Fabricated Soil Using Coal Mine Waste

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Abstract The objective of this work was to produce fabricated soil using coal mine waste as raw material. Coal mine waste from the Carboniferous region of Santa Catarina, Brazil, was ground and amended with steel slag powder and sewage sludge to, respectively, adjust acidity and provide organic matter as well as nutrients. Fabricated soils had pH, macro, and micronutrients analyzed while plant growth (*Sorgum bicolor*) was monitored. Balanced mixtures of coal waste, steel slag, and sludge can be used as a substitute for natural topsoil.

Keywords coal, waste, fabricated soil, sewage sludge

Introduction

Brazilian run-of-mine coals (ROM) contain high levels of impurities (rock minerals and pyrite), requiring concentration procedures (Kalkreuth 2010). It demands tailing deposits which occupy large physical areas, change topography, and generate acid mine drainage (AMD). Millions of tons of coal tailings cover 3,195.22 ha in the carboniferous region of Santa Catarina, generating environmental impacts and significant economic costs to avoid and treat AMD (Ministério Público 2012).

Amaral Filho *et al.* (2010), analyzing a typical coal waste tailing by a gravity concentration process, produced three output streams: (a) a low specific gravity material (relative density < 2.4) predominantly composed of shaley coal and carbonaceous shale; (b) an intermediated material (2.4 < relative density < 2.8) mainly composed of shale, siltstone and sandstone; and (c) a high specific gravity material (relative density > 2.8) rich in pyrite. The intermediate density material comprises 56.6 % of the total amount of waste and presents low sulfur content (from 1.8 to 2.8 %).

There have been some attempts, in Brazil, to reprocess coal waste deposits in order to recover valuable products such as carbonaceous materials for energy uses and, alternatively, concentrate pyrite for sulfuric acid production. However, the intermediate density material still remains, which is considered in this study as raw material to fabricate soils. Kefeli *et al.* (2008) defines "fabricated soil" as a mixture of substrates containing balanced amounts of carbon, nitrogen, phosphorus, potassium, and mineral elements that support plant growth.

Fabricated and mine soils have much in common. Soil developed from mine spoils depends greatly upon rock and soil mixes, soil amendments, geomorphology, hydrology, and the vegetation introduced (Wick *et al.* 2010). Studies from Sydnor and Redente (2002), Straken (2005), and Strzyszcz and Lukasik (2010) have shown that it is possible to establish new vegetation directly on spoils or waste once pH is adjusted and amendments (fertilizers as well as organic matter) are applied. Acid substrates are predominantly adjusted with calcium carbonate, but other alkaline amendments, *e.g.* steel slag, can be used (US EPA 2007). Biossolids (sewage sludge) are a source of nutrients and organic matter of much interest (Wick *et al.* 2010).

The aim of this work was to produce fabricated soil using coal mine waste, steel slag, and sewage sludge. The methods included materials characterization and fabrication of soil relating its fertility parameters to plant (*Sorghum bicolor*) growth. Results are discussed in terms of the possible use of fabricated soils in Brazilian coal mine degraded areas.

Methods

Three materials were selected: coal mine waste (CW – main material), steel slag (SLAG – alkalinity and micronutrients source), and sewage sludge (SLUDGE – nutrients and organic matter supply). Coal waste was obtained directly from a coal preparation plant which mines the Barro Branco seam (Santa Catarina State, Brazil). The material was submitted to a Fe-Si gravity separation process to obtain the fraction between the relative densities of 2.2 – 2.7, that are lower in sulfur and carbonaceous rock. Slag samples were obtained from a secondary refining furnace in special steel plant located in the state of Rio Grande do Sul, Brazil. Sewage sludge samples came from an UASB reactor operating on a local sewage water treatment plant in Criciúma, Santa Catarina State. In order to compare the fabricated soils behavior to native soils, a sample from the latter was collected. All samples were collected accordingly the Brazilian sampling standard NBR 10.007 (ABNT 2004). Coal waste and steel slag were ground in a jaw crusher followed by a roller mill crusher to particle size below 2 mm. Sewage sludge was dried at 100 °C and pounded to break up the clods.

