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Findings from the application of coal combustion by-products (CCB) for forest reclamation on spoil banks of the North Bohemian Brown Coal Basin

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ABSTRACT: Coal combustion by-products (stabilizate, FDG gypsum) generated by the thermal power station in Ledvice were tested on an above-level dump of the Bílina Mine in the North Bohemian Brown Coal Basin during the reclamation of its surface for forestry purposes. A part of the experimental object was treated with coal combustion by-products at a dose of 700–1,000 t/ha that were incorporated into the soil profile by very deep ploughing and the other part was left untreated for comparison. A one-year preparatory agrocycle was conducted on the entire experimental object – growing of *Leucosinapis alba* for green manuring and for reforestation bareroot and container-grown planting material was set out into dug holes [*Larix decidua* L., *Pinus nigra* Arn., *Pinus sylvestris* L., *Quercus robur* L., *Carpinus betulus* L., *Acer pseudoplatanus* L., *Acer platanoides* L., *Alnus glutinosa* (L.) Gaertn., *Fraxinus excelsior* L., *Tilia cordata* Mill., *Betula verrucosa* Ehrh.]. The assessment of the experimental object at the age of 7 years indicated that as a result of the application of stabilizate and FDG gypsum there was an increase in porosity, water-retaining capacity, soil alkalinity and carbonate content; the soil-forming process was characterized by a decrease in soil alkalinity whereas the high alkalinity of the soil horizon treated with this amendment did not negatively influence the growth vitality of most tree species taxa used for reforestation.

Keywords: spoil bank Anthroposols; forest reclamation; coal combustion by-products; soil properties; growth vitality; root system

Texturally heterogeneous substrates of the already coal seam with adverse chemical and physical properties of soil also belong to the important category of stripped overburden rocks during the open-cast mining of brown coal in the North Bohemian Basin that are deposited on above-level dumps and reclaimed for forestry purposes. Loess loams, removal of low-quality humus horizons, marls and marlstones are used the most frequently to improve their soil properties while bentonites were also applied for these purposes in the past (Ondráček et al. 2003; Řehoř et al. 2006). After 1990, wastes of different organic origin were used on a larger scale for these purposes (Čermák, Kuráž 1995) in connection with the attenuation of agriculture in the region concerned; in 2000 available coal combustion by-products (stabilizate, FDG gypsum) generated by the Ledvice thermal power station were included in the programme of testing other amendments in the Bílina Mine locality. This treated power-station fly ash is used the most frequently as certified products in the building industry or it is deposited as waste at dumpsites in dry state. Greater experience with the use of this treated power-station fly ash for the improvement of chemical and physical soil properties of spoil bank soils has been missing until

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now whereas an alternative is the knowledge of the adjustment of soil properties of spoil bank soils for forestry purposes by means of other amendments (Špiřík 1982; Katzur et al. 1998; Schaaf et al. 1999; Weber et al. 1999).

MATERIAL AND METHODS

Establishment of experimental plot: the plot 2.8 ha in size with tested coal combustion by-products (CCB) is situated on a flatland and on adjacent south-eastern slope of the inner spoil bank of Bílina Mine (Fig. 1). The area belongs to the warm and dry climatic region (T1) with average annual temperature 8–9°C, average annual precipitation amount below 500 mm and vegetation precipitation amount below 310 mm, and 40–50% probability of the occurrence of dry growing seasons. Heterogeneous overburden rocks (grey clays, clayey sands, admixture of coal and porcelanites) were dumped onto the spoil bank surface.

In the framework of technical reclamation the entire plot was overlaid with a topsoil stratum 0.2 to 0.35 m in thickness; about a half of the plot was applied the stabilizate (a mixture of fly ash treated with 1–2% CaO, 25% water, slag and FDG gypsum) and FDG gypsum (dihydrate of calcium sulphate – a product of flue gas scrubbing by wet limestone washing) at an amount of 700–1,000 t/ha, which was incorporated into the soil profile by repeated and very deep ploughing. A one-year agrocycle with the growing of *Leucosinapis alba* for green manuring was realized on the entire experimental plot; the crop was cut in the stage of flowering and incorporated into the soil profile by disking. In autumn 2000 and in spring 2001 the plot after such a reclamation was reforested with bareroot planting material 2/0–3/0 [*Quercus robur* L., *Carpinus betulus* L., *Acer pseudoplatanus* L., *Acer platanoides* L., *Alnus glutinosa* (L.) Gaertn., *Fraxinus excelsior* L., *Tilia cordata* Mill., *Betula verrucosa* Ehrh.] and with container-grown planting material 2/1 (*Pinus sylvestris* L., *Pinus nigra* Arn., *Larix decidua* L.) set out at a 1 × 1.5 m spacing into dug holes 0.3 × 0.3 m in size.

