt loam, whereas fresh bottom ash was a sand (Table 2). All studied soils had a texture of sandy loam or loamy sand. A layer of autochthonous material in the subsoil of BE3 (i.e. 2C horizon) had a texture of sand. Characteristic feature of all studied ashes and soils was the occurrence of very low contents of clay fraction (< 0.002 mm) not exceeding 5% (Table 2).

Investigated soils were characterized by very low bulk density ranging from 0.69 to 0.93 g·cm^{-3} (Table 2). Bulk density did not differ much in all studied profiles. Total porosity was high (61.4–76.0%). Particle density was in the range from 2.28 to 3.00 g·cm^{-3} (Table 2).

Chemical properties and salinity of ashes and soils

Fresh ashes were alkaline materials having the pH of 11.0 (fly ash) and 8.7 (bottom ash) (Table 3). They contained low concentrations of carbonates (1.5% in

TABLE 2. Physical properties of the studied ash and soils

Profile	Horizon	Depth (cm)	Bulk density (g·cm^{-3})	Particle density (g·cm^{-3})	Total porosity (%)	% of rock fragments	Percentage of fractions (in mm)			Soil textural class (U.S.D.A.)
							2.0–0.05	0.05–0.002	< 0.002	
Fresh fly ash			–	–	–	0	31	68	1	Silt Loam
Fresh bottom ash			–	–	–	14.0	93	6	1	Sand
BE1	C	0–12	0.73	2.30	68.4	0	50	45	5	Sandy Loam
	2C	12–58	0.72	3.00	76.0	0	48	48	4	Sandy Loam
	3C	58–80	0.72	2.28	68.6	0	49	48	3	Sandy Loam
BE2	Oi	0–1	–	–	–	–	–	–	–	–
	OC	1–5	–	–	–	0	49	48	3	Sandy Loam
	AC	5–15	0.69	2.53	72.8	0.7	79	19	2	Loamy Sand
	C1	15–35	–	–	–	2.6	77	21	2	Loamy Sand
	C2	35–60	0.88	2.29	61.4	1.1	86	12	2	Loamy Sand
	C3	60–90	0.93	2.65	65.0	1.2	82	16	2	Loamy Sand
BE3	Oi	0–1	–	–	–	–	–	–	–	–
	OC	1–3	–	–	–	0	54	45	1	Sandy Loam
	Oe	3–10	–	–	–	0	65	33	2	Sandy Loam
	AC	10–25	0.70	2.30	69.6	1.4	63	33	4	Sandy Loam
	C	25–60	0.65	2.42	73.2	4.6	68	30	2	Sandy Loam
	2C	60–70	–	–	–	15.1	91	5	4	Sand

Explanations: – not determined; 0 – below detection limit.

both ashes), variable contents of TOC (1.2% – fly ash, 6.9% – bottom ash) related with the residues of unburned lignite, and very low contents of TN (0.03% in both ashes). The C:N ratio was high (33.6 – fly ash, 197.2 – bottom ash). Electrical conductivity (EC_e) was 2.6 and 2.1 $dS \cdot m^{-1}$ in fly ash and bottom ash, respectively.

Profile BE1 indicated pH from 9.2 to 10.0 (Table 3). Contents of carbonates were in the range 2.4–3.3%, TOC 1.3–1.7%, and TN less than 0.04%. The C:N ratio was very high and ranged from 63.3 to 1361.8. EC_e in profile BE1 was in a range of 2.7–4.0 $dS \cdot m^{-1}$.

Profiles BE2 and BE3 had the pH from 7.9 to 9.1. They contained higher contents of carbonates (from 1.5 to 7.9%, 4.3% on average) than fresh ashes and ashes in profile BE1. Profiles BE2 and BE3 had O horizons developed in the topsoil in which TOC reached about 38%, whereas contents of TOC in A horizons of these profiles was in the range 1–2%. EC_e in profiles BE2 and BE3 was in the range 0.8–1.5 $dS \cdot m^{-1}$.

