PROPERTIES OF FLY ASH USED AS A TOPSOIL SUBSTITUTE IN MINELAND RECLAMATION

by

J.M. Gorman, D.K. Bhumbla, and J.C. Sencindiver

Abstract: Fly ash, used as a topsoil substitute, may provide a desirable alternative to conventional methods in the reclamation of adverse mine sites such as abandoned mine lands (AML) and coal refuse in the eastern United States. In August 1987, fly ash from three different power plant sources was surface-applied as a topsoil substitute at a rate of 1,200 metric tons/ha on an acidic minesoil representative of AML in northcentral West Virginia. In May 1990 (3 years after reclamation) and June 1999 (12 years after reclamation) both fly ash treated and untreated minesoil plots were sampled and analyzed for selected soil properties. Results indicated substantial differences between minesoil and fly ashes for most of the soil properties examined. Fly ashes had lower bulk density and higher total porosity values than the untreated minesoil. Fly ashes had a higher percentage of mesopores (0.0002-0.01 mm) and lower percentage of micropores (<0.0002 mm) than untreated minesoil, and as a result, fly ashes had much greater plant available water retention than minesoil. Silty textures and lower saturated hydraulic conductivity values for fly ash indicate that it may be more susceptable to erosion than minesoils. When applied to a pyritic minesoil, alkaline fly ashes with high neutralization potential had more favorable long-term effects on soil properties than the more neutral fly ash.

Additional Key Words: minesoils, abandoned mine lands.

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[1] Paper presented at the 2000 National Meeting of the American Society for Surface Mining and Reclamation, Tampa, Florida, June 11-15, 2000. This research was supported in part by funding from the National Mine Land Reclamation Center and the Allegheny Power Service Corporation.

[2] James M. Gorman, Research Instructor, Devinder K. Bhumbla, Assistant Professor, and John C. Sencindiver, Professor, Division of Plant and Soil Sciences, West Virginia University, P.O. Box 6108, Morgantown, WV 26506-6108.

Proceedings America Society of Mining and Reclamation, 2000 pp 627-643
DOI: 10.21000/JASMR00010627

https://doi.org/10.21000/JASMR00010627

Introduction

Fly ash or precipitator ash is the powdery residue which remains after the combustion of pulverized coal in electric power generating plants. The United States produces about 78 million Mg of coal combustion products annually (Bedick 1995). Approximately 80% (62 million Mg) of this is fly ash. Only 30% of the fly ash generated is utilized in any form with the remainder placed in storage or disposal areas (Bedick 1995). Millions of dollars are spent annually to dispose of this "waste" product and costs are continually increasing. Recently costs for disposal in unlined solid waste facilities were generally less than $5 per ton. Many states now require lined landfills with leachate and groundwater monitoring, and in some cases leachate collection and treatment. As a result, costs for disposal in these new landfill facilities run from $10 to $20 per ton (Bedick 1995). With these rising costs of disposal, alternative uses such as land application may be more economical. Research has indicated potential for further utilization of this "waste" product in the form of land appplications in both the agronomic and land reclamation fields (Capp and Engle 1967, Adams et al. 1971, Salter et al. 1971, Capp and Gillmore 1973, Capp et al. 1975).

In the last 30 years fly ash has been successfully used, on a relatively small scale, as a soil amendment in reclaming surface mined lands in the eastern United States. In these situations, it has mainly been used as a slow-release neutralizing material and to supply certain plant nutrients (Plass and Capp 1974, McLean and Dougherty 1979, Keefer et al. 1979). But fly ash, when applied at large rates on minesoil, has also demonstrated improvements in certain physical properties including reducing bulk density, increasing porosity, and increasing water holding capacity (Adams et al. 1971, Plass and Capp 1974).

