PHYSICAL PROPERTIES OF FLY ASH-TREATED MINESOILS[1]

by

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Abstract. Fly ash, when used as a topsoil substitiute, may provide a desirable alternative to conventional methods in the reclamation of abandoned mine land (AML) and coal refuse in the eastern United States. In August 1987, fly ash from 3 different power-plant sources was surface applied at a rate of 1,200 metric tons/ha on an acidic minesoil representative of AML in northcentral West Virginia. In May 1990, physical properties of the fly ash-treated plots and minesoil control plots were analyzed. Results indicated substantial differences between minesoil and fly ashes for most of the physical properties examined. With the exceptions of particle density and aggregate stability, there was little difference in physical properties among the 3 fly ash sources. In contrast, there were major differences between the fly ash-treated and minesoil control plots. Minesoil control plots contained 10-20% rock fragments by volume while fly ash contained no rock fragments. Minesoil exhibited higher bulk density (1.25-1.45 Mg m^{-3}) and lower total porosity (38-46%) than fly ash (1.10-1.20 Mg m^{-3} and 52-57% respectively). There were also significant differences in pore-size distribution with most of the minesoil control porosity consisting of macropores (>0.1 mm) and micropores (<0.001 mm) with a very low percentage of mesopores (0.001-0.1 mm). As a result, infiltration rate and saturated hydraulic conductivity were higher in the minesoil control plots due to the larger pore sizes. In contrast, moisture retention (plant-available) was more than 3 times greater in the fly ash plots due to their high percentage of mesopores (0.001-0.1 mm).

Additional Key Words: Fly Ash, Physical Properties, Reclamation, Abandoned Mine Land.

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Introduction

Fly ash or precipitator ash is the powdery residue that remains after the combustion of pulverized coal in electric power generating plants. The United States is currently producing over 71 million tons of solid combustion products annually, of which approximately 80% or 56.8 million tons is fly ash (Golden 1987). In 1985, only 27% of the fly ash produced was utilized with the remainder being placed in storage or landfills. Millions of dollars are being spent annually to dispose of this "waste" product. Research has shown that there is great 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, McLean and Dougherty 1979, Keefer et al 1979).

In the last 20 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 (Adams et al 1971, 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 reclamation costs due to the added time and energy required for the incorporation. One alternative, which could be applicable in land reclamation, 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 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 the 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 applications (Rees and Sidrak 1955, Holliday et al 1955, Martens 1971, Townsend and Hodgson 1973, Keefer et al 1983), but little information is available concerning the physical 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 physical properties of minesoils, where fly ash was used as a topsoil substitute.

Methods

In August 1987, fly ash from 3 different power plant sources (Albright, Fort Martin, and Harrison) was surface applied at a rate of 1,200 metric tons/ha on an acidic minesoil representative of

AML in northcentral West Virginia. Details of the original experiment including design and chemical data were reported elsewhere (Bhumbla et al 1991). The minesoil on the site was classified as toxic with reduced sulfur averaging slightly over 1 percent and a pH averaging 3.4. Sustained, successful revegetation could not be established on this site despite repeated previous attempts using conventional methods. Due to the high pyritic sulfur content of the minesoil, massive fly ash application appeared to be a favorable solution in revegetating this site.

All 3 sources of the fly ash used in this study were from northcentral West Virginia and were classified as non-hardening, class F ash. Two of the fly ashes (Fort Martin and Harrison) were alkaline in reaction with pH values of 11.4 and 11.3, respectively. The third fly ash (Albright) was only slightly alkaline with a pH of 8.4 (Bhumbla et al 1991).

