ACIDIC MINESPOIL RECLAMATION WITH AFBC BY-PRODUCT AND YARD-WASTE COMPOST[1]

by

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Abstract. Economic and environmental incentives to reduce solid waste volumes have spurred interest in the development of beneficial uses for urban and industrial by-products. This project investigated the reclamation efficacy and impacts on soil and water quality of two such materials: atmospheric fluidized bed combustion (AFBC) by-product and yard-waste compost. Six 1-acre watersheds were constructed on acidic abandoned mined land spoil (pH range 3.5 to 4.5). Two watersheds each were then reclaimed with 8 in of borrow soil, 125 tons/acre of AFBC, or 125 tons/acre of AFBC and 50 tons/acre of compost, and planted with a grass-legume seed mix. Watersheds were instrumented to record hydrographs of storm-water runoff events, measure erosion, and collect samples of surface- and percolate-water flow. One year after reclamation the AFBC and AFBC+compost treatments compared favorably with the traditional resoil reclamation practice. Spoil pH in the 0 to 4 in depth was increased to the range 6 to 8 which was similar to the resoil pH, and complete vegetative cover was successfully established on all watersheds. However, plant biomass production was approximately 2 times larger on the resoiled watersheds than on the amended spoil. Consequently, erosion was smallest on the resoiled watersheds. All three reclamation treatments increased runoff water pH to >7 and decreased soluble Al. Concentrations of Ca and S were larger in runoff- and percolate-water samples from AFBC-treated watersheds than from the resoiled watersheds. Trace element concentrations in all water samples remained very low and showed almost no treatment effects.

Additional Key Words: runoff, water quality, soil quality

Introduction

Conventional reclamation of abandoned mined lands (AML) involves placement of a layer of topsoil over the graded minespoil. Because topsoil was generally not conserved when AML sites were mined, soil must be "borrowed" from adjacent land thereby creating another disturbed area. The cost of reclamation becomes prohibitive if sufficient topsoil is not available adjacent to the minesite. The need for borrow soil could be reduced or eliminated by direct revegetation of acidic minespoil to which sufficient alkaline and organic amendments have been added. The use suitable of by-product or waste product materials for amendment of acidic minespoil would further reduce reclamation costs and also remove these materials from the solid waste stream.

The scrubbing of SO_2 from the stack gasses of coal-fired boilers (flue gas desulfurization, FGD) produces large quantities of FGD by-products, which in many cases are highly alkaline (Carlson and Adriano, 1993). The industries which produce FGD by-products (primarily electric utilities) have strong economic and environmental incentive to beneficially use FGD by-products. Although there is considerable variation among FGD by-products produced by various scrubber technologies, most consist of 3

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components; calcium sulfite/sulfate (gypsum), residual alkalinity (lime/limestone), and coal ash. Because of their alkalinity, FGD by-products can be used to neutralize acidity in soils (Stehouwer et al., 1995a, Marsh and Grove, 1992, Korcak, 1980) and minespoils (Stehouwer et al., 1995b). Because of its mobility, the gypsum component of FGD by-products may help to alleviate toxic conditions below the depth to which they are incorporated (Sumner et al., 1986; Farina and Channon, 1988; Alva and Sumner, 1990; Alva et al., 1990).

Atmospheric fluidized bed combustion (AFBC) is a type of FGD in which pulverized coal is combusted in the presence of lime or limestone sorbent. The SO_2 reaction product is anhydrite ($CaSO_4$) and is collected, together with unspent sorbent, in both the bed and fly ash streams.

Similarly, bans on landfilling of organic wastes, and legislative mandates to reduce solid waste volumes, have provided strong incentives for composting organic waste materials. Organic amendments, primarily sewage sludge, have been shown to significantly improve long-term minespoil revegetation success (Sopper, 1992). Composted organic wastes would likely provide similar benefits, and large volumes could be utilized in minespoil reclamation.

Large amounts of these materials were required (>100 tons AFBC acre^{-1}, >50 tons compost acre^{-1}) in order to improve spoil quality parameters such as pH, base status, pH buffering, microbial activity, and mineralizable C. However, these materials also contain large quantities of soluble salts and some trace elements of environmental concern. These could negatively impact soil and water quality both directly and through mobilization of trace elements in the spoil. Greenhouse experiments showed that when used at the appropriate rate, FGD by-products could ameliorate phytotoxic conditions in the spoil without adversely affecting plant growth (Stehouwer et al., 1995b, c). Analysis of greenhouse pot leachates also showed that at agronomically appropriate application rates trace element concentrations remained at very low levels. When used at lower rates, pH amelioration was insufficient resulting in poor plant growth. When applied at higher rates excessively high pH and soluble salts limited plant growth, and solubilization of organic C increased transport of trace elements.

This watershed-scale field study was initiated to compare conventional reclamation of an acidic minespoil by topsoiling, with direct revegetation of the spoil amended with an AFBC by-product alone and AFBC combined with yard-waste compost. The study was designed to investigate the revegetation success and the impacts on soil, plant, and water quality of the three reclamation practices.

Materials and Methods

In the summer and fall of 1994, during reclamation of an abandoned coal mine site located near New Philadelphia in east central Ohio, six 1-acre watersheds were constructed for the study described in this paper (Fig. 1). Exposed underclay material on the site was graded to a 4% slope and recompacted to serve as an aquitard. Thickness of the clay pad ranged from 10 to greater than 30 ft in an area 670 by 450 ft. A 5 ft wide by 1 ft high clay berm was constructed on the clay surface to hydrologically separate each 1-acre watershed. Following preparation of the clay aquitard, 4 ft of acidic minespoil material was placed over the recompacted clay and graded to a 4% slope. Each watershed was hydrologically separated by building a 10 ft wide by 2 ft high berm directly above the underlying clay berm. Berms were similarly constructed at the lower end of each watershed to direct surface water flow into a 10 ft long approach. Water flowed through an H-flume instrumented with a stilling well and a water stage recorder. Approximately 0.3% of total surface water flow was automatically diverted to a holding tank to allow sampling of each flow event. A trench was dug 5 ft up slope from the lower end of each watershed to allow the placement of a perforated 4 in tile line in a shallow trench (6 in deep) on the clay