Assessment of soil properties of Anthroposols and growth vitality of the forest tree species plants: the assessment of texture, chemical and other soil properties of Anthroposols was done on the basis of collections and laboratory analyses of disturbed soil samples taken from characteristic soil horizons (spoil bank soils, topsoils, topsoils influenced by the ploughing-in of CCB) at 3 replications in each assessed state of reclamation ("A", "B"). To determine the characteristics of soil reaction and carbonate content the number of collections and analyses in the soil horizon influenced by CCB ploughing-in was increased to 15. These parameters were determined in disturbed soil samples: texture (Novák), exchange soil reaction, content of carbonates, total nitrogen and organic matters, sorption properties and content of available nutrients – P, K, Mg, Ca (Mehlich III). Physical soil properties were determined on the basis of collections and analyses of 10 undisturbed soil samples (Kopecký´s cylinders 100 cm^3 in volume) from the same soil horizons and assessed states of reclamation as in disturbed samples. Maximum capillary suction, maximum capillary water capacity, porosity and volume weight were determined in undisturbed soil samples.

Fig. 1. A general view of the experimental plot, the treatment with the application of CCB is on the left

Fig. 2. *Acer platanoides* L. in the treatment with the application of CCB

Fig. 3. *Fraxinus excelsior* L. in the treatment with the application of CCB

Fig. 4. *Populus tremula* L. in the treatment with the application of CCB

The growth vitality of the forest tree species plants was assessed by determining total height after 7 years of development when 20–50 individuals (in relation to the frequency of their representation in the stand composition) from each taxon used for the reforestation of the state of reclamation "A" and "B"

Fig. 5. *Tilia cordata* Mill. and *Pinus nigra* Arn. in the treatment with the application of CCB

Fig. 6. Deformations of the root system in the used containerized plant material of *Pinus sylvestris* L.

were evaluated. One-factor ANOVA was used for the analysis of the growth data. With respect to the applied amendment (CCB) the evaluation of the growth vitality of forest tree species plants at the evaluated age also comprised the nutrient status of assimilatory organs (P, K, Ca, Mg, N) including the content of hazardous elements (As, Be, Cd, Cr, Cu, Mn, Ni, V, Pb, Zn, Hg) on the basis of collections and analyses of leaf (needle) samples of different tree species taxa from the assessed state of reclamation "A" and "B". The methodical procedure of the analysis of leaf biomass consists in its mineralization with nitric and perchloric acid, followed by determination of metals with an AAS – VARIAN 240 apparatus; phosphorus is determined with a SKALAR flow automatic analyzer.

RESULTS AND DISCUSSION

***Pedological characteristics of Anthroposol improved by CCB*:** the soil horizon (0–0.1 m) formed of topsoil and not influenced by the applied CCB represents clay-loamy soil in terms of texture that is characterized by high water-retaining capacity and medium porosity. Soil reaction is neutral to weakly alkaline, the soil is slightly calcareous, with a medium content of organic matters, full sorption, and medium cation exchange capacity; as for the available nutrients the content of phosphorus is low, that of potassium is high to very high, of magnesium very high and calcium content is good to high. As a result of CCB ploughing-in into the soil horizon formed of topsoil (pedological characteristics of soil horizon 0.1–0.35 m) the content of soil particles < 0.01 mm decreased below the limit 45% (already loamy soil), maximum capillary water capacity and porosity increased, soil alkalinity increased by up to 3°, carbonate content rose by up to 12% and calcium reserve increased by up to 35,000 mg/kg. Unimportant soil changes as a result of CCB application were observed in the content of organic matters and total nitrogen, degree of base cation saturation, content of phosphorus and potassium. On the contrary, cation exchange capacity and magnesium content decreased as a result of CCB application. The soil-forming process of the soil horizon influenced by CCB ploughing-in is characterized at the age of 7 years by an invariability of the achieved initial state of improvement of physical soil properties (water-retaining capacity, porosity) and by a decrease in soil alkalinity and carbonate content. Tables 1 and 2 show the soil properties of evaluated Anthroposols.