Most of the studies concerning fly ash in mined-land reclamation have involved the incorporation of fly ash into the minesoil. Although incorporation of fly ash does provide the advantages of rapid neutralization of soil acidity as well as improvements in soil physical properties to the incorporation depth, it also increases the reclamation costs due to the added time and energy required for incorporation. One alternative is the use of fly ash as a topsoil substitute rather than a soil amendment, thus eliminating the costs of incorporation while also allowing greater land application rates. This would be especially beneficial in reclaiming extremely toxic coal refuse and abandoned mine land (AML). The combination of low pH and high percentage of rock fragments increases the costs of reclaiming these sites by conventional methods. Use of fly ash as a soil substitute, therefore, may offer an economical reclamation alternative.

High levels of boron and/or high levels of soluble salts may cause problems when using fly ash at high application rates. These problems can be avoided by using fly ash that is naturally low in boron and soluble salts, or by using fly ash that has been pre-weathered by leaching or lagooning (Page et al.1979). Due to the high degree of variability in chemical composition of fly ash (Adriano et al. 1980), complete chemical analysis is desired before using fly ash in large scale land applications.

Much information is available concerning changes on soil chemical properties and plant nutrition with fly ash amended soils (Rees and Sidrak 1956, Holliday et al. 1955, Martens 1971, Townsend and Hodgson 1973, Keefer et al 1983), but little information is available concerning soil properties of fly ash when used as a topsoil substitute.

The objective of this study was to examine the effects of massive fly ash applications on the properties of an acidic minesoil, where fly ash was used as a topsoil substitute.

Methods

In August 1987, fly ash from three different power plant sources (Albright, Fort Martin, and Harrison) was surface-applied at a rate of 1200 metric tons/ha on an acidic minesoil representative of AML in northcentral West Virginia. The study site was located approximately 1 km southwest of Lenox, West Virginia ($39^0 33$'N, $79^0 36$'W). The coal bed mined at this site was the Elk Lick Coal (Conemaugh Group of Pennsylvanian System) which is found in the geologic column between the Bakerstown and Pittsburgh coals. It is usually too thin to be mined economically, but at this location it was approximately 1.2 meters thick and was mined by a small scale bulldozer-endloader operation. The site was first mined in the early 1970's prior to the Federal Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87-SMCRA). The minesoil on the site was classified as toxic with reduced sulfur averaging slightly > 1% and a pH averaging 3.4. Revegetation of this site was unsuccessful despite repeated previous attempts by the coal operator using conventional methods. In the early to mid 1980's, the site was remined to remove the remaining coal, leaving very little original topsoil. Due to the high pyritic sulfur content of the minesoil and lack of topsoil material, massive fly ash application appeared to be a favorable solution in revegetating this site. The 1200 metric ton/ha rate amounted to a total fly ash depth of approximately 20 cm on the fly ash treated plots.

All three sources of the fly ash used in this study were from northcentral West Virginia and were classified as non-hardening class C ash. Two of the fly ashes (Fort Martin and Harrison) were alkaline with initial pH values of 11.4 and 11.3 respectively. The third fly ash (Albright) was only slightly alkaline with a pH of 8.4.

Details of the original experiment including design and chemical data were reported elsewhere (Bhumbla et al. 1991a).