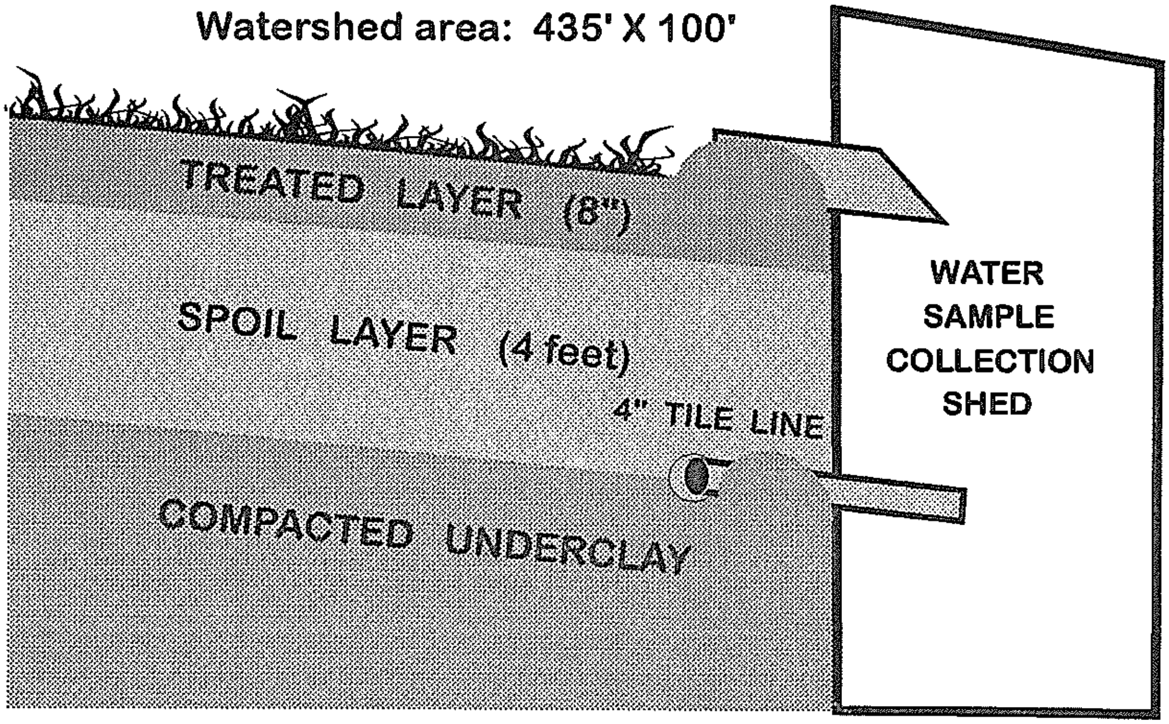

Fig. 1. Watershed design

surface. The tile line was covered with river-run gravel and the trench was backfilled. Any water which percolated through the spoil and flowed laterally over the clay was collected by the tile line and directed to an outlet pipe located below the surface water H-flume. All tile flow water was retained in a holding tank and sampled following each flow event.

Following completion of the construction phase, the three surface treatments listed below were applied to the spoil surface in each of 2 watersheds.

1. The conventional reclamation practice of application of 50 tons/acre of agricultural limestone on the spoil surface followed by placement of 8 in of borrowed topsoil material. Agricultural limestone was spread on the topsoil surface at a rate of 20 tons/acre and incorporated with a chisel plow and offset disc.
2. Application of 125 tons/acre of AFBC by-product followed by incorporation to a depth of approximately 8 in by multiple passes with a chisel plow and an offset disk.
3. Application of a mixture of AFBC by-product and yard waste compost applied at a rate of 125 tons/acre AFBC and 50 tons/acre compost followed by incorporation to a depth of approximately 8 in by multiple passes with a chisel plow and an offset disk.

Chemical characteristics of the minespoil and amendment materials are given in Table 1. The AFBC material used in this study was a blend of by-product collected from both the bed and fly ash streams. The by-product was conditioned with water at the power plant which resulted in the hydration of anhydrite to form gypsum, and of lime to form portlandite ($Ca(OH)_2$). The AFBC by-product had a neutralizing potential of 39% calcium carbonate equivalency. The source of the alkalinity in this material was predominantly $Ca(OH)_2$ with minor amounts of $CaCO_3$.

Watershed construction was completed in October, 1994 and plots were seeded to a grass-legume sward in

Table 1. Chemical characterization of minespoil, topsoil, yard-waste compost, and AFBC.

Parameter	Spoil	Topsoil	Compost	AFBC
Major Elements (%)				
Organic C	11.1	na	16.7	na
Total N	na	na	0.84	na
Aluminum	11.5	8.6	na	2.5
Calcium	0.04	0.07	1.69	26.1
Magnesium	0.50	0.53	0.35	3.65
Iron	5.57	3.96	1.77	5.9
Potassium	2.36	2.35	0.56	0.36
Phosphorus	0.07	0.04	0.15	0.03
Silicon	22.7	19.0	na	6.4
Sulfur	1.02	0.06	na	12.3
Trace Elements (µg g^{-1})				
Arsenic	46.3	5.5	11.47	71.5
Barium	701	503	na	204
Boron	na	na	39.11	418
Cadmium	0.8	3.3	<0.2	1.5
Chromium	94.4	95.6	284	42.2
Copper	26.8	62.8	69	49.5
Lead	78.0	15.9	26	17.4
Molybdenum	14.0	<0.2	27.79	22.4
Nickel	28.5	44.8	383	78.8
Selenium	4.5	<0.7	0.25	8.6
Sodium	150	150	207.9	1100
Zinc	<0.3	137.8	108	112
pH (1:1 water)	3.1	4.3	7.4	12.4

[z] Not analyzed.

November, 1994. The seeding mix included orchard grass (*Dactylis glomerata*), timothy (*Phleum pratense*), annual ryegrass (*Lolium multiflorum*), ladino clover (*Trifolium repense* Ladino), birdsfoot trefoil (*Lotus* sp.), and winter wheat (*Agropyron* sp.).

Baseline soil/spoil samples were collected in November, 1994 and again in June, 1995 by digging 3 cores (2 in diam) in each watershed. Cores were sampled in 2 in increments in the upper 12 in, and in 4 in increments from the 12 in depth down to the compacted clay layer. Soil samples were air-dried and ground to pass a 2-mm screen. Samples were analyzed for pH, electrical conductivity (EC), and for water soluble and Mehlich extractable concentrations of Al, Ag, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, S, Sb, Se, Si, Sr, V, and Zn by ICP.

Water sample collection began in the spring of 1995. Following each surface-flow event a hydrograph was constructed for the event, sediments deposited in the approaches and H-flumes were removed, weighed and sampled, and 2-L water and suspended sediment samples were collected from the holding tanks. Water samples were analyzed for pH, EC, acidity and alkalinity before and after filtering through a 0.45µm membrane filter. Sediment concentration was determined by drying and weighing the filter cake. Filtrates were analyzed by ICP for dissolved concentrations of the same elements as listed above. Total element concentrations of water samples were determined by digesting unfiltered samples in hot perchloric and nitric acid. Digests were analyzed by ICP for the same elements listed above. Tile flow water samples were collected after each flow event and analyzed as described for the surface water samples. Water samples were also collected and similarly analyzed from a sediment pond which collected surface-water flow from the entire reclamation site. Surface water samples collected before reclamation (before pond construction) were obtained from intermittent stream flow draining the site.

Plant biomass production was determined by cutting three strips (2.5 x 70 ft) across each watershed in August, 1995. Plant material from each strip was dried for 48 h at 60°C and weighed.

Results and Discussion

All three treatments resulted in profile surface pHs near or slightly above neutral (Fig. 2). With all three surface treatments, profile pH decreased with increasing depth. The pH of topsoil and AFBC+compost profiles decreased to the range 4 to 4.5. In the AFBC profile, however, pH was somewhat higher, in the range 5 to 6. The reasons for the higher pH with AFBC are not clear. Although the gypsum component of AFBC is expected to be more mobile than agricultural limestone (Sumner et al., 1986), downward transport of Ca^{2+} and SO_4^{2-} would not be expected to have such a large influence on pH. Furthermore, if the pH increase was due to the AFBC, the AFBC+compost treatment would be expected to show a similar pH response with depth. It remains to be seen if this pH difference persists in subsequent sampling.

Soluble salt concentrations in the surface layer of topsoil were much lower than in the AFBC- or AFBC+compost-amended minespoil (Fig.