***Growth vitality of evaluated taxa of forest tree species*:** generally, irrespective of the evaluated reclamation treatments ("A", "B"), the highest losses as a

Table 1. Chemical and other soil properties

Reclamation treatment	Soil horizon (cm)	pH KCl	$CaCO_3$ (%)	N_{tot} (%)	C_{ox} (%)	CEC ($cmol^+/kg$)	Available nutrients (mg/kg)			
							P	K	Mg	Ca
2001										
"A"	0–10	6.9–7.3	0.3–0.9	0.09–0.13	1.1–1.3	15.2–21.7	6–8	175–396	774–810	3,950–4,370
	10–35	8.2–9.5	4–13	0.05–0.07	1.0–1.2	7.5–15.7	7–9	277–464	510–516	26,325–39,665
	> 40	4.3–7.2	< 0.1	< 0.05	0.5–3.2	5.8–17.1	< 1	148–261	564–1,015	2,458–2,737
"B"	0–20	6.8–7.2	0.1–0.9	0.08–0.11	0.9–1.5	13.5–20.8	5–7	202–440	510–690	3,440–4,125
	> 40	5.1–7.2	< 0.1	< 0.05	0.1–0.9	5.0–15.7	1–7	136–264	327–540	1,471–2,404
2007										
"A"	10–35	7.7–7.9	5–11	0.05–0.1	0.7–1.2	5.0–13.8	4–6	344–574	433–618	31,393–42,991

Explanations to Tables 1 and 2: treatment "A" (0–10 cm = humus horizon not significantly influenced by the stabilizate, 10–35 cm = horizon significantly influenced by the stabilizate, > 40 cm = spoil bank soil), treatment "B" (0–20 cm = humus horizon, > 40 cm spoil bank soil)

Table 2. Physical soil properties (2000)

Reclamation treatment	Soil horizon (cm)	Maximum capillary soil suction (% by vol.)	Maximum capillary moisture capacity (% by vol.)	Porosity (%)	Bulk density (g/cm^3)
2001					
"A"	0–10	45–53	32–36	49–58	1.1–1.4
	10–35	65–69	47–50	63–68	0.9–1.0
	> 40	35–42	33–39	36–42	1.6–1.7
"B"	0–20	47–54	32–37	49–59	1.1–1.3
	> 40	38–41	35–37	36–42	1.5–1.7
2007					
"A"	10–35	61–67	44–51	59–69	0.8 – 1.1

result of plant mortality in the first year after reforestation were identically recorded in *Quercus rubra* L. (90–100%), *Larix decidua* L., *Betula verrucosa* Ehrh. and *Alnus glutinosa* (L.) Gaertn. (30–50%), *Fraxinus excelsior* L., *Quercus robur* L., *Carpinus betulus* L., *Acer platanoides* L., *Acer pseudoplatanus*

Table 3. Characteristics of forest tree species development

Tree species	Reclamation state	Total height of seedlings (cm), 2001		Total height of seedlings (cm), 2007, average	Value *P*	Value *F*	Difference
		dispersion	average				
Larix decidua L.	"A"	43–81	55	236	0.052	4.07	conclusive
	"B"	34–84	59	264			
Pinus nigra Arn.	"A"	23–36	29	190	0.306	1.08	inconclusive
	"B"	23–44	36	178			
Pinus sylvestris L.	"A"	24–38	30	269	0.154	2.11	inconclusive
	"B"	35–54	44	248			
Quercus robur L.	"A"	48–96	70	191	0.123	2.48	inconclusive
	"B"	61–102	80	213			
Carpinus betulus L.	"A"	27–61	39	181	0.243	1.40	inconclusive
	"B"	24–59	42	168			
Acer pseudoplatanus L.	"A"	49–101	69	256	0.012	6.93	conclusive
	"B"	71–95	94	293			
Acer platanoides L.	"A"	55–89	69	402	0.010	7.28	conclusive
	"B"	61–112	76	332			
Alnus glutinosa (L.) Gaertn.	"A"	39–93	71	305	0.297	1.12	inconclusive
	"B"	46–101	86	291			
Fraxinus excelsior L.	"A"	46–80	66	286	0.188	1.79	inconclusive
	"B"	43–65	49	263			
Tilia cordata Mill.	"A"	20–59	44	187	0.784	0.08	inconclusive
	"B"	33–68	43	184			
Betula verrucosa Ehrh.	"A"	35–78	49	361	0.317	1.03	inconclusive
	"B"	52–96	59	342			

$F_{\text{crit.}} = 4.098$, $\alpha = 0.05$

Table 4. Contents of basic and hazardous elements in assimilatory tissues of the tree species (2007)