The experimental design was a randomized complete block with 4 treatment groups (3 fly ash sources and minesoil control) and 4 replications. Plot sizes were 5 m by 40 m. The fly ash was transported to the site by truck and spread onto the experimental plots by bulldozer. Total fly ash depth, at the rate of 1,200 metric tons/ha, amounted to approximately 18 to 20 cm (7 to 8 inches). Minesoil control plots received agricultural lime at a rate of 11.8 tons/ha (4.8 tons/acre), which was the amount recommended by the soil testing laboratory to neutralize acidity in the top 15 cm (6 inches) of spoil. Following application of lime and fly ash, each plot was disced lengthwise and hay mulch was applied at a rate of 5 tons/ha (2 tons/acre) using a mulch blower. Complete fertilizer (10-20-20) was then broadcast spread to all plots at a rate of 560 Kg/ha (500 lbs/acre) followed by discing on contour. All plots were then broadcast seeded with a mixture of wheat (*Triticum aestivum*), Kentucky-31 tall fescue (*Festuca arundinacea*), and two inoculated legumes, Weevilchek alfalfa (*Medicago sativa*) and Empire birdsfoot trefoil (*Lotus corniculatus*), followed by the application of another 5 tons/ha hay mulch.

Vegetation growth after the first year was highest on the Albright and minesoil control plots (Bhumbla et al 1991). Vegetation growth was very low for the first year on the Fort Martin and Harrison plots due to high levels of soluble salts and high concentrations of boron. 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 control plots due to decreasing pH as a result of pyrite oxidation (Bhumbla et al 1991).

In May 1990, 3 years after fly ash application, both minesoil control plots and fly ash-treated plots were analyzed for a number of physical properties using undisturbed soil clods and undisturbed soil cores (7.62 by 7.62 cm). Clods were taken at 2 depths (0-8 cm and 20-28 cm) on the fly ash-treated plots. The lower depth corresponds to the minesoil beneath the fly ash. Clods were taken at 0-8 cm and 8-16 cm depths on the minesoil control 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 0-8 cm fraction only. Undisturbed soil cores were used to determine the following physical properties: 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 particle-size distribution (Gee and Bauder 1986), particle density (Blake and Hartge 1986), aggregate stability (Kemper and Rosenau 1986), and bulk density and total porosity of minesoil materials using a Varsol method (Sobek et al 1978). Infiltration rates were determined in the field using single-ring infiltrometer (Bouwer 1986, Tricker 1978).

Results and Discussion

Particle Density

The particle density of the fly ash materials was significantly lower than that of the minesoils (See Table 1). Particle density values were also significantly different among the fly ash sources. Other investigators have also found a high degree of variability in particle density among fly ash sources (Page et al 1979, Adriano et al 1980). Variability in fly ash particle density is largely a function of its chemical composition (mainly the percentage of iron oxides present) and physical properties of the individual particles comprising the fly ash matrix (percentage of cenospheres, plerospheres, and amorphous materials present). Thus, particle density of fly ash is expected to be highly variable from one source to another depending on the chemical composition of the coal used, the combustion process, and methods of collection (emission control devices). The particle density in the surface 8 cm of the minesoil control plots (See Table 1) was significantly lower than at the 8-16 cm depth, probably due to large amounts of residual organic matter originating

Table 1. Particle density of fly ash and minesoil materials.

TREATMENT	PARTICLE DENSITY (Mg/m^3)
ALBRIGHT FLY ASH (0-8 cm)	2.30a*
FORT MARTIN FLY ASH (0-8 cm)	2.39b
HARRISON FLY ASH (0-8 cm)	2.66c
MINESOIL UNDER ALBRIGHT FLY ASH (20-28 cm)	2.69d
MINESOIL UNDER FORT MARTIN FLY ASH (20-28 cm)	2.71de
MINESOIL UNDER HARRISON FLY ASH (20-28 cm)	2.70de
MINESOIL CONTROL (0-8 cm)	2.69d
MINESOIL CONTROL (8-16 cm)	2.73e

*means with the same letter are not significantly different at the 0.05 level using analysis of variance statistical procedure.

from previous vegetation cover and hay mulch. The lower particle density of fly ash should result in increased erosion potential (by both wind and water) of these materials when surface applied to land.

Particle-size Distribution

Fly ash particle-size distibution was also significantly different from the minesoil (See Table 2). Fly ashes were very low in clay (<5%) and very high in silt (65-80%). This also suggests a high erosion potential for the fly ash due to a lack of cohesion from the low clay content, and to 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), which has been found by others (Wischmeier and Mannering 1969) to behave more like silt than