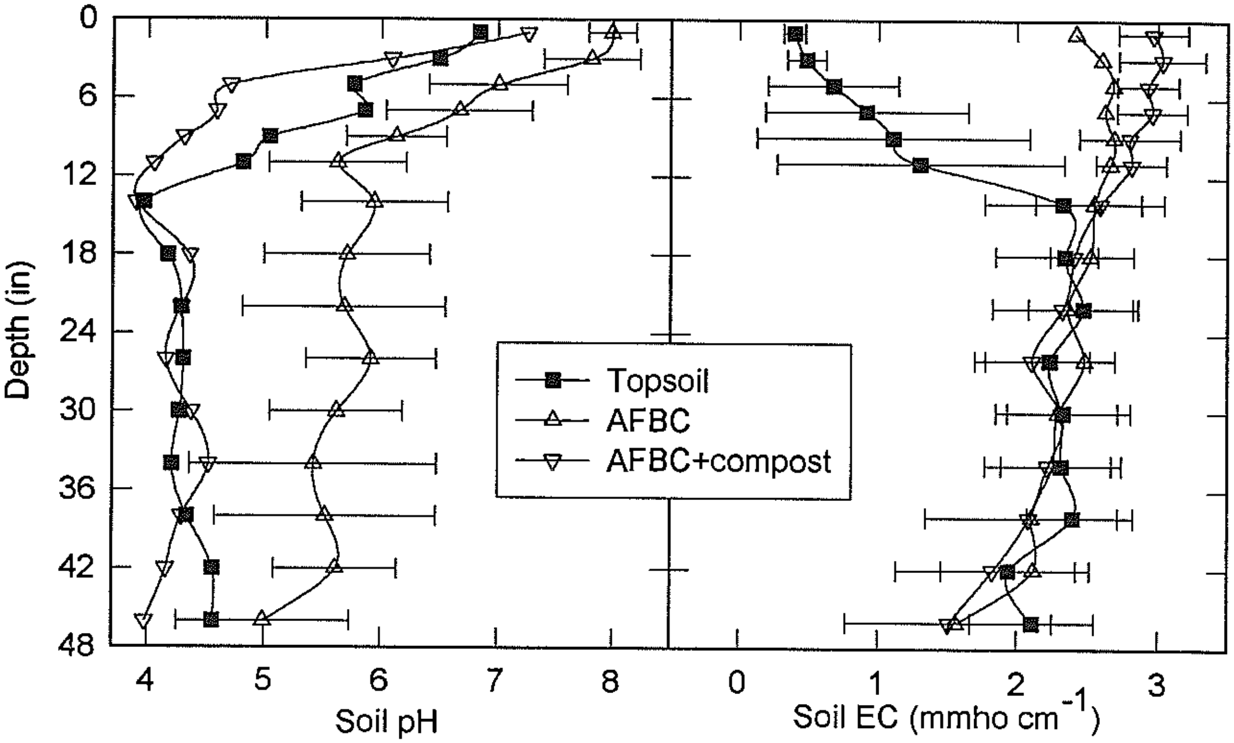

Fig. 2. Profile pH and electrical conductivity of acidic minespoil 9 mo after reclamation with topsoil, AFBC, or AFBC+compost surface treatments. (Error bars indicate plus and minus one standard deviation.)

2). Although AFBC alone did not increase spoil soluble salt concentrations, the addition of 50 tons acre^{-1} of yard-waste compost did increase salt concentrations slightly. Below the treated layers there were no differences among the three treatments with respect to soluble salts.

Establishment of vegetative cover was successful on all reclamation treatments, with 100% vegetative cover on almost all areas of all watersheds throughout the summer of 1995. Establishment was more rapid and growth was more vigorous on the topsoil treated watersheds. Topsoiled watersheds produced over twice as much plant biomass than did either the AFBC or the AFBC+compost treatments (Fig. 3). Although topsoil is clearly a better medium for plant growth than the minespoil material, amendment with AFBC did permit establishment of good vegetative cover on this otherwise toxic material. The high soluble salt concentration in the spoil material may account in large part for the less vigorous growth than on topsoil. It is expected that over time these salts will be leached downward. When this occurs, and if the spoil begins to develop other properties of a natural soil, plant growth may begin to approach that of the topsoil.

Prior to reclamation erosion rates from this abandoned mined land site were estimated at 420 tons acre^{-1} for a two-year storm. During the summer of 1995 no storm event produced greater than 2 tons acre^{-1} erosion from any watershed regardless of the surface reclamation practice. Thus both the conventional and the alternative reclamation practices were effective in greatly reducing erosion. However, both runoff volume (data not shown) and sediment losses (Fig. 4) tended to be smallest from topsoil watersheds and largest from the AFBC treated watersheds. Most of these differences appear to be directly related to the more vigorous vegetative growth on the topsoil watersheds.

All three reclamation treatments improved surface water quality. Prior

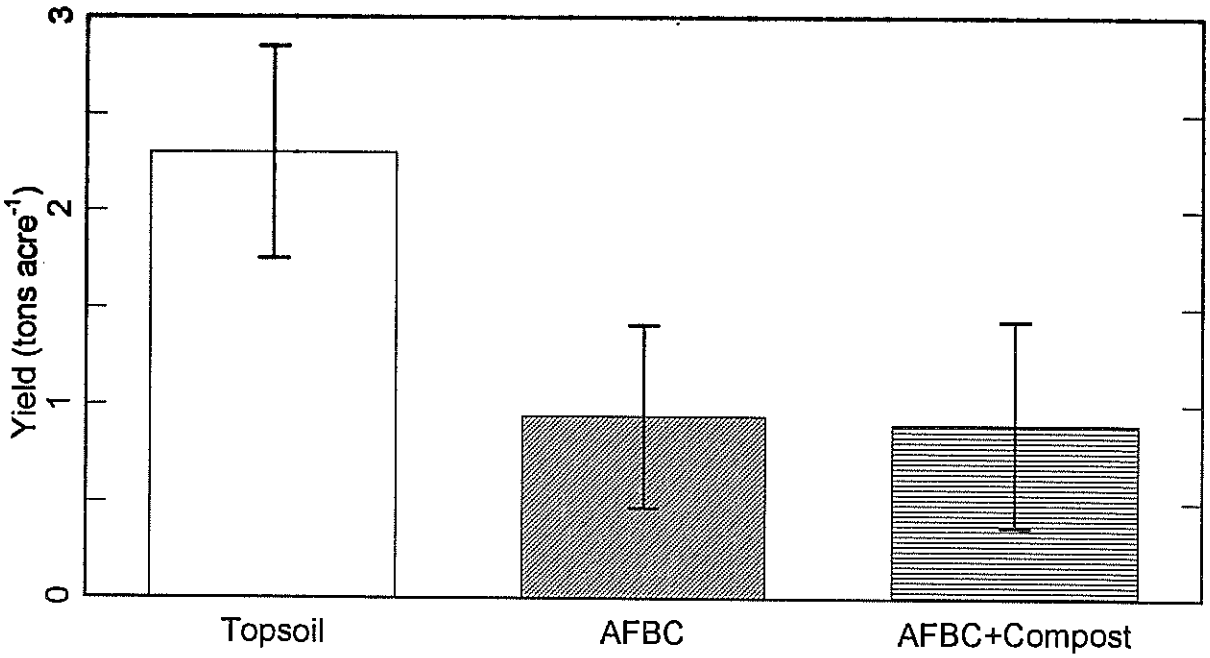

Fig. 3. Plant biomass yield in summer of 1995 on minespoil reclaimed with topsoil, AFBC, or AFBC+Compost. (Error bars indicate plus and minus one standard deviation.)