In May 1990 (3 years after fly ash application), and June 1999 (12 years after fly ash application), both minesoil plots and fly ashtreated plots were analyzed for selected soil properties using undisturbed soil clods, undisturbed soil cores (7.62 by 7.62 cm), and bulk soil samples. Soil samples were taken at two depths: 1) the surface 0-8 cm in both fly ash treated and untreated minesoil plots; and 2) lower depths corresponding to the first 8 cm of the minesoil beneath the fly ash layer on the fly ash treated plots, and at 8-16 cm on the untreated minesoil plots. Due to the extreme rockiness of the spoil, cores could not be taken at the lower depths, therefore physical properties determined from cores are for the surface 8 cm only. Undisturbed soil cores were used to determine the following physical properties for the surface 0-8 cm depth: bulk density (Blake and Hartge 1986), total porosity and pore-size distribution (Danielson and Sutherland 1986), saturated hydraulic conductivity (Hill and King 1982), and water retention (Klute 1986). Soil clods were used to determine bulk density and total porosity of minesoil materials at the lower sampling depth using a non-polar liquid method (Sobek et al. 1978). Bulk soil samples were used to determine particle-size distribution (Gee and Bauder 1986), aggregate stability (Kemper and Rosenau 1986), soil pH (McLean 1982), and soluble salts as measured by electrical conductivity (Rhoades 1982). Other chemical properties are not reported in this manuscript due to undetermined amounts of lime and fertilizer which had been applied to the site by the landowner during the period 1995 to 1999. Lime, fertilizer, and barnyard manures had been applied mainly to the untreated minesoil and Albright fly ash plots to promote revegetation and facilitate bond release on the site. During the last three years of the study (1997 to 1999), the landowner has been removing an annual hay crop from the site.

Results and Discussion

pH and EC

Vegetation growth (dry matter yields) after the first year (1987) was highest on the Albright and conventionally prepared minesoil plots (data not shown). Vegetation growth was very low for the first year on the Fort Martin and Harrison plots due to high levels of soluble salts (Table 1) and high concentration of boron (Bhumbla et al. 1991b). In subsequent years, this was reversed with vegetative growth improving on the Fort Martin and Harrison plots as the soluble salts were leached out, while vegetation declined on the Albright and minesoil plots due to decreasing pH as a result of pyrite oxidation. Vegetation

Table 1. pH and soluble salts as measured by electrical conductivity (EC) for fly ashes and minesoil.

TREATMENT	YEAR	pH	EC (dS/cm)
MINESOIL	1990	3.4	1.48
0-8 cm	1999	5.5	1.51
MINESOIL	1990	-	-
8-16 cm	1999	3.5	0.77
FT. MARTIN	1990	11.4	2.04
FLY ASH	1999	7.5	0.52
MINESOIL UNDER	1990	-	-
FT. MARTIN ASH	1999	5.6	0.68
HARRISON	1990	11.3	3.60
FLY ASH	1999	7.6	0.49
MINESOIL UNDER	1990	-	-
HARRISON ASH	1999	6.0	0.64
ALBRIGHT	1990	8.4	1.13
FLY ASH	1999	5.9	0.46
MINESOIL UNDER	1990	-	-
ALBRIGHT ASH	1999	3.8	1.67

samples for yield determinations were not taken in 1999 because the region was experiencing a severe drought.

In 1999 (12 years after fly ash treatment), soil pH was still in the alkaline range (7.5 and 7.6) in the Ft. Martin and Harrison fly ash plots (Table 1), while soil pH was slightly acidic (5.9) in the Albright fly ash plots. After 12-years, soil pH was still highly acidic in the untreated minesoil, especially at the lower sampling depth (8-16 cm), despite heavy lime applications by the landowner during the previous 1995 to 1999 period. The last 25 years has revealed that conventional lime applications are not very effective on this site due to continued acid production from pyrite oxidation. Soil pH was also extremely acidic (3.8) in the minesoil beneath the Albright fly ash due to continued pyrite oxidation and the depletion of alkalinity from the Albright fly ash over the 12-year period (Table 1). Soil pH was only slightly acidic (5.6 and 6.0) in the minesoils under the alkaline fly ashes (Ft. Martin and Harrison), indicating continued alkalinity release from the fly ash layer to the minesoil even after a 12-year period.

Particle-size Distribution

Fly ash particle-size distibution was significantly different from the minesoil (Table 2). Fly ashes were very low in clay (<5%) and very high in silt (65-80%), which suggests a high erosion potential due to a lack of cohesion from the low clay content, and the high percentage of erodible silt-size particles. Added to this is the fact that approximately 80% of the sand-size fraction in the fly ash was classified as very fine sand (0.05-0.10 mm) (Gorman 1996), which has been found by others (Wischmeier and Mannering 1969) to behave more like silt than sand from an erodibility perspective. Recent studies (Lehrsch and Baker 1991, Gorman et al. 1997) have shown that fly ash is highly erodible when exposed to raindrop impact and surface runoff.