All three materials were analyzed for ash and volatile matter (ABNT 1983a,b,c) and for C, H, N, and S concentrations (Elementar Vario Macro analyzer). Coal waste and steel slag had their crystalline material structure analyzed by X-ray diffraction (XRD). Acid–base accounting (ABA), as described by Sobek *et al.* (1978), was carried out to determine the net acidity generation potential.

In order to study for an isolated materials effect in the fabricated soils a factorial 2^{k-1} delineation experiment was implemented resulting in four different mixtures/fabricated soils shown in Table 1. Three repetitions of all fabricated soils and native soil were placed in plant growth trays. Each soil cell received seven *Sorghum bicolor* seeds whose growth was monitored for seven weeks. Fabricated soil samples and a control were analyzed for pH, P, K, Ca, Mg, S, Al, H+Al, organic matter, Zn, Cu, B, and Mn; cation exchange capacity (CEC); V % SMP index (EMBRAPA 1997). One repetition was kept for pH and SMP index analysis at 20 weeks. Environmentally available Cd, Co, Cr, Cu, Fe, Ni, Pb, and Zn (EPA 3050) were analyzed in the fabricated soils.

Results and Discussion

Coal waste (2.2 – 2.7) and steel slag have particles sizes between 0.1 – 2.0 mm (with a D50 approximately 0.9 mm), typical of a sandy soil. The XRD results reveal that main crystalline compounds are: (a) coal waste (2.2 – 2.7): quartz – SiO_2, plagioclase – $(Ca,Na)Al(Al,Si)Si_2O_8$, illite – $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$, alkaline feldspar – ($NaAlSi_3O_8$), gypsum – $CaSO_4.2H_2O$, and kaolinite – $Al_2Si_2O_5(OH)_4$; (b) steel slag: gehlenite – $Ca_2Al_2Si_2O_7$, merwinite – $Ca_3Mg(SiO_4)_2$, calcium oxide – CaO, magnetite – Fe_3O_4, wustite – FeO and periclase – MgO.

Table 2 summarizes results for elemental analysis, immediate analysis, and ABA. Total sulfur content in coal mine waste (1.1 %) implies an acid potential (AP) generation of 35 kg $CaCO_3.t^{-1}$. On the other hand, steel slag neutralization potential (NP) is equivalent to 353.1 kg $CaCO_3$ t^{-1}. Thus, acid base balance de-

	CW	CW+ SLUDGE	CW+ SLAG	CW+ SLUDGE+SLAG	Control
Coal mine waste – 170.0 g	X	X	X	X	-
Steel slag – 17.0 g	-	-	X	X	-
Sewage sludge – 27.5 g	-	X		X	-
Native soil – 170.0 g	-	-	-	-	X

Table 1 *Fabricated soils and their composition and native soil as control.*

	CW (2.2-2.7)	SLAG	SLUDGE
Elemental analysis			
C %	3.9	0.8	21.5
H %	1.1	0.1	5.2
N %	0.3	0.02	2.7
S %	1.1	0.7	8.4
Immediate analysis			
Ash %	88.3	100.0	-
Volatile matter %	8.4	0.0	-
Fixed carbon %	1.0	0.0	-
Acid Base Accounting			
AP kg $CaCO_3$ t^{-1}	35.0	0.0	-
NP kg $CaCO_3$ t^{-1}	0.0	353.1	-
NNP kg $CaCO_3$ t^{-1}	-35.0	353.1	-

***Table 2** Coal waste, steel slag, and sewage sludge elemental composition, immediate analysis and acid base accounting parameters.*