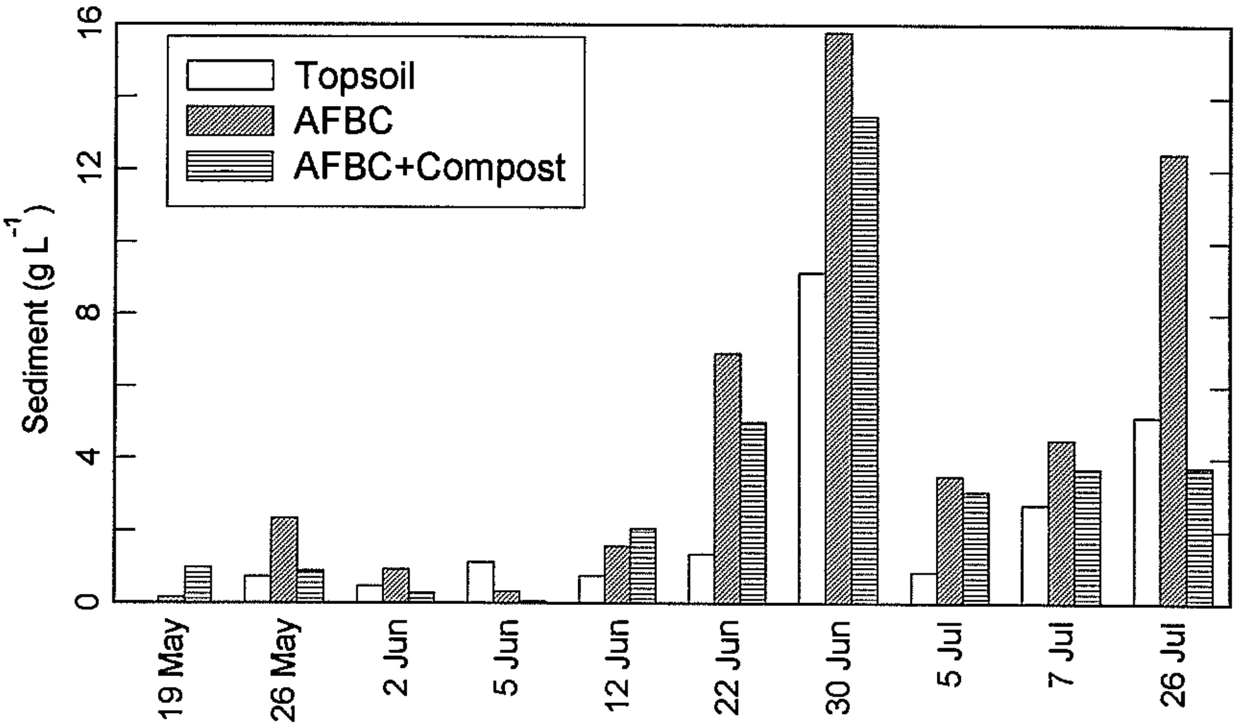

Fig. 4. Sediment concentration of 1995 summer storm runoff water from minespoil watersheds reclaimed with topsoil, AFBC, or AFBC+Compost.

to reclamation surface water pH was in the range of 2 to 3 with soluble Al concentrations as high as 120 mg L^{-1} (Figs. 5 and 6). All three reclamation treatments increased surface runoff water pH to the range 7 to 8, although the AFBC treatments tended to produce runoff water with slightly higher pH than did the topsoil. Changes in soluble Al showed just the opposite result. All three treatments decreased soluble Al to less than 0.3 mg L^{-1}. This result is expected given the increased pH and the low solubility of Al at near neutral pH.

Calcium concentrations in surface runoff water were clearly larger from the AFBC-treated watersheds than from the topsoiled watersheds (Fig. 7). This difference can be attributed to the much larger solubility of gypsum (a major component of AFBC) than limestone. As soluble gypsum is leached downward, and if vegetative cover becomes more vigorous, it is expected that the differences in soluble Ca between the AFBC and topsoil treatments will decrease. Similar results were observed with respect to soluble S (Fig. 8). Again the larger S concentrations with AFBC treatments can be attributed to the presence of relatively soluble gypsum in the AFBC. These differences are also expected to diminish gradually with time.

Several observations suggest that most of the water that reached the perforated tile line buried on the clay surface percolated through the spoil at the point where the trench was dug to install the tile rather than percolated through the spoil over the whole watershed area and flowed laterally over the clay surface. The spoil material was placed over the clay in several lifts using large earthmoving pans which resulted in significant compaction of the spoil. Surface runoff began very soon after the onset of a storm event and runoff volumes were large indicating there was little opportunity for percolation. Spoil core samples taken from just above the clay layer were quite dry even when the surface was wet. Finally, during surface flow

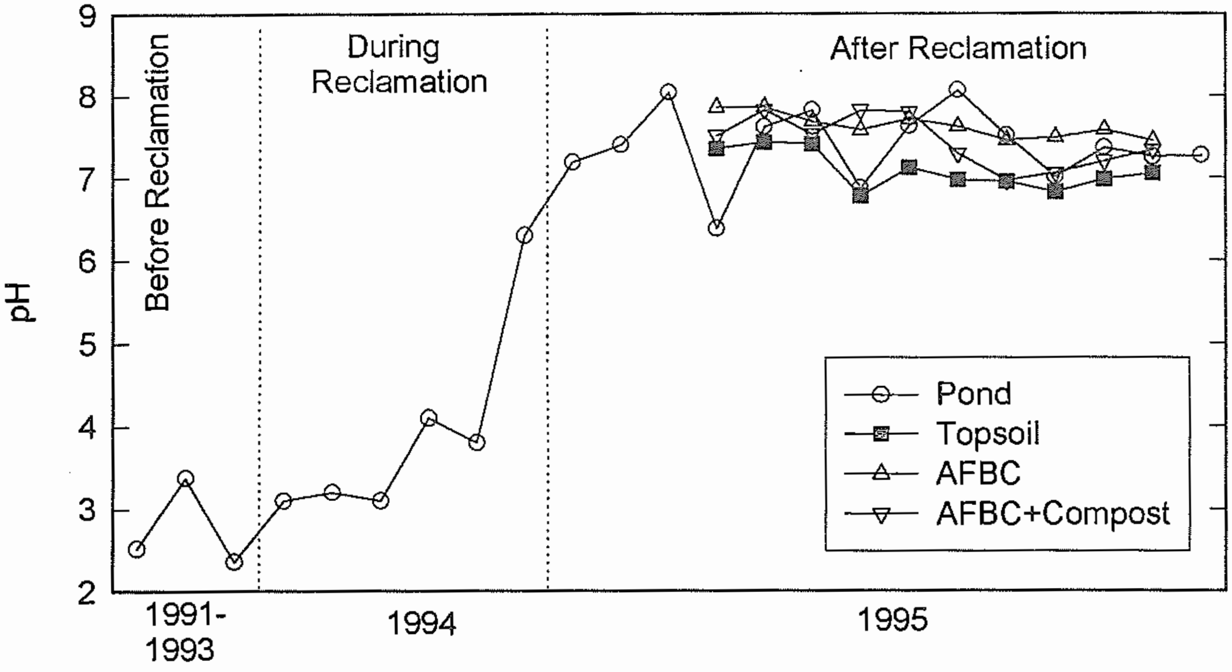

Fig. 5. pH of surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+Compost.