Table 2. Particle size distribution of fly ashes and minesoil at the 0-8 cm depth.

TREATMENT	YEAR	SAND	SILT	CLAY
		%		
MINESOIL 0-8 cm	1990	13.9c*	33.9d	52.2a
	1999	18.3bc	45.0c	36.7b
FT. MARTIN FLY ASH	1990	28.7a	66.7b	4.6c
	1999	21.4b	74.5ab	4.1c
HARRISON FLY ASH	1990	18.8bc	78.0a	3.2c
	1999	15.1c	82.0a	2.9c
ALBRIGHT FLY ASH	1990	17.7bc	77.5a	4.8c
	1999	16.7bc	80.5a	2.8c

*means in columns with the same letter are not significantly different at p>0.05 level

There appeared to be a trend (although not statistically significant) of decreases in sand, increases in silt, and decreases in clay size particles in the fly ashes from 1990 to 1999 (Table 2). This may be a result of weathering and breakdown of fly ash particles from sand to silt sizes along with eluviation of clay size fly ash particles out of the sampling depth. The surface 0-8 cm of the untreated minesoil also exhibited evidence of eluviation with increases in the proportion of sand size particles and corresponding decrease in clay during the 9-year period from 1990 to 1999 (Table 2).

There were also significant differences in particle-size distribution among the minesoil materials (Table 3). Minesoil under fly ash treated plots was generally higher in sand and lower in clay, while minesoil in the 8-16 cm depth of the untreated plots generally contained less sand and more clay. There appeared to be a definite trend in decreasing amounts of sand and increasing amounts of clay corresponding to decreasing pH, suggesting acid sulfate weathering of minerals due to pyrite oxidation in the spoil. This trend was also observed in another study (Singh et al. 1982). Alkaline recharge generated by the fly ashes with high neutralization potential retarded the rate of pyrite oxidation (Bhumbla et al. 1991a), and as a result an increase in clay did not occur in minesoils under the alkaline fly ash treated plots (Table 3). This trend was less evident in the minesoil under the neutral Albright fly ash where particle size distribution more closely resembled that in the 8-16 cm depth of the untreated minesoil (Table 3).

Table 3. Particle size distribution of minesoils at the lower sampling depths.

TREATMENT	YEAR	SAND	SILT	CLAY
		%		
MINESOIL	1990	15.7c*	36.4ab	47.9a
8-16 cm	1999	17.3bc	35.2ab	47.5a
MINESOIL UNDER	1990	29.3a	37.0ab	33.7c
FT. MARTIN FLY ASH	1999	24.9ab	34.4b	40.7bc
MINESOIL UNDER	1990	28.2a	42.4a	29.4c
HARRISON FLY ASH	1999	27.7a	37.6ab	34.7c
MINESOIL UNDER	1990	20.9bc	36.3ab	42.8b
ALBRIGHT FLY ASH	1999	21.0bc	35.0b	44.0b

*means in columns with the same letter are not significantly different at p>0.05 level

Aggregate Stability

Substantial differences in the water-stable aggregation were observed between fly ash and minesoil materials, as well as among the fly ash sources (Table 4). The highest aggregate stability was found in the alkaline fly ashes (Fort Martin and Harrison). The lowest aggregate stability was found in the Albright fly ash. The dominant aggregating agent in the fly ash materials was likely calcium carbonate ($CaCO_3$). The highly alkaline fly ashes (Fort Martin and Harrison) exhibited very high percentage of aggregation and aggregate stability due to the abundance of calcium (Bhumbla et al. 1991a). Albright fly ash, in contrast, exhibited much lower percent aggregation and aggregate stability due to much lower levels of calcium. The primary aggregating agent in the untreated minesoil was likely the strong flocculating effect of H^+ and Al^{3+}, which would have been prevalent at the low pH, on the clay-size particles.

