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Reprint of "Properties of soil materials derived from fly ash 11 years after revegetation of post-mining excavation"☆

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ABSTRACT

We investigated properties of soil materials derived from reclamation and revegetation on fly ash used to fill-in an area excavated during earlier mining. Changes in the soil environment that take place after this practice have to be well recognized, since knowledge of all aspects of fly ash revegetation is essential to sustainable reclamation. Fly ash was a by-product of lignite-burning in an electric power plant, and it was mixed with biosolids (3000 tonnes of sewage sludge per ha) or boulder clay (4000 tonnes per ha). Eight non-native tree and shrub species were planted in a random pattern on several areas reclaimed in different ways. Raw fly ash and fly ash mixed with biosolids or clay were amended with a mineral fertilizer (yearly doses of 300 kg ha^{-1} N, 100 kg ha^{-1} P_2O_5, 100 kg ha^{-1} K_2O) in years 2000–2003 and in 2006. Eleven years after revegetation, main physical and chemical properties of newly formed soil substrate were determined. Raw fly ash, due to its alkaline character, high salinity, and ability to cement, constituted unfavorable environment for plant growth. However, fly ash with the addition of biosolids or boulder clay exhibited granular soil structure in the surface layers, which facilitated plant root penetration and created favorable conditions for plant growth. In contrast, raw fly ash had lamellar structure, typical for materials of sedimentary origin. The soil substrates investigated on the reclaimed and revegetated materials did not reveal any features of genetic soil horizons, and we concluded that 11 years was insufficient to develop regosols or technosol. However, introduced vegetation resulted in an improvement of the structure of the soil substrate. Mixing of the surface fly ash with biosolids and boulder clay clearly improved several substrate properties, including neutralization of the reaction, a decrease of salinity level, and improvement in physical properties; these effects contributed to an increase in efficiently useful water retention and the amount of water available for plants.

1. Introduction

World economic growth increases the demand for energy, which in many countries is produced by coal combustion. Coal-fired power generation accounts for 29.9% of the world supply of electricity, while worldwide consumption of coal is projected to increase by 36% by the year 2020 (Jala and Goyal, 2006), and 46% by 2030 (Yao et al., 2014). Opencast mining of lignite is connected with the activity of electric power plants, which use this material as an energy source. Power plants generate vast quantities of fly ash as a by-product, which generation is estimated globally at 750 mln tonnes annually. Fly ash can be divided into coarse-bottom and fine fly ash (Yao et al., 2014). Because ashes produced by burning of anthracite, bituminous, and lignite coals contain different levels of calcium, silica, aluminum and iron, they are grouped into two classes: C and F. Ashes produced by burning of lignite belong to Class C, and contain 12–25% of CaO, while those produced from anthracite belong to Class F, and contain < 10% of CaO (Ahmaruzzaman, 2010; Ukwattage et al., 2013).

Fly ashes resulting from the burning of lignite exhibit alkaline properties because they contain hydroxides as well as Ca and Mg carbonates (Ahmaruzzaman, 2010; Ukwattage et al., 2013; Yao et al., 2014). High amounts of soluble salts in fly ashes contribute to their high electrical conductivity, ranging from 0.63 to 5.5 dS m^{-1}. Such values indicate to increased salinity and may cause serious problems in the soil environment (Miralles et al., 2002). Furthermore, fly ashes contain different amounts of non-burnt particles of lignite, which, due to low nitrogen content, contribute to high C:N ratio. Deposited fly ash undergoes crusting processes, often becoming strongly cemented; as such, it

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acquires unfavorable physical properties, especially those related to water permeability (Cheung et al., 2000; Haynes, 2009; Jala and Goyal, 2006). Due to the chemical properties of this silicate-calcium material, mainly high alkalinity and salinity, as well as its ability to crust, fly ash is difficult to use for reclamation purposes (Yao et al., 2014).

Nevertheless, fly ash may be used in forestry or agriculture as a source of nutrients, or additives to soils to improve their properties (Augusto et al., 2008; Demeyer et al., 2001; Elseewi et al., 1980; Gupta et al., 2002; Mudd et al., 2007; Pandey et al., 2009; Rai et al., 2004; Saarsalmi et al., 2012; Shen et al., 2008; Thind et al., 2012; Tripathi et al., 2004; Yunusa et al., 2006). It may also be used as a structural filling in mining, and for building or road construction. However, 70–75% of fly ash is stored in landfills or in heaps (Yao et al., 2014), contributing to the increase in unproductive waste areas (Ahmaruzzaman, 2010; Demeyer et al., 2001; Haynes, 2009) that need to be revitalized. Despite unfavorable properties, several plant species are able to survive and grow in fly ash (Jusaitis and Pillman, 1997; Krzaklewski et al., 2012; Pandey et al., 2009; Pandey et al., 2014; Podgaiski and Rodrigues, 2010; Rai et al., 2004; Xu et al., 2012; Vandecasteele et al., 2008; Żołnierz et al., accepted for publication). Moreover, by producing biomass, these plants stabilize the surface, improve the structure of the substrate, and help protect it against wind and water erosion. Revegetation of areas covered or filled with fly ash may be the most promising reclamation system (Kolay and Singh, 2010; Krzaklewski et al., 2012; Pandey et al., 2009; Podgaiski and Rodrigues, 2010; Vandecasteele et al., 2008). The best effects may be obtained when fly ash is either covered or mixed with soil (Haynes, 2009; Jusaitis and Pillman, 1997; Tripathi et al., 2004) or organic material (Cheung et al., 2000; Jusaitis and Pillman, 1997; Rai et al., 2004; Shen et al., 2008; Tripathi et al., 2004; Wong, 1995; Xu et al., 2012; Yunusa et al., 2006). Changes in the soil environment that take place following such practice have to be monitored because knowledge of all aspects of fly-ash revegetation is essential to sustainable reclamation. The aim of this study was to determine main physical and chemical properties of the soil substrate derived from revegetation on fly ash mixed with biosolids (sewage sludge) and boulder clay.