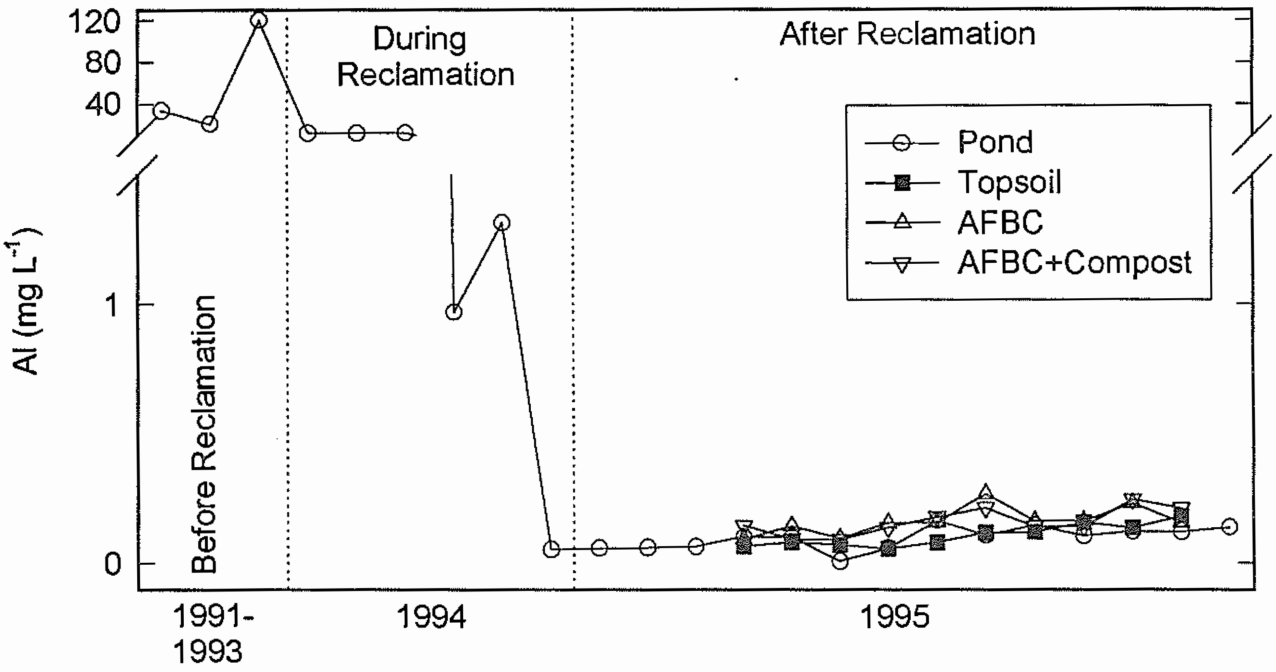

Fig. 6. Dissolved aluminum concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

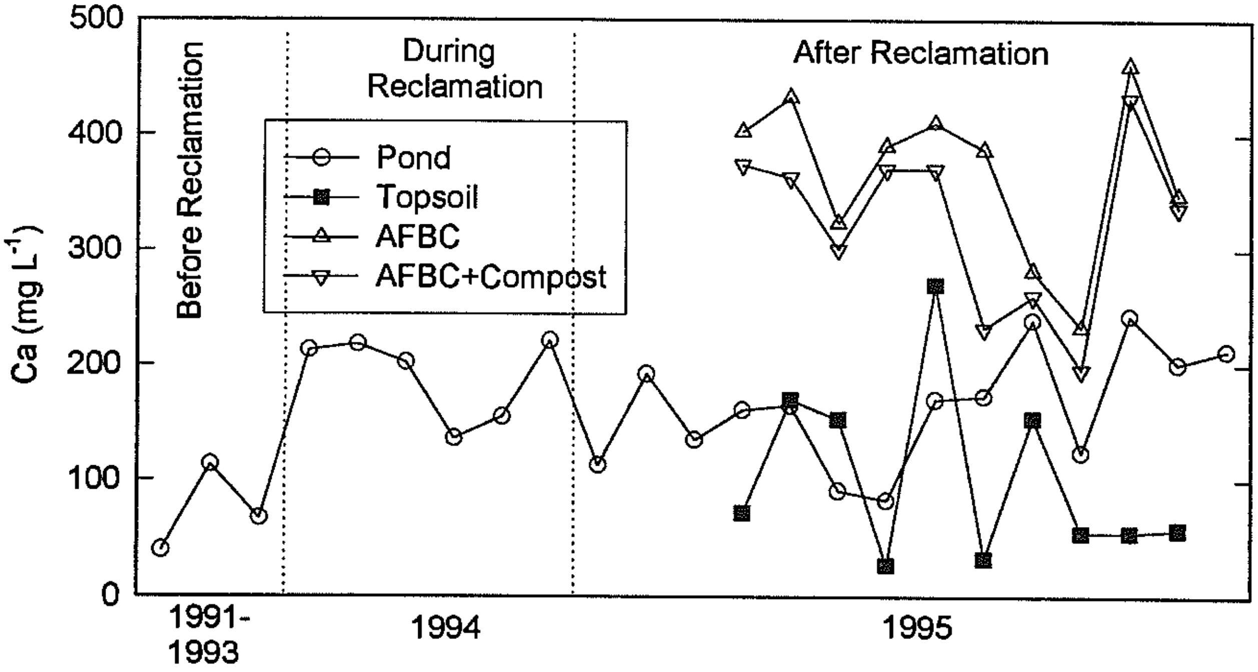

Fig. 7. Dissolved calcium concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

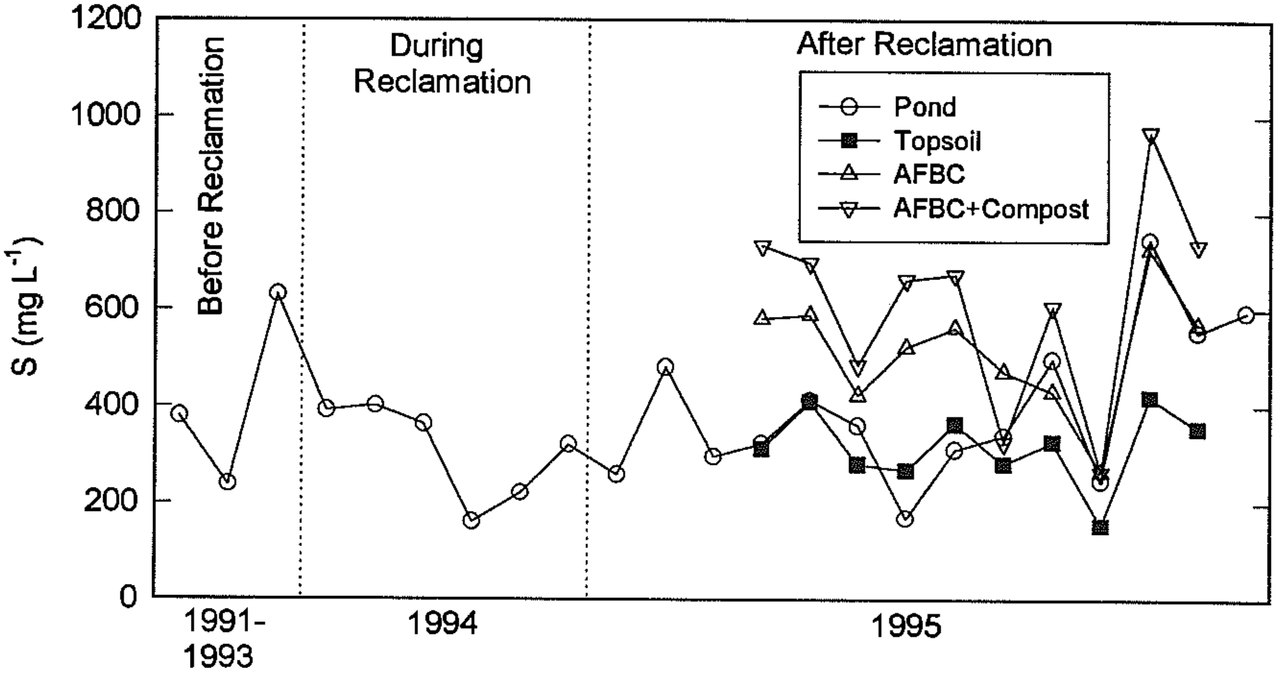

Fig. 8. Dissolved sulfur concentration in surface water runoff from minespoil reclaimed with topsoil, AFBC, and AFBC+Compost.

events water often puddled over the location of the trench. The tile water pH data also suggests limited interaction with subsurface acidic spoil and clay material (Fig. 9). Tile flow water from all three watersheds was only slightly lower than that of the surface water, and much higher than the pH of the subsurface spoil. Likewise soluble Al concentrations were in nearly the same range as that of the surface water (Fig. 10). Thus it appears that surface water is reaching the tile line via relatively rapid preferential flow paths and has limited interaction with the acidic spoil material.