There was little change in water-stable aggregation in the alkaline fly ashes (Ft. Martin and Harrison) from 1990 to 1999 (Table 4), while aggregation increased significantly during the same period in the Albright fly ash. Since Albright fly ash was decreasing in alkalinity during this time period (Table 1), the increase in water-stable aggregation may be attributed to biological processes. The most dramatic increase in water-stable aggregation occurred in the 0-8 cm depth of the untreated minesoil plots where aggregate stability nearly doubled in the 9-year period from 1990 to 1999 (Table 4). Water-stable aggregation also increased during this same time period in minesoils at the lower sampling depth (Table 5). The largest increase was exhibited in the minesoils under the alkaline fly ashes (Ft. Martin and Harrison) where values doubled during the 9-year period (Table 5). Increases in aggregation in the minesoil under the Albright fly ash were similar to those at the 8-16 cm depth in the untreated minesoil plots (Table 5).

Table 4. Water-stable aggregation of fly ashes and minesoil for the surface 0-8 cm.

TREATMENT	YEAR	TOTAL AGGREGATION
		--------%---------
MINESOIL 0-8 cm	1990	34.8de*
	1999	64.7c
FT. MARTIN FLY ASH	1990	94.0a
	1999	82.2b
HARRISON FLY ASH	1990	94.5a
	1999	94.3a
ALBRIGHT FLY ASH	1990	25.6e
	1999	47.6d

*means in columns with the same letter are not significantly different at $p>0.05$ level

Table 5. Water-stable aggregation of minesoil at the lower sampling depths.

TREATMENT	YEAR	TOTAL AGGREGATION
		-------------%-------------
MINESOIL	1990	38.5c*
8-16 cm	1999	51.7b
MINESOIL UNDER	1990	30.8c
FT. MARTIN FLY ASH	1999	65.5a
MINESOIL UNDER	1990	32.9c
HARRISON FLY ASH	1999	62.8a
MINESOIL UNDER	1990	33.3c
ALBRIGHT FLY ASH	1999	48.4b

*means in columns with the same letter are not significantly different at p>0.05 level

Bulk Density and Total Porosity

Bulk density and total porosity also differed significantly among the fly ash and minesoil materials (Table 6). Bulk density in the surface 8 cm was significantly lower in the fly ash compared to the untreated minesoil. This agrees with other findings (Adams et al. 1971, Plass and Capp 1974, Chang et al. 1977, Page et al. 1979, Adriano et al. 1980) where fly ash additions to most soils resulted in consistently lowered bulk densities. It should be noted that the somewhat higher bulk density values for the Harrison fly ash as compared to the other fly ashes was a function of the higher particle density of the Harrison ash (Gorman, 1996) and not related to the relative packing of the soil particles. This was evident in that all three fly ashes exhibited greater total porosity than the untreated minesoil (Table 6). The combination of low bulk density and high porosity would tend to favor better seedling emergence and better root growth with the fly ash. Bulk density values in 1990 among the minesoil materials (Table 7) showed significantly lower bulk density and higher total porosity in the minesoil under the Harrison fly ash. This difference may have been due to the greater plant root penetration into the minesoil under the Harrison fly ash at this time (based on visual observation). Bulk density values were much lower in the upper 0-8 cm sampling depth than at the 8-16 cm sampling depth of the untreated minesoil (Tables 6 and 7). This lower bulk density in the surface layer of the untreated minesoil plots may be the result of organic residues as well as the greater effect of freeze-thaw, wet-dry cycles, and structure development at this depth. It should also be noted that the minesoil contained 10-20%

Table 6. Bulk density and total porosity of fly ashes and minesoil for the surface 0-8 cm.