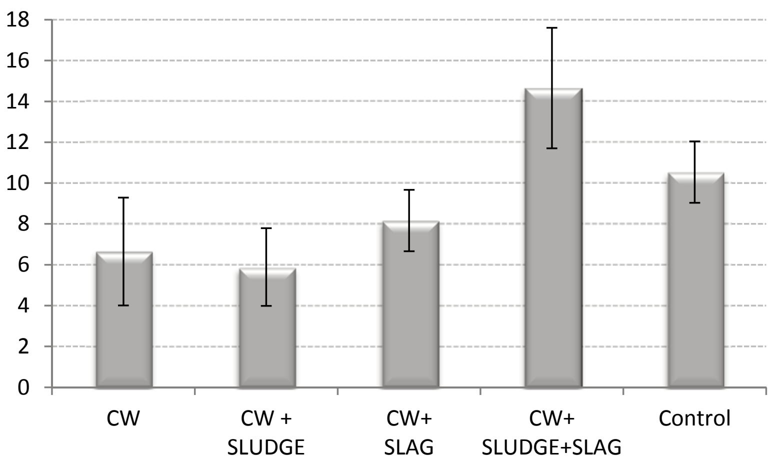

***Fig. 1** Fabricated soil and control* Sorghum bicolor*'s height at seven weeks (mean and standard deviation)*

termines a 10:1 ratio between coal waste and slag to establish neutrality.

Fig. 1 shows *Sorghum bicolor* height (mean and standard deviation) for each fabricated soil and control after seven weeks. Fabricated soils where steel slag was used had significantly higher heights than those without it (ANOVA – significance level p ≤ 5 %). Also, sewage sludge promoted a significant contribution to *Sorghum bicolor* development where pH was neutralized by slag – seedlings grew about two times more than in other mixtures. CW+SLUDGE+SLAG treatment had heights even higher than control. Fig. 2 depicts *Sorghum bicolor* grown in native soil (control) and in a fabricated soil amended with sewage sludge and steel slag.

Analysis of the soil pH ($pH_{H_2O\ 1:1}$) at 7 and 20 weeks are presented in Table 3. The fabricated soils that received steel slag (CW+SLAG and CW+SLUDGE+SLAG) had pH values significantly higher (significance level p ≤ 5 %) than those without steel slag (CW and CW+SLUDGE). A tendency of pH decrease, yet

Fig. 2 Sorghum bicolor *seven weeks old: (a, left) native soil – control and (b, right) CW+SLUDGE+SLAG fabricated soil.*

significant, was observed in all situations, but it was less expressive in the mixtures with steel slag.

Table 4 shows the fertility parameters – macro and micronutrients – of the fabricated soil and control (native soil) seven weeks after sowing *Sorghum bicolor* seeds. Clay content in all fabricated soils is 5 % while in the control it is 18 %.

The addition of steel slag significantly increased the values of calcium, magnesium, boron, cation exchange capacity (CEC), and base saturation percentage (V %), but decreased sulfur and manganese. Sewage sludge significantly increased phosphorus, organic matter (OM), sulfur, boron, and zinc. Potassium and copper were not influenced by any treatment. All results considered $p \leq 5$ %. Native soil shows very low quality in terms of fertility, especially when compared to the fabricated soil comprised of steel slag and sewage sludge. The native soil shows low pH and CEC is occupied mainly by aluminum and hydrogen, while there is low availability of nutrients.

Table 5 shows the concentration of the metals Cd, Co, Cr, Cu, Fe, Ni, Pb, and Zn (EPA 3050) in all fabricated soils as well the Brazilian standard values for prevention and intervention levels (CONAMA 420–2009). Among all metals analyzed, Cr is above prevention level when steel slag is applied, but still under agricultural intervention level. *Sorghum bicolor* growth has shown promising results, however, further research with Cr free steel slag as well as $CaCO_3$ as alkaline amendment will be taken.