Tree species	Content (% dry matter)						Content (mg/kg)										
	Ash	P	Ca	Mg	K	N	As	Be	Cd	Cr	Cu	Mn	Ni	V	Pb	Zn	Hg
Treatment “A”																	
Pinus sylvestris L.	3.26	0.15	0.20	0.11	1.08	1.29	0.04	0.005	0.02	1.04	2.85	12.3	0.21	0.30	0.10	34.6	0.010
Betula verrucosa Ehrh.	5.02	0.15	0.31	0.12	0.84	1.24	0.04	0.005	0.02	0.38	1.43	11.8	0.20	0.50	0.15	32.6	0.009
Alnus glutinosa (L.) Gaertn.	8.72	0.17	1.38	0.29	1.21	2.79	0.10	0.018	0.03	1.96	2.73	40.2	0.66	1.10	0.30	27.7	0.022
Acer platanoides L.	12.69	0.31	2.23	0.41	1.52	2.25	0.09	0.010	0.01	1.29	6.26	18.6	1.13	0.80	0.20	15.1	0.023
Tilia cordata Mill.	12.50	0.20	1.68	0.28	1.74	2.59	0.05	0.009	0.02	1.13	5.10	27.8	0.52	0.70	0.15	24.5	0.018
Fraxinus excelsior L.	12.02	0.30	1.68	0.28	1.26	2.02	0.10	0.016	0.05	1.19	3.05	37.6	0.69	1.30	0.40	34.4	0.026
Treatment “B”																	
Pinus sylvestris L.	3.21	0.15	0.18	0.12	0.94	1.38	0.03	0.009	0.02	3.52	3.19	11.8	0.55	0.30	0.10	34.7	0.011
Betula verrucosa Ehrh.	2.98	0.16	0.26	0.12	0.86	1.50	0.02	0.013	0.08	0.60	2.94	11.0	0.35	0.30	0.10	38.4	0.011
Alnus glutinosa (L.) Gaertn.	9.09	0.18	1.28	0.30	1.10	2.89	0.08	0.017	0.03	1.83	3.01	41.6	0.87	1.20	0.40	29.0	0.027
Acer platanoides L.	12.49	0.25	2.28	0.49	1.52	1.96	0.07	0.010	0.01	2.02	5.28	19.0	1.05	0.80	0.25	16.3	0.024
Tilia cordata Mill.	9.30	0.21	1.65	0.30	1.53	1.92	0.06	0.010	0.02	0.91	2.18	24.2	0.45	0.60	0.24	17.9	0.020
Fraxinus excelsior L.	10.18	0.17	1.09	0.30	1.15	2.65	0.08	0.022	0.01	2.30	5.44	39.9	0.55	1.60	0.48	34.3	0.017

L. and *Tilia cordata* Mill. (2–15%) whereas the used containerized planting material of *Pinus sylvestris* L. and *Pinus nigra* Arn. was characterized by practically no mortality (max. 1%). The majority of the evaluated tree species taxa showed the identical growth prosperity, regardless of different reclamation treatment ("A", "B"). The tallest stand height after seven years of development was reached by *Acer platanoides* L. (Fig. 2), *Betula verrucosa* Ehrh., *Fraxinus excelsior* L. (Fig. 3) and among the other unmentioned taxa also by *Populus tremula* L. (Fig. 4); the smallest stand height was recorded in *Pinus nigra* Arn. and *Tilia cordata* Mill. (Fig. 5), *Carpinus betulus* L. and *Quercus robur* L. Some observed differences in recorded heights (Table 3) in the evaluated reclamation treatments may be influenced by other important site factors; in the evaluated area it is the heterogeneity of the soil profile influenced by spoil bank earth, thickness of the overlaying topsoil stratum, state of the mixing of CCB with topsoil including the water regime (slope, flatland) that continues to change as a result of the building of other storeys of the spoil bank body. The taxa responding to different reclamation treatments ("A", "B") in a significant manner are particularly *Acer platanoides* L., which shows better growth prosperity at the site with stabilizate, and *Acer pseudoplatanus* L., which however prospers better in the treatment without stabilizate. Problematic are some growth differences detected in *Pinus sylvestris* L., *Pinus nigra* Arn. and *Larix decidua* L. As a consequence of the quality of containerized planting material permanent developmental deformations were observed in up to 80% of evaluated individuals – flat, one-sided, spiral-coiled root system, root penetration of the soil profile max. to a depth of 0.4 m (Fig. 6), while the stems of these tree species frequently suffer from attrition damage caused by the wild boar. On chemically abnormal soils, among which Anthroposols are very often classified, mainly the natural selection of forest tree species takes place that are able to adapt themselves in the best way to the given environment, having the capacity to absorb a large amount of "specific" elements. The chemical analysis of their organs allows the phytogeochemical determination of significances in nutrition realized in connection with the soil conditions created by reclamation. Based on the performed leaf analyses the determined differences in element contents between the evaluated reclamation variants "A" and "B" can be considered as insignificant. Beneš (1994) reported the following contents of basic and trace elements in natural soils in broadleaved tree species: N 1.7 to 4.0%, P 0.15–0.30%, K 1.0–1.8%, Ca 0.2–1.5%, Mg 0.15–0.40%, Mo 0.05–0.26 mg/kg, Cu 5–12 mg/kg, Mn 30–100 mg/kg, Zn 15–50 mg/kg and in conifers: N 1.1–2.5%, P 0.11–0.35%, K 0.4–2.0%, Ca 0.2–1.2%, Mg 0.1–0.4%, Mo 0.01–0.40 mg/kg, Cu 2–12 mg/kg, Mn 35–500 mg/kg, Zn 15–100 mg/kg.