Sorption properties of ashes and soils

The studied ashes and soils were characterized by very low or even absence of total potential acidity (PA), which was in the range from 0 to 1.2 $cmol \cdot kg^{-1}$ (Table 4). PA was the highest in the oldest Technosol (profile BE3). Base cations predominated in sorption complex of the investigated ashes and soils. Calcium was the most abundant base cation, followed by magnesium, potassium, and sodium (Table 4). Cation exchange capacity (CEC) was 97.1 $cmol \cdot kg^{-1}$ in fresh fly ash and 34.7 $cmol \cdot kg^{-1}$ in fresh bottom ash. The CEC in soils was in the range 18.2–82.7 $cmol \cdot kg^{-1}$. Base saturation (BS) of fresh ashes and profile BE1 was nearly 100%, whereas in older Technosols (profiles BE2 and BE3) it was slightly lower (from 98.2 to 99.1%) (Table 4).

DISCUSSION

Specific features of studied Technosols and comparison of studied Technosols with similar soils developed from lignite ashes in Poland

Technosols developed from ashes originated in TPSs have specific physical properties. For example, low bulk density seems to be a typical feature of such soils (Weber et al. 2015, Uzarowicz et al. 2017). Another characteristic feature is a very low content of clay fraction (< 0.002 mm). This feature was typical of the studied soils (Table 2), but was also observed in Technosols developed from bituminous coal ashes in Upper Silesia region, southern Poland, as well as lignite ashes from TPSs from Konin region, central Poland (Uzarowicz et al. 2017).

The soils under study are characterized by high cation exchange capacity (CEC), which is constituted in major part by exchangeable bases (EB) (Table 4) where Ca and Mg predominated. Although the samples were washed using deionised water prior to extraction of EB, the contents of EB were still high. This feature is likely a result not only of the occurrence of exchangeable cations, but also is an effect of partial dissolution of the most soluble minerals (e.g. calcium sulphates and carbonates) by the extracting solution (ammonium chloride). Therefore, on the one hand it seems that CEC values for the investigated soils can be overestimated while on the other, the results obtained in the present study are comparable with the results by Zikeli et al. (2004), who studied CEC of soils derived from lignite ashes in Germany and found that mean CEC_{pot} ranges from 25.1 to 88.8 $cmol \cdot kg^{-1}$.

The results presented herein shows that Technosols developed from lignite ashes from Bełchatów TPS are different from similar soils developed from lignite ashes from the Pątnów and Konin TPSs (Uzarowicz et al. 2017, 2018). First of all, the former soils are not so alkaline (pH_{KCl} from 8.0 to 9.4) as the latter Technosols (pH_{KCl} from 8.9 to 12.1). Secondly, common feature of soils developed from lignite ashes from the Pątnów and Konin TPSs is a strong cementation of ash material due to crystallization of Ca carbonates the contents of which were up to 82.7% (Uzarowicz et al. 2017). Such cementation was not observed in Technosols studied herein where contents of carbonates were from 0.3 to 7.9% (Table 3). Properties similar to those found in Technosols near Bełchatów TPS were typical of Technosols developed on ash landfill of the Adamów TPS located near the town of Turek, central Poland (Weber et al. 2015). This shows that there are strong differences in properties between ashes from different TPS combusting lignite. These differences depend among other on quality of lignite and contents of admixtures (e.g. chalk, clay) in lignites.

Indicators of pedogenesis in the studied soil sequence

In the conducted study, it was assumed that analysis of the sequence of samples comprising fresh ashes generated in the Bełchatów TPS and a chronosequence of soils developed from these ashes on settling pond can show the directions of transformations of parent ash material in soil environment. It seems this assumption is correct in case of the investigated samples. The present study showed that 30 years of pedogenesis le-