TREATMENT	YEAR	BD	BD<2 mm	TOTAL POROSITY
		---------Mg m^{-3}---------		%
MINESOIL 0-8 cm	1990	1.4a*	1.2a	46.8c
	1999	1.3a	1.2a	47.7c
FT. MARTIN FLY ASH	1990	1.1c	1.1b	57.0a
	1999	1.1c	1.1b	53.3ab
HARRISON FLY ASH	1990	1.3b	1.2ab	54.5ab
	1999	1.2c	1.1b	56.0ab
ALBRIGHT FLY ASH	1990	1.2c	1.2b	52.4b
	1999	1.1c	1.1b	53.9ab

*means in columns with the same letter are not significantly different at p>0.05 level

Table 7. Bulk density and total porosity of minesoil at the lower sampling depths.

TREATMENT	YEAR	BD	BD<2 mm	TOTAL POROSITY
		---------Mg m^{-3}---------		%
MINESOIL	1990	1.6a*	1.4ab	38.8b
8-16 cm	1999	1.7a	1.5a	36.3b
MINESOIL UNDER	1990	1.6a	1.5a	38.5b
FT. MARTIN FLY ASH	1999	1.7a	1.5a	36.2b
MINESOIL UNDER	1990	1.5b	1.3b	42.9a
HARRISON FLY ASH	1999	1.6a	1.4ab	37.8b
MINESOIL UNDER	1990	1.6ab	1.4a	39.3b
ALBRIGHT FLY ASH	1999	1.7a	1.5a	36.3b

*means in columns with the same letter are not significantly different at p>0.05 level

rock fragments by volume, with higher percentages at the lower depth (8-16 cm), as reflected by the differences between total bulk density and the bulk density of the less than 2 mm fraction (Tables 6 and 7). Fly ash, on the other hand, while containing some water-stable aggregates greater than 2 mm in size, did not have any rock fragments. There was almost no change in minesoil bulk density or total porosity values at the lower sampling depth during the 9-year period (1990 to 1999) (Table 7). This is similar to results obtained by Gorman and Sencindiver 1999, where there was also little change in minesoil bulk density and total porosity values on another site over a 9-year period at lower sampling depths.

Pore-size Distribution

There were significant differences in pore-size distribution between fly ashes and untreated minesoil. Fly ash was much higher in mesopores (0.0002-0.01 mm) and lower in micropores (<0.0002 mm) than untreated minesoil throughout the study period (Table 8). Initially (1990), fly ashes had fewer macropores (>0.01 mm) than the untreated minesoil (Table 8). The amount of fly ash macropores in 1990 appeared to be related to vegetational effects such as root channels. Roots, as revealed in excavated soil profiles, were much more profuse in the Harrison and Fort Martin plots than in the Albright plots at this time. The lower percentage of macropores in the Albright plots may have resulted from dislodged fine soil particles being washed into the larger pores because of the lower vegetational ground cover and less protection against raindrop impact on the Albright plots in 1990. By 1999, the amount of macropores had dramatically increased in the fly ash treated plots, while remaining unchanged in the untreated minesoil plots (Table 8).

Table 8. Pore size distribution of fly ashes and minesoil for the surface 0-8 cm.

TREATMENT	YEAR	Macropores >0.01 mm	Mesopores 0.0002-0.01 mm	Micropores <0.0002 mm
		----------------------	%	----------------------
MINESOIL 0-8 cm	1990	23.0b*	31.0e	46.0a
	1999	23.0b	54.7d	15.3b
FT. MARTIN FLY ASH	1990	19.0bc	70.9b	10.1c
	1999	34.8a	60.4c	4.8d
HARRISON FLY ASH	1990	20.2bc	63.1c	16.7b
	1999	33.2a	62.3c	4.6d
ALBRIGHT FLY ASH	1990	13.1c	76.4a	10.5c
	1999	29.3ab	67.1bc	3.5d

*means in columns with the same letter are not significantly different at p>0.05 level

Untreated minesoil, which was very acidic and practically devoid of vegetation during much of the study period, did not exhibit the same degree of pedogenic structure development as fly ashes and therefore the proportion of macropores in untreated minesoil did not increase. But in the period from 1990 to 1999, the amount of mesopores in the surface 0-8 cm of the untreated minesoil had increased dramatically (Table 8), while the percentage of micropores correspondingly decreased. These changes in pore size distribution in the untreated minesoil coincided with the eluvial loss of clay (Table 2) and possible development of microstructure over the 9-year period (1990 to 1999).