CONCLUSION

The used technology of incorporation of coal combustion by-products CCB into the soil profile, also by several ploughing operations, including subsequent treatment of soil by disking for the growing of a crop for green manuring, is a condition for the profile formation of Anthroposol with the chemically and physically largely heterogeneous soil environment. To achieve the appropriate reclamation state in the improvement of soil properties by CCB will require the use of means of mechanization operating as homogenizers – rotary tillers that can perfectly work the soil profile 0.4–0.5 m in thickness.

The knowledge of the CCB application in conditions of Anthroposols of the Bílina Mine was acquired in a pedologically relatively luxurious environment represented by the overlaying of the spoil bank surface with stripped humus horizon – humic Anthroposol (Němeček 2001) designed rather for agricultural purposes and where this reclamation measure is of experimental character and can be considered as above standard from practical aspects. This technology of improvement of soil properties will be of substantially greater reclamation importance in conditions of lighter-textured spoil bank soils with frequent admixture of substrates of the already coal seam where the complex character of the improvement of soil properties becomes a priority requirement, and this technology will be applicable in texturally similar conditions of natural forest soils as a replacement of various calcareous fertilizers and important amendment applicable for the improvement of some physical soil properties (water-retention capacity, porosity). An amount of 500–1,000 t/ha can be recommended as a suitable dose of CCB with a longer-term effect on the adjustment of the soil profile 0.3–0.4 m in thickness (in relation to the soil reaction of improved soil and CaO content in CCB).

Interesting are also data on the growth prosperity of the initial development of the tested assortment of forest tree species in the environment of high soil alkalinity. The influence of this factor was not significant either on the survival rate or on development during 7 years, and it was interesting mainly in *Alnus glutinosa* (L.) Gaertn., *Fraxinus excelsior* L., *Pinus sylvestris* L. and *Betula verrucosa* Ehrh.

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Poznatky z aplikace vedlejších energetických produktů k lesnické rekultivaci na výsypce v Severočeské hnědouhelné pánvi

ABSTRAKT: Na převýšené výsypce Dolu Bílina v Severočeské hnědouhelné pánvi byly při rekultivaci jejího povrchu k lesnickým účelům ověřovány vedlejší energetické produkty (stabilizát, energosádrovec) pocházející z tepelné elektrárny v Ledvicích. Část experimentálního objektu byla upravena vedlejšími elektrárenskými produkty v dávce 700–1 000 t/ha, které byly velmi hlubokou orbou zapraveny do půdního profilu, a ostatní část byla ponechána pro porovnávací účely. Na celém experimentálním objektu proběhl dále jednoroční přípravný agrocyklus – pěstování *Leucosinapis alba* na zelené hnojení a k zalesnění byl použit prostokořenný a krytokořenný sadební materiál vysázený do kopaných jamek [*Larix decidua* L., *Pinus nigra* Arn., *Pinus sylvestris* L., *Quercus robur* L., *Carpinus betulus* L., *Acer pseudoplatanus* L., *Acer platanoides* L., *Alnus glutinosa* (L.) Gaertn., *Fraxinus excelsior* L., *Tilia cordata* Mill., *Betula verrucosa* Ehrh.]. Posouzením experimentálního objektu ve stáří sedmi let bylo zjištěno, že v důsledku aplikace stabilizátu a energosádrovce dochází ke zvýšení pórovitosti, vododržnosti, půdní alkality, obsahu karbonátů, půdotvorný proces charakterizuje snížení půdní alkality a vysoká alkalita půdního horizontu upraveného tímto melioračním sorbentem negativně neovlivnila růstovou vitalitu většiny taxonů dřevin použitých k zalesnění.

Klíčová slova: antropozemě výsypek; lesnická rekultivace; vedlejší energetické produkty; půdní vlastnosti; růstová vitalita; kořenový systém

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