TABLE 3. Chemical properties and salinity of the studied ash and soils

Profile	Horizon	Depth (cm)	pH (H_2O)	pH (KCl)	eq $CaCO_3$ (%)	TOC (%)	TN (%)	C:N	ECe ($dS \cdot m^{-1}$)
Fresh fly ash			11.0	11.1	1.5	1.2	0.03	33	2.56
Fresh bottom ash			8.7	8.8	1.5	6.9	0.03	197	2.09
BE1	C	0–12	9.2	9.4	3.0	1.3	0.02	68	4.03
	2C	12–58	9.4	8.9	3.3	1.7	0.03	63	2.98
	3C	58–80	10.0	9.3	2.3	1.7	0	1361	2.73
BE2	Oi	0–1	–	–	–	38.8	0.90	42	–
	OC	1–5	8.5	8.5	7.9	2.2	0.16	13	1.32
	AC	5–15	8.7	8.5	2.6	1.9	0.09	20	1.48
	C1	15–35	8.8	8.0	4.0	1.1	0.01	141	0.89
	C2	35–60	9.1	8.4	2.0	1.2	0.01	157	0.83
	C3	60–90	8.9	8.1	1.5	1.6	0.01	253	1.08
BE3	Oi	0–1	–	–	–	37.1	0.88	42	–
	OC	1–3	7.9	8.5	7.0	2.9	0.17	17	1.07
	Oe	3–10	9.0	8.6	4.0	6.4	0.41	15	1.35
	AC	10–25	8.9	8.7	4.2	1.3	0.02	56	1.46
	C	25–60	8.0	8.5	5.2	1.4	0.04	34	0.78
	2C	60–70	8.8	8.9	0.3	0.4	0.01	29	6.21

Explanations: – not determined; 0 – below detection limit.

TABLE 4. Sorption properties of the studied ash and soils

Profile	Horizon	Depth (cm)	PA	Ca^{2+}	Mg^{2+}	K^+	Na^+	EB	CEC	BS (%)
			$cmol \cdot kg^{-1}$							
Fresh fly ash			0	86.6	10.1	0.1	0.4	97.1	97.1	100
Fresh bottom ash			0.2	29.4	4.5	0.1	0.4	34.5	34.7	99.4
BE1	C	0–12	0	36.2	11.5	0.2	0.5	48.4	48.4	100
	2C	12–58	0	34.9	8.6	0.2	0.5	44.3	44.3	100
	3C	58–80	0	73.6	8.4	0.2	0.5	82.7	82.7	100
BE2	Oi	0–1	–	–	–	–	–	–	–	–
	OC	1–5	0.6	57.6	7.2	0.8	0.6	66.2	66.8	99.1
	AC	5–15	0.6	47.5	6.2	0.8	0.5	55.0	55.6	98.9
	C1	15–35	0.6	50.0	5.8	0.3	0.5	56.6	57.2	98.9
	C2	35–60	0.6	31.7	3.9	0.1	0.1	35.8	36.4	98.2
	C3	60–90	0.6	36.3	6.0	0.3	0.5	43.0	43.5	98.7
BE3	Oi	0–1	–	–	–	–	–	–	–	–
	OC	1–3	0.6	62.0	8.2	1.0	0.5	71.7	72.3	99.2
	Oe	3–10	1.2	45.4	18.9	0.5	0.4	65.2	66.4	98.2
	AC	10–25	0.6	46.4	4.1	0.3	0.3	51.1	51.7	98.9
	C	25–60	0.6	48.2	5.6	0.2	0.1	54.0	54.6	98.8
	2C	60–70	0.3	16.3	0.9	0.1	0.4	17.8	18.2	98.3

Explanations: – not determined; 0 – below detection limit.

ads to the transformation of parent ash material into a soil (Fig. 2). The indicators of these transformations are as follows: (1) changes of consistence of ash material from firm to friable/very friable due to root action, (2) accumulation of soil organic matter in the topsoil and formation of O and A horizons, (3) decrease of pH, (4) formation of pedogenic carbonates in soils and (5) decrease of soil salinity.

The study shows that the major soil-forming factor influencing soil formation is the development of