The tile water is, however, interacting with the treated layers to a greater extent than the surface runoff water. Calcium concentrations in the tile water from all three watershed treatments were similar and in the range of 300 to 400 mg L^{-1} (Fig. 11). This was the same range as the surface water Ca for the AFBC treatments, but higher than for the topsoil treatment. Apparently the water percolating through the topsoil dissolved Ca from the ground agricultural limestone added to these watersheds. Reaction of the limestone with the acidic spoil released Ca^{2+} into the soil solution. Because of the large sulfate concentrations in the spoil (due to pyrite oxidation), the solubility of the Ca was controlled by gypsum, just as it was in the AFBC watersheds where gypsum was added.

For most of the summer, tile water S concentrations were larger in the AFBC watersheds than in the topsoil watersheds, reflecting the large addition of soluble sulfate in the gypsum component of the AFBC (Fig. 12). Toward the end of the summer, S concentrations from all three surface treatments and the pond appeared to be approaching a similar level. This may indicate that the system is approaching a new steady state condition where S concentrations are controlled by gypsum solubility.

Trace metal concentrations in surface water, tile water, and pond water generally remained very low and

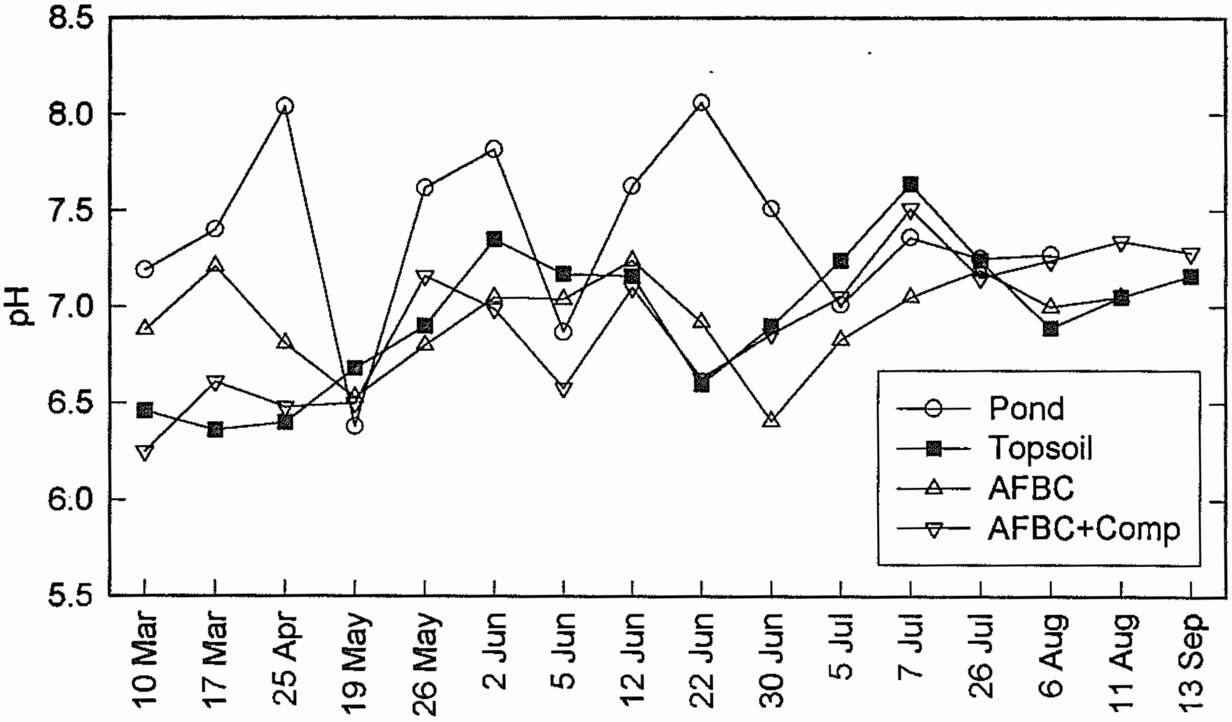

Fig. 9. pH of subsurface tile water flow from minespoil reclaimed topsoil, AFBC, and AFBC+compost.

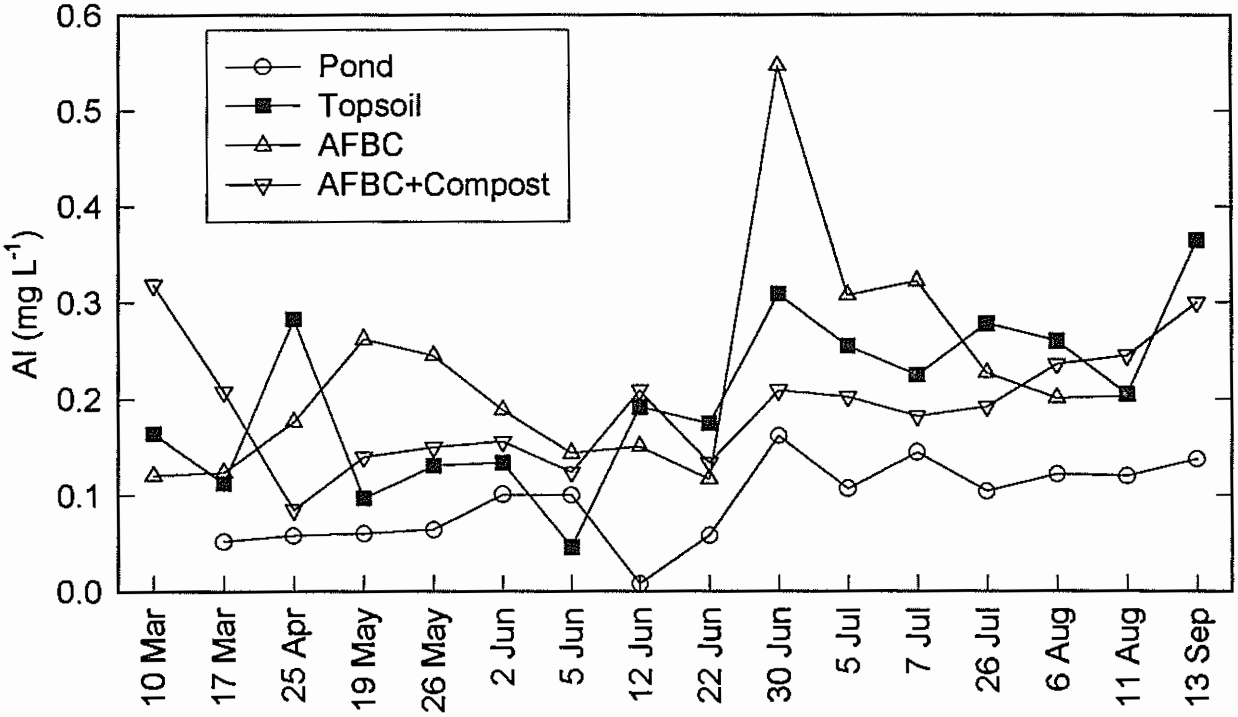

Fig. 10. Dissolved aluminum concentration in subsurface tile water flow from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