Sheoran *et al.* (2010) considered that reclamation strategies must address soil structure, soil fertility, microbe populations, top soil management, and nutrient cycling in order to return the land as closely as possible to its undisturbed condition and continue as a self-sustaining ecosystem (Sheoran *et al.* 2010). The close relationship between soil and vegetation quality is clear. Yet, in Brazil it is common to reclaim degraded areas using soils from nearby deposits, which can mean additional environmental damage. Thus, the use of alternative soils and amendments mitigates not only the area to reclaim, but also avoids environmental impact in other sites and disposal costs of other wastes (slags and sewage). Using

	CW	CW+ SLUDGE	CW+ SLAG	CW+ SLUDGE+SLAG	Control
pH 7 weeks	3.5	4.3	7.7	6.8	4.6
pH 20 weeks	2.5	3.3	7.2	7.0	4.9
SMP 7 weeks	5.9	5.8	7.8	7.3	4.9
SMP 20 weeks	3.2	3.6	7.6	7.3	5.0

***Table 3** pH and SMP index for fabricated and native soil.*

Parameter		CW	CW+ SLUDGE	CW+ SLAG	CW+ SLUDGE+SLAG	Control
Al	mg dm^{-3}	1.9	1.8	0.0	0.0	3.7
H + Al	mg dm^{-3}	4.9	5.5	0.6	1.0	15.4
P	mg dm^{-3}	9.3	100.0	20.0	100.0	3.4
K	mg dm^{-3}	132	163	158	148	69
Ca	cmol$_c$ dm^{-3}	15.9	22.6	37.3	35.4	1.0
Mg	cmol$_c$ dm^{-3}	1.3	2.8	10.3	9.4	0.6
S	mg dm^{-3}	1455	2729	516	1997	24
Zn	mg dm^{-3}	9.4	71.0	9.1	51.0	1.7
Cu	mg dm^{-3}	8.5	6.7	5.0	4.0	1.6
B	mg dm^{-3}	0.9	1.1	1.3	1.8	0.7
Mn	mg dm^{-3}	72	103	7	24	94
CEC	cmol$_c$ dm^{-3}	22.6	31.5	48.6	46.2	17.4
V	%	78.0	82.0	99.0	98.0	10
OM	%	4.4	6.6	4.3	6.3	0.5

P e $K_{exch.\ Mehlich\ 1}$, $Ca_{exch.}$, $Al_{esch.}$, $Mg_{exch.}$ and $Mn_{exch.}$ KCl 1 mol L^{-1}, S $CaHPO_4$ 500 mg L^{-1}, Zn e Cu HCl 0.1 mol L^{-1}, B $_{hot\ water}$ e OM $_{humid\ digestion}$

***Table 4** Fabricated soils and native soil fertility parameters.*

	fabricated soils				prevention	intervention level		
	CW	CW+ SLUDGE	CW+ SLAG	CW+ SLUDGE+ SLAG	level	agricultural	residential	industrial
Cd mg kg^{-1}	0.15	0.16	0.17	0.17	1.3	3	8	20
Co mg kg^{-1}	8.83	9.74	9.51	10.42	-	-	-	-
Cr mg kg^{-1}	25.98	27.21	143.87	145.10	75	150	300	400
Cu mg kg^{-1}	27.04	28.94	37.23	39.13	60	200	400	600
Ni mg kg^{-1}	15.76	16.20	23.85	24.29	30	70	100	130
Pb mg kg^{-1}	19.97	20.74	20.99	21.76	74	180	300	900
Zn mg kg^{-1}	50.00	66.39	59.47	75.86	300	450	1000	2000

Table 5 *Concentration of Cd, Co, Cr, Cu, Ni, Pb, and Zn (accordingly method EPA 3050b) in fabricated soils and Brazilian standards values for prevention, and intervention for agricultural, residential and industrial uses.*

fabricated soil in mine reclamation projects is a part of this context.

Conclusion

Fabricated soil produced by the mixture of coal mine waste, steel slag and sewage sludge facilitated *Sorghum bicolor* development. Steel slag increased pH and levels of calcium, magnesium, and CEC in fabricated soils. On the other hand sewage sludge added organic matter, phosphorous, sulfur, and zinc. Results showed that ABA is an efficient methodology to achieve a neutral pH in fabricated soils when mixing coal mine waste (acidic) with steel slag (basic). Fabricated soils are a potential substitute for natural soils in mine reclamation projects. This study contributes to enhance environmental protection through mine waste management based on the concept of "zero waste production".

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