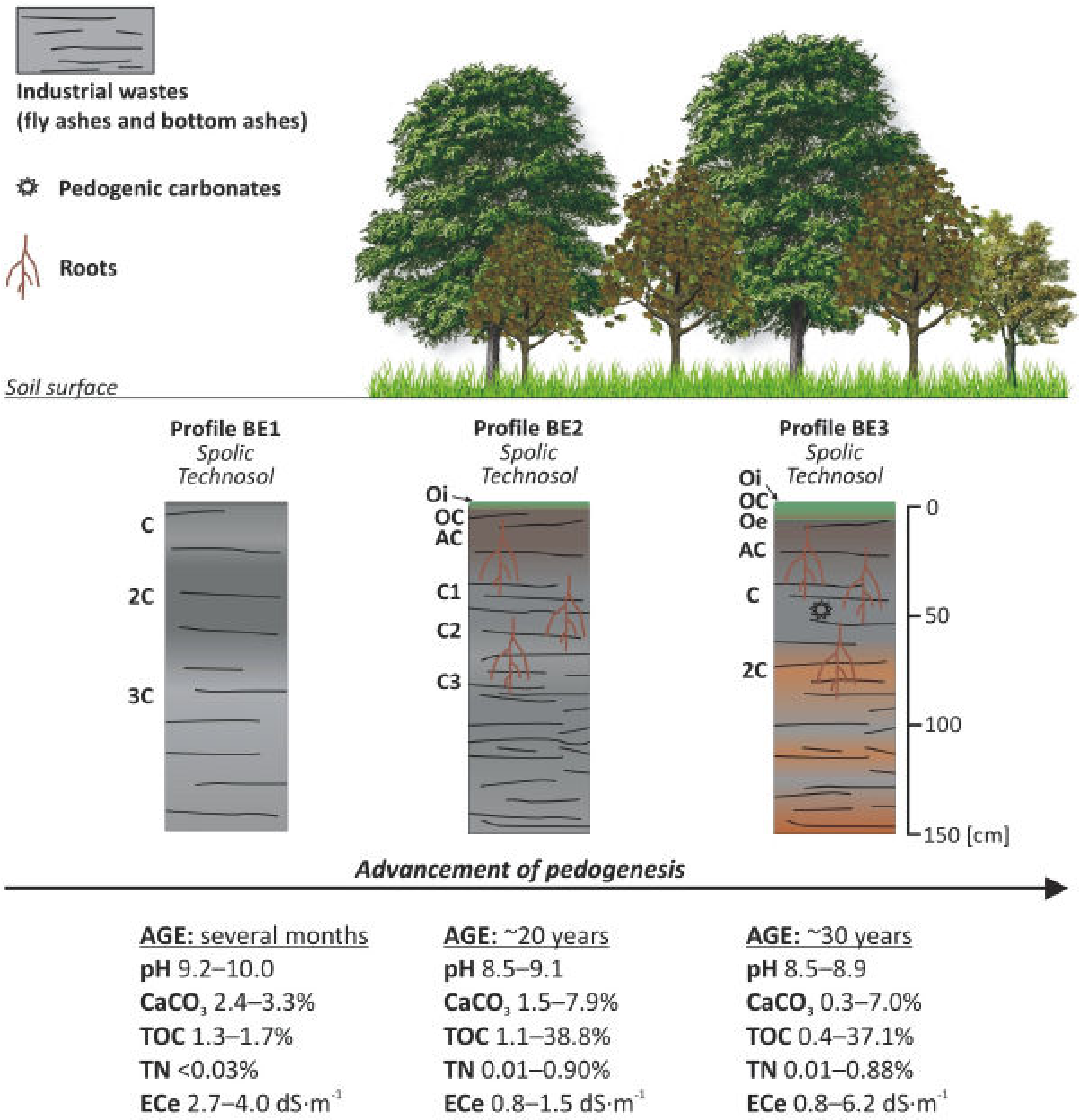

FIGURE 2. Changes of soil properties in the investigated soil sequence

vegetation. That factor causes the accumulation of plant remnants in the topsoil, which is accompanied with the formation of organic (O) and humus (A) horizons. Accumulation of soil organic matter is one of the first soil-forming processes occurring in initial technogenic soils developed from industrial wastes (e.g. Maciak et al. 1976; Świtoniak et al. 2011; Uzarowicz et al. 2017). Moreover, the development of roots changes physical properties of parent ash material. After deposition in a settling pond, ash has a firm consistence, and after development of plant cover, the consistence of soil material becomes very friable or loose.