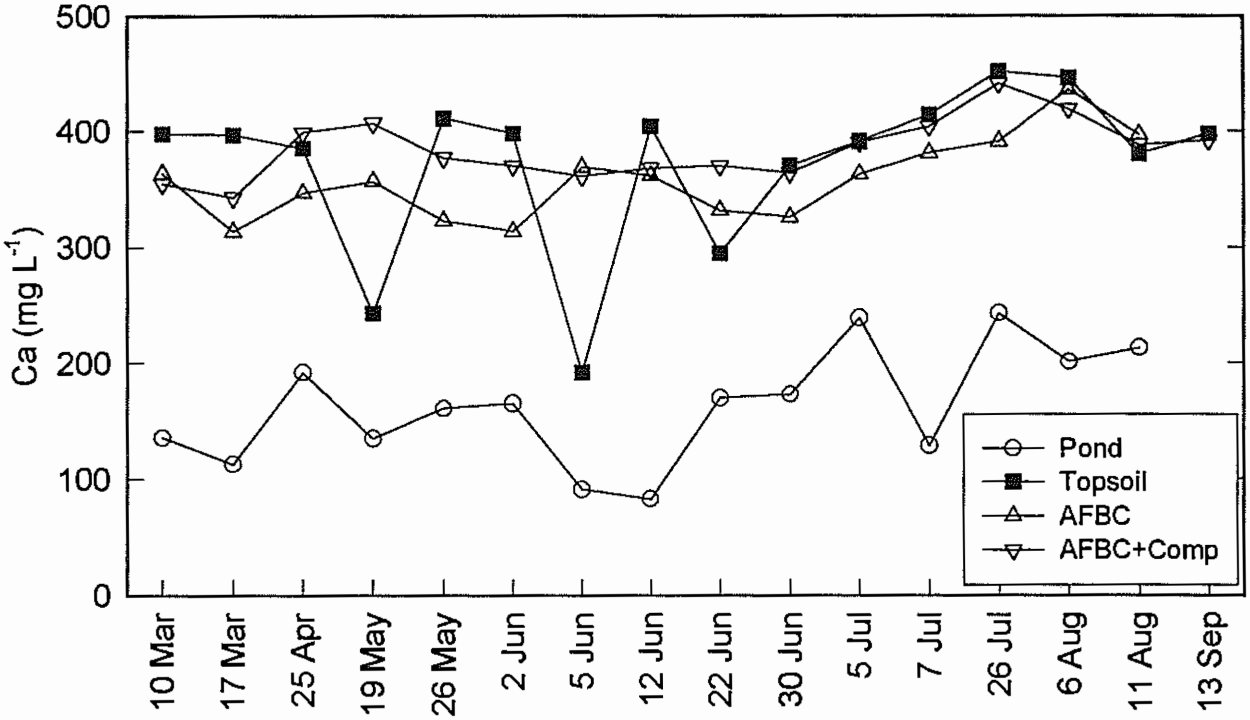

Fig. 11. Dissoved calcium concentration in subsurface tile water flow from minespoil reclaimed topsoil, AFBC, and AFBC+compost.

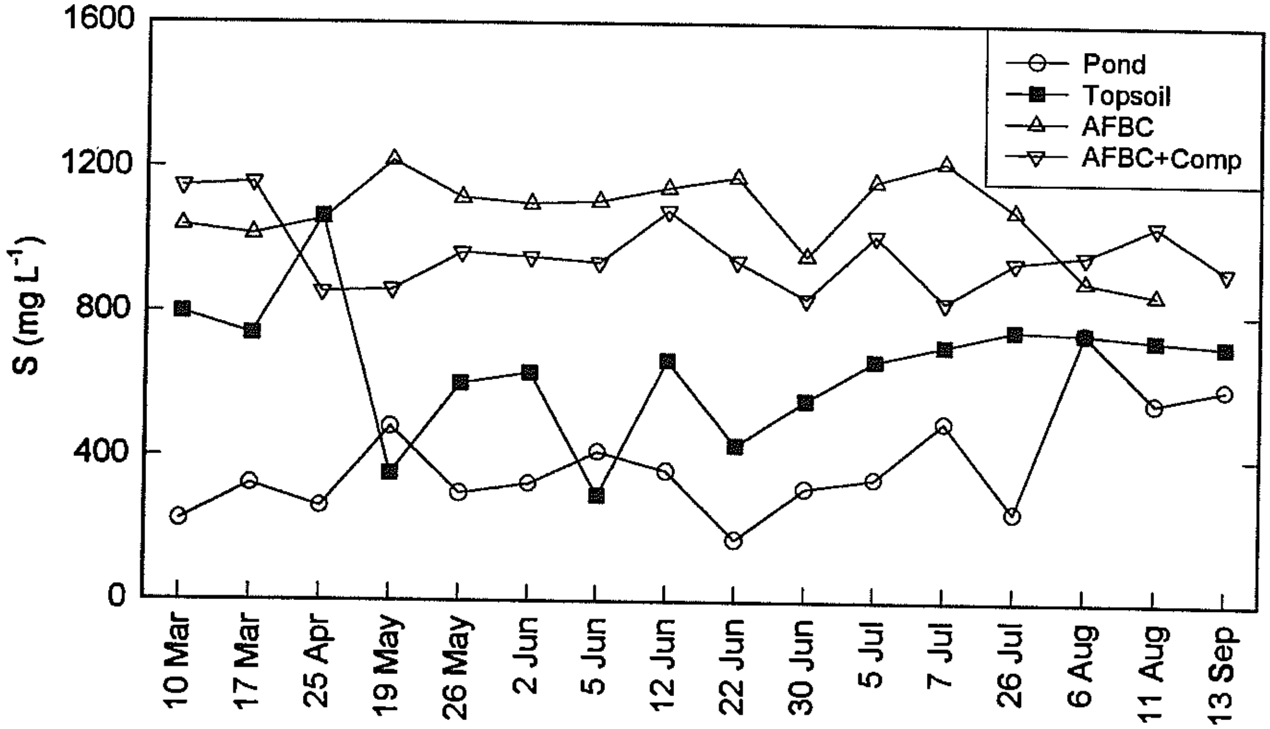

Fig. 12. Dissolved aluminum concentration in subsurface tile water flow from minespoil reclaimed with topsoil, AFBC, and AFBC+compost.

unaffected by the reclamation treatments (Table 2). Mean concentrations of As, Ba, Cd, Cr, Cu, and Se were below detection limits or below primary drinking water standards. Although occasional samples had higher concentrations of these regulated metals, these hits could not be ascribed to the AFBC or compost as all three reclamation practices gave values generally in the same range. This was generally the case for all measured trace elements. Mean Ni and Pb concentrations were above drinking water standards for the tile flow, but both mean and maximum concentrations were similar for all three reclamation treatments.