Saturated Hydraulic Conductivity

Initial (1990) saturated hydraulic conductivity (K_{sat}) values for the untreated minesoil were greater than values for the fly ash treatments (Table 9). These higher values may be related to the differences in pore-size distribution between the fly ashes and minesoil in 1990 (Table 8). Ksat values, although showing some degree of variability, were not significantly different among the fly ash treatments throughout the study period (Table 9). Differences in Ksat values were not statistically significant among the fly ash sources due to large variability among the samples and due to the low number of samples analyzed (16 cores/treatment). Soil hydraulic properties are highly variable among measurements, thus requiring a large number of samples to reveal statistically significant differences.

Table 9. Saturated hydraulic conductivity of fly ashes and minesoil for the surface 0-8 cm.

TREATMENT	YEAR	Ksat
		cm sec^{-1}
MINESOIL 0-8 cm	1990	6.2×10^{-3}a*
	1999	3.7×10^{-3}ab
FT. MARTIN FLY ASH	1990	1.6×10^{-3}b
	1999	1.1×10^{-3}b
HARRISON FLY ASH	1990	2.0×10^{-3}b
	1999	2.9×10^{-3}b
ALBRIGHT FLY ASH	1990	7.6×10^{-4}b
	1999	1.2×10^{-3}b

*means in columns with the same letter are not significantly different at $p>0.05$ level

Moisture Retention

Plant available water holding capacity was significantly different between the fly ashes and untreated minesoil. Plant available water holding capacity has most commonly been defined as the moisture retained by the soil at tensions between 33 and 1500 kPa (1/3 to 15 bar). Plant available water holding capacity in 1990 averaged more than three times higher in the surface 8 cm of the fly ash plots than in the untreated minesoil plots (Table 10). Other investigators (Adams et al. 1971, Capp and Gilmore 1973, Plass and Capp 1974, McLean and Dougherty 1979) found similar results with fly ash applications greatly increasing water holding capacity. The moisture retention characteristics of a soil are largely a function of the pore-size distribution with plant available water retention being mainly a function of the total porosity found in the 0.0002 to 0.01 mm pore-size range. The untreated minesoil plots in 1990 had a smaller percentage of pores occurring in this size range (Table 8), and thus had lower moisture retention values (Table 10). On the other hand, the fly ashes had a large proportion of pores occurring in the mesopore range (Table 8) along with higher total porosity (Table 6), and therefore had much higher moisture retention values (Table 10). By 1999, as soil microstructure developed and percentage of clay size particles decreased in the surface 0-8 cm of the untreated minesoil plots (Table 2), plant available water retention increased to near the levels found in the fly ashes (Table 10).

Table 10. Plant available water retention of fly ashes and minesoil for the surface 0-8 cm.

TREATMENT	YEAR	PLANT AVAILABLE WATER (1/3-15 BAR)
		cm/cm
MINESOIL 0-8 cm	1990	.09d*
	1999	.25c
FT. MARTIN FLY ASH	1990	.30b
	1999	.32ab
HARRISON FLY ASH	1990	.29b
	1999	.35a
ALBRIGHT FLY ASH	1990	.32b
	1999	.36a

*means in columns with the same letter are not significantly different at p>0.05 level