The decrease of pH seems to be one of the most important chemical indicators of pedogenesis in Technosols developing from ashes from TPSs (Maciak et al. 1976, Zikeli et al. 2002, Uzarowicz et al. 2017). The study herein shows that 30 years of pedogenesis caused the drop of pH from 9.2–10.0 in young Technosol (profile BE1) to 7.9–9.1 in old Technosols (profiles BE2 and BE3) (Table 3). Initially high pH is related with the formation of Ca and Mg hydroxides in the first stage of weathering of ashes in a settling pond (Warren and Dudas 1984; Uzarowicz et al. 2017). Subsequent decrease of alkalinity is most likely caused by partial leaching of Ca and Mg from soils or transformations of Ca and Mg hydroxides into carbonates. Moreover, organic acids forming due to decomposition of soil organic matter in the topsoil are most likely agents causing the decrease of alkalinity.

Another indicator of pedogenesis of the investigated Technosols is a formation of pedogenic carbonates. Similar conclusion was drawn for another soils developed from ashes from TPSs (Maciak et al. 1976; Zikeli et al. 2002; Uzarowicz et al. 2017). Well-developed efflorescences of carbonates were found in profile BE3 (Table 1, Fig. 2). Carbonates originate because soil solutions are rich in Ca coming from ash weathering. The CO_3^{2-} ion form most likely due to adsorption of CO_2 from atmosphere or rhizosphere by soil water. Leaching of carbonates from topsoil is a frequent phenomenon in soils developed from ashes from TPSs (Maciak et al. 1976; Zikeli et al. 2002; Uzarowicz et al. 2017). However, this phenomenon was not found in the studied Technosols because the eolian input of ashes that enriched topsoil in carbonates coming from the deposited ash.

Pedogenesis decreases soil salinity. Initially, fresh ashes are slightly saline (EC_e in the range about 2.0–2.5 $dS \cdot m^{-1}$) according to the classification of FAO (Jackson 1958). After deposition of ashes in a settling pond, they become moderately saline (EC_e slightly exceeding the value of 4 $dS \cdot m^{-1}$) most likely due to accumulation of salts from slurry waters. However, the EC_e in Technosols after 30 years of pedogenesis drops below the values of 2 $dS \cdot m^{-1}$, which permits the classification of old Technosols as non-saline soils (Jackson 1958). High EC_e in autochthonous sand underlying profile BE3 (2C horizon, Table 3) indicates that soluble salts washed from ashes can concentrate in sandy material in the subsoil.

Transformations of soil properties in the topsoil of the studied soils are masked by the eolian input of ash material blown away from the adjacent settling pond. The blowing of ash is due to the lack of plant cover on the surface of settling ponds. Therefore ash particles are transported by the wind and subsequently are deposited adjacent to settling ponds. The deposition of ash particles influence the morphology and chemical properties (e.g. contents of carbonates) of investigated old Technosols (profiles BE2 and BE3) due to accumulation of ashes in the topsoil and simultaneous mixing them with organic litter. Moreover, it was found in a number of studies that eolian input of ash material can change the properties of soils located in the surroundings of ash disposal sites (Hartmann et al. 2009, 2010a, 2010b). A similar impact of ash was observed in Podzols occurring in close vicinity of the Bagno-Lubień settling pond near the Bełchatów TPS (Weber et al. 2017). The addition of ash to soil changes its chemical properties (pH, content of available forms of nutrients, content of soil organic matter) (Ciećko et al. 2015).

CONCLUSIONS

The following conclusions can be drawn from the obtained results:

1. The results indicate that 30 years of pedogenesis changed the original properties of fresh (unweathered) ashes deposited on land surface.
2. The major morphological and physical indicator of pedogenesis of Technosols developed on settling ponds receiving lignite ashes originated in the Bełchatów TPS is the change of consistence of soil material due to root action. Plant roots mix soil material and change initially firm ash material into a soil having very friable or loose consistence.
3. The main chemical indicators of pedogenesis of the studied Technosols are (a) the decrease of pH, (b) the increase of contents of total organic carbon and total nitrogen in the topsoil due to accumulation of soil organic matter, (c) formation of pedogenic carbonates as well as (d) a decrease of salinity.

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Wskaźniki pedogenezy w glebach technogenicznych (Technosols) ukształtowanych na składowisku popiołów przy Elektrowni Bełchatów

Streszczenie: Badaniami objęto gleby technogeniczne (Technosols) ukształtowane na składowisku popiołu przy elektrowni Bełchatów w centralnej Polsce. Celem badań była identyfikacja przemian właściwości gleb w ciągu 30 lat pedogenezy. Analizom poddano świeże odpady z elektrowni (tj. popiół lotny i żużel), a także materiały pochodzące z trzech profili glebowych na składowisku Bagno-Lubień, różniących się wiekiem (od kilku miesięcy do około 30 lat). W celu określenia właściwości badanych odpadów i gleb zastosowano standardowe metody używane w nauce o glebie. Wszystkie badane utwory glebowe zostały sklasyfikowane według WRB jako Spolic Technosols z różnymi kwalifikatorami uzupełniającymi (Alcalic/Hypereutric, Arenic/Loamic, Protocalcic, Hyperartefactic, Immisic, Laxic, Ochric i Protosalic). Badane materiały występowały w chronosekwencji począwszy od świeżych (niezwietrzałych) odpadów, przez młody profil BE1 (wiek: kilka miesięcy), aż do starszych utworów glebowych BE2 (około 20 lat) i BE3 (około 30 lat). Badania wykazały, że procesy wietrzeniowe i glebotwórcze zmieniły właściwości materiału popiołowo-żużlowego w środowisku glebowym. Świeży popiół charakteryzował się wysokim wartościami pH (11,0 – popiół lotny, 8,7 – żużel), niską zawartością węglanów (1,5% w obu próbkach), zmienną zawartością węgla organicznego (1,2% – popiół lotny, 6,9% – żużel), oraz bardzo niską całkowitą zawartością azotu ogólnego (do 0,03%). Przewodność elektryczna (EC_e) wynosiła odpowiednio 2,6 i 2,1 $dS \cdot m^{-1}$ w popiele lotnym i żużlu. Młody profil gleby technogenicznej BE1 miał pH 9,2–10,0, zawartość węglanów mieściła się w przedziale 2,4–3,3%, węgla organicznego 1,3–1,7%, a zawartość azotu ogólnego wynosiła <0,04%. Wartość EC_e w profilu BE1 mieściła się w przedziale 2,7–4,0 $dS \cdot m^{-1}$. Profil ten nie był pokryty roślinnością, nie występowały w nim dobrze rozwinięte poziomy genetyczne. Starsze gleby technogeniczne BE2 i BE3 miały niższe pH (od 7,9 do 9,1) i generalnie większą zawartość węglanów (od 1,5 do 7,9%) niż świeże odpady i profil BE1. Profile BE2 i BE3 zawierały duże ilości węgla organicznego (do około 38% w poziomie Oi) i azotu całkowitego (do 0,9%) w wierzchniej warstwie gleby, gdzie w wyniku akumulacji materii organicznej ukształtowały się poziomy O i A. Wartość EC_e w profilach BE2 i BE3 mieściła się w zakresie 0,8–1,5 $dS \cdot m^{-1}$. Wszystkie badane odpady i utwory glebowe charakteryzowały się bardzo niską lub wręcz brakiem kwasowości hydrolitycznej. Kationy zasadowe dominowały w kompleksie sorpcyjnym badanych odpadów i gleb. Kationy te mogą być ułożone w następującej kolejności w zależności od zawartości: Ca>Mg>K>Na. Stopień wysycenia kompleksu sorpcyjnego kationami zasadowymi w badanych odpadach i utworach glebowych wynosił prawie 100%. Badania wykazały, że pierwszymi wskaźnikami procesów glebotwórczych w badanych glebach technogenicznych w ciągu pierwszych 30 lat pedogenezy są: (1) zmiany zwięzłości materiału popiołowo-żużlowego ze zwięzłego na luźny z powodu działania korzeni roślin, (2) akumulacja glebowej materii organicznej w wierzchniej warstwie gleby i tworzenie się poziomów O i A, (3) spadek pH, (4) powstawanie pedogenicznych węglanów i (5) spadek zasolenia gleby.

Słowa kluczowe: technogeniczne utwory glebowe, popiół lotny, żużel, proces glebotwórczy, WRB