2. Materials and methods

We conducted this investigation on a reclaimed part of the fly-ash landfill of the Adamów Power Plant, located near the town of Turek in central Poland. This 600-MW power plant is fuelled by lignite, which generates vast amounts of fly ash. Produced fly ash is transported from the power plant as a slurry, and deposited in an artificial water reservoir, created nearby in a former open-cast mine. The periphery of the reservoir had turned into a waste land after drying due to the crusting of filling material and its strong alkaline reaction; this material did not support any vegetation. Power plant, as an owner of the area, initiated reclamation of the waste land by dividing several areas of 60 m × 16 m, separated by 2 m wide borders. Those areas were reclaimed by mixing with different materials: fly ash mixed with biosolids (3000 tonnes of sewage sludge per ha), and fly ash mixed with boulder clay (4000 tonnes per ha). The areas were prepared by covering the fly ash with 0.25 m thick layer of biosolids, and 0.25 m thick layer of boulder clay, followed by deep (1 m) crushing and mixing of the substrate. These processes were done with special mining machines, provided by the opencast lignite mine that cooperated with the power plant. After mixing of the material, eight non-native tree and shrub species were planted in a random pattern on all reclaimed areas (Żołnierz et al., accepted for publication). Soil was fertilized with yearly doses of 300 N, 100 P_2O_5, and 100 K_2O kg ha^{-1} in years 2000–2003 and in 2006. The current study was conducted 11 years after revegetation of the reclaimed fly ash.

We conducted a detailed investigation of raw fly ash without biosolids or boulder clay (I-0), fly ash mixed with 0.25 m layer of biosolids (II-biosolids) and fly ash mixed with 0.25 m layer of boulder clay (III-clay).

Soil samples were taken in three replications at the depths of 0–25, 25–50, and 50–75 cm. We determined the following properties: soil texture with the hydrometric method (Pansu and Gautheyrou, 2006), pH_{KCl} potentiometrically; salinity in a saturated extract conductometrically, $CaCO_3$ content with the Scheibler method, organic carbon content (C_{org}) with a CS-MAT 5500 analyzer (Ströhlein GmbH&Co., Kaarst, Germany, currently Bruker AXS Inc., Madison, WI, USA), total nitrogen content (Nt) with the Kjeldahl method, available forms of phosphorus and potassium — with the Egner–Riehm method, and available form of magnesium — with the Schachtschabel method.

Specific density was determined with the picnometric method, while soil physical properties (bulk density and water capacity) were determined using Kopecky cylinders of 100 cm^3 volume sampled from the depth of 5–10 and 35–40 cm. Water capillary capacity and water field capacity were determined by the desorption method on sandy block (pF 0–2.0); while water retention at higher values of pF was measured with the sand/kaolin block and Richard's apparatus: potentially useful retention (pF 2.0–4.2); efficiently useful retention (pF 2.0–2.7); and plant-unavailable water content (pF 4.2–7.0).

Humic and fulvic acids were separated from the following fractions (except FF) extracted as follows:

- FF: low-molecular compounds (the so-called fulvic fraction), extracted with 0.05 M H_2SO_4,
- F2: free humic substances as well as humic substances bound with Ca and non-silicate forms of R_2O_3, extracted with 0.1 M NaOH from the residuum after FF separation, and
- F3: humic substances bound with silicate forms of R_2O_3, extracted by alternate treatment with 0.05 M H_2SO_4 and 0.1 M NaOH (extraction from residuum after F2 separation).

3. Results and discussion

Properties of biosolids (sewage sludge) obtained from a local mechanical–biological treatment plant were as follows: dry matter (d.m.) at 35%, organic matter content at 38% d.m., pH = 7.3, nitrogen

Table 1
Texture and chemical properties of the soil material.

Substrate	Depth cm	Percent			USDA textural	pH (KCl)	C_{org}	Nt.	C:N	$CaCO_3$ g kg^{-1}	Salinity	
		Sand	Silt	Clay	Class		g kg^{-1}				mg kg^{-1}	dS m^{-1}
I-0	0–25	82	17	1	Loamy sand	8.5	21.2	0.0	–	11.9	2754	1.020
	25–50	66	30	4	Sandy loam	9.7	10.8	0.0	–	19.4	3510	1.300
	50–75	56	40	4	Sandy loam	9.9	18.0	0.0	–	22.3	3580	1.326
II-Biosolids	0–25	87	11	2	Sand	7.3	13.4	1.4	9.6	0.4	427	0.158
	25–50	91	5	4	Sand	8.3	5.9	0.0	–	9.3	1652	0.612
	50–75	87	13	0	Sand	10.1	5.8	0.0	–	19.3	2479	0.918
III-Clay	0–25	76	13	11	Sandy loam	7.7	5.4	0.2	27	4.8	1652	0.612
	25–50	74	23	3	Loamy sand	8.0	2.9	0.0	–	8.6	5233	1.938
	50–75	75	25	0	Loamy sand	8.1	10.8	0.0	–	25.3	3308	1.225