Moisture retention values were also significantly different among the minesoil materials at the lower sampling depths (Table 11). Initially (1990), the highest moisture retention was in the minesoils directly under the alkaline fly ashes (Fort Martin and Harrison) (Table 11). The higher values found under these fly ash plots may have resulted from two factors: 1) the effects of plant roots penetrating the underlying minesoil and 2) possible flocculation of clays in the minesoil from divalent cations such as Ca^{2+} and Mg^{2+} which were being leached out of the fly ash layer (Bhumbla et al. 1991a). Both of these theories are somewhat supported by evidence on the site. First, excavated soil profiles on the plots, revealed a considerable amount of plant roots extending into the minesoils beneath the Fort Martin and Harrison plots. Very few roots were observed to enter the minesoils under the Albright plots in 1990. Second, minesoils beneath Fort Martin and Harrison plots were receiving alkaline recharge including available calcium from the alkaline fly ash above as indicated by Bhumbla et al. (1991a). Since there was much less exchangeable calcium present in the Albright fly ash, it is also likely that there was less calcium leached down into the minesoil to aid in flocculation. Thus, moisture retention of the minesoil under the Albright fly ash differed little from that of the untreated minesoil plots at this time (Table 11). By 1999, as soil structure developed at these depths, there was little difference in plant available water among treatment goups in minesoils at the lower sampling depth (Table 11).

Table 11. Plant available water retention of minesoil at the lower sampling depths..

TREATMENT	YEAR	PLANT AVAILABLE WATER (1/3-15 BAR)
		cm/cm
MINESOIL	1990	.06e*
8-16 cm	1999	.19b
MINESOIL UNDER	1990	.19b
FT. MARTIN FLY ASH	1999	.22a
MINESOIL UNDER	1990	.15c
HARRISON FLY ASH	1999	.18b
MINESOIL UNDER	1990	.10d
ALBRIGHT FLY ASH	1999	.21ab

*means in columns with the same letter are not significantly different at p>0.05 level

Summary

This study revealed substantial differences between fly ash and minesoil for most of the soil properties examined. Overall, fly ash appeared to be superior to the untreated minesoil for most of the soil properties which affect plant growth. Bulk density of the fly ash was significantly lower than that of the untreated minesoil. This would tend to favor better seedling emergence and better root growth with fly ash treatment. Total porosity, which can be related to the soil's air capacity, was also higher in the fly ash, thus providing better conditions for root respiration. One of the more interesting results of this study, which greatly helps in explaining water relations, was the striking differences in pore-size distribution between fly ash and minesoil. Fly ash contained a higher percentage of mesopores in the 0.0002 to 0.01 mm size range, which are very important in determining soil water holding capacity. As a result, it was not surprising that plant available moisture retention was much greater in the fly ashes than in the minesoil. This suggests that vegetation growing on fly ash would be less susceptable to drought stress.

The fly ashes examined in this study initially exhibited lower saturated hydraulic conductivity than the minesoil. Lower water conductivity values, along with fine particle size, suggest that surface-applied fly ash may be more susceptable to erosion than minesoils. This would be especially true in the period preceeding and during vegetation establishment when the soil surface is most susceptable to erosive processes. Thus, use of fly ash as a topsoil substitute may require more moderate slope factors (length of slope and slope gradient) than are possible with many minesoils, as well as the use of management practices which will protect the soil surface from raindrop impact, such as promoting rapid vegetation establishment and the liberal use of mulches.

In conclusion, fly ash, when used as a topsoil substitute, has a number of advantages over conventional methods in the reclamation of adverse mine sites such as pyritic minesoils and coal refuse. These include increased water holding capacity, greater total porosity, medium soil texture, neutral to slightly alkaline pH, and lower bulk density. All of these are important factors affecting plant growth. When reclaiming pyritic minesoils that have very low pH values, alkaline fly ashes with high neutralization potential would be preferred as a topsoil sustitute over the more neutral fly ashes. Although fly ash used as a topsoil substitute can improve these soil properties, it may also require more careful planning and management practices due to the potential problems of boron toxicity, high soluble salts, and its inherent erosion potential.

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