Boron and Mn concentrations both showed some response to the reclamation surface treatments (Table 2). These elements are of interest because of their potential for phytotoxicity at elevated concentrations. Boron was enriched in both surface and tile waters from the AFBC and AFBC+compost treated watersheds. This reflected the B added with the coal ash component of the AFBC by-product. It should be noted that B toxicity was not observed in the vegetation on these watersheds. Furthermore, the most phytotoxic B species are also highly water-soluble. Therefore the B enrichment indicated that the most phytotoxic B was being removed from the spoil rooting zone. Manganese concentrations in surface waters were similar for the three treatments, but in tile flow AFBC treatments had larger Mn concentrations than did the topsoil treatments. This indicated Mn was mobilized from the spoil in these watersheds. Mobilization of Mn following FBC by-product application has also been observed in acidic agricultural soil (Stehouwer et al., 1995a). The mechanism for this mobilization was not clear.

Conclusions

In the first year after reclamation, good vegetative growth on minespoil amended with AFBC or AFBC and yard-waste compost was achieved. Vegetative cover was nearly 100% over all areas of the 1-acre test

Table 2. Concentrations of trace elements in various water sources from minespoil reclaimed with topsoil, AFBC, and AFBC+compost. Values are means and maximum levels of all flow events in the spring and summer of 1995.

Element	Pond		Surface Runoff Water						Tile Flow Water					
			Topsoil		AFBC		AFBC+Compost		Topsoil		AFBC		AFBC+Compost	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Max
	mg kg^{-1}													
Ag	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
As	<0.04	0.083	<0.04	0.088	<0.04	0.096	<0.04	0.069	<0.04	0.106	<0.04	0.162	<0.04	0.095
B	0.526	1.082	0.147	1.867	3.163	6.875	1.977	3.681	0.207	0.961	2.945	5.178	1.644	3.279
Ba	0.023	0.040	0.017	0.032	0.012	0.020	0.010	0.017	0.017	0.032	0.017	0.024	0.019	0.042
Be	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001	<0.001	0.001	<0.001	0.002	<0.001	0.001
Cd	<0.001	0.001	<0.001	0.001	<0.001	0.001	<0.001	0.002	<0.001	0.010	0.001	0.011	<0.001	0.004
Co	0.008	0.024	0.008	0.025	0.010	0.034	0.014	0.036	0.223	1.216	0.416	2.258	0.341	1.266
Cr	0.003	0.009	0.003	0.010	0.005	0.012	0.005	0.011	0.009	0.019	0.010	0.031	0.010	0.019
Cu	0.009	0.023	0.010	0.030	0.006	0.029	0.013	0.027	0.005	0.048	0.002	0.022	0.006	0.035
Mn	1.33	3.527	1.63	7.330	1.06	3.722	2.68	8.042	23.94	124.7	32.80	198.4	34.27	122.4
Mo	<0.011	0.030	<0.011	0.020	0.028	0.065	0.018	0.043	<0.011	0.017	<0.011	0.033	<0.011	0.018
Ni	0.023	0.053	0.014	0.075	0.015	0.101	0.035	0.091	0.738	2.935	1.195	4.246	0.940	2.986
Pb	<0.02	0.048	<0.02	0.055	<0.02	0.050	<0.02	0.055	0.026	0.087	0.027	0.105	0.023	0.050
Se	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	0.100	<0.09	<0.09	<0.09	<0.09
Zn	0.065	0.144	0.065	0.135	0.021	0.139	0.002	0.113	0.139	0.192	0.382	0.204	0.131	0.217

watersheds. The establishment of vegetative cover directly on amended minespoil reduced erosion rates to less than 2 tons acre^{-1} for a 2-year storm. Although vegetative growth was more vigorous, biomass production was greater, and erosion was less on topsoiled watersheds than on watersheds with direct revegetation of minespoil, it is expected that these differences will become less as the spoil material begins to develop more soil-like properties. The successful revegetation of the minespoil can be attributed to increased pH and decreased concentrations of soluble Al and Fe in the minespoil. The less vigorous plant growth in the minespoil may be attributed in part to the large soluble salt concentrations in the spoil. It is expected that these concentrations will decrease over time as salts are leached from the profile surface.

No detrimental environmental effects were observed or measured as a result of using AFBC or compost in reclamation of acidic minespoil. Similar improvements in surface runoff and tile flow water quality were observed with topsoil, AFBC, or AFBC+compost. All three reclamation practices increased water pH to neutral levels and greatly decreased soluble Al. Concentrations of trace elements of environmental concern remained at very low concentrations in waters from all three reclamation practices. In those cases where measurable concentrations were present, there were no differences among the three reclamation treatments.

Results during the first year following reclamation show that the use of AFBC or AFBC and yard-waste compost will allow successful direct revegetation of acidic minespoil without adverse environmental effects. This site will continue to be monitored for several years to determine the long-term revegetation success and environmental impact of direct reclamation of minespoil with AFBC and yard-waste compost amendments.

Literature Cited

Alva, A.K., and M.E. Sumner. 1990. Amelioration of acid soil infertility by phosphogypsum. Plant and Soil 128:127-134.
https://doi.org/10.1007/BF00011101

Alva, A.K., M.E. Sumner, and W.P. Miller. 1990. Reactions of gypsum or phosphogypsum in highly weathered acid subsoils. Soil Sci. Soc. Am. J. 54:993-998.
https://doi.org/10.2136/sssaj1990.03615995005400040010x

Carlson, C.L., and D.C. Adriano. 1993. Environmental impacts of coal combustion residues. J. Environ. Qual. 22:227-247.
https://doi.org/10.2134/jeq1993.00472425002200020002x

Farina, M.P.W., and P. Channon. 1988. Acid-subsoil amelioration: II. Gypsum effects on growth and subsoil chemical properties. Soil Sci. Soc. Am. J. 52:175-180.
https://doi.org/10.2136/sssaj1988.03615995005200010031x

Marsh, B.H., and J.H. Grove. 1992. Surface and subsurface soil acidity: Soybean root response to sulfate-bearing spent lime. Soil Sci. Soc. Am. J. 56:1837-1842.
https://doi.org/10.2136/sssaj1992.03615995005600060031x

Korcak, R.F. 1980. Fluidized bed material as a lime substitute and calcium source for apple seedlings. J. Environ. Qual. 9:147-151.
https://doi.org/10.2134/jeq1980.00472425000900010031x

Sopper, W.E. 1992. Reclamation of mine land using municipal sewage sludge. Adv. In Soil Sci. 17:351-431.
https://doi.org/10.1007/978-1-4612-2820-2_11

Stehouwer, R.C., P. Sutton, and W.A. Dick. 1995a. Use of clean coal technology by-products as agricultural liming materials. p. 1-1 to 1-14. *In* Proceedings: 11th International Symposium on Use and Management of Coal Combustion By-Products (CCBs). Orlando, FL., January 15-19, 1995. EPRI TR-104657-V1

Stehouwer, R.C., P. Sutton, R.K. Fowler, and W.A. Dick. 1995b. Minespoil amendment with dry flue gas desulfurization by-products: element solubility and mobility. J. Environ. Qual. 24:165-174.
https://doi.org/10.2134/jeq1995.00472425002400010023x

Stehouwer, R.C., P. Sutton, R.K. Fowler, and W.A. Dick. 1995c. Minespoil amendment with dry flue gas desulfurization by-products: plant growth. J. Environ. Qual. 24:861-869.
https://doi.org/10.2134/jeq1995.00472425002400050011x

Sumner, M.E., H. Shahandeh, J. Bouton, and J. Hammel. 1986. Amelioration of an acid soil profile through deep liming and surface application of gypsum. Soil Sci. Soc. Am. J. 50:1254-1258.
https://doi.org/10.2136/sssaj1986.03615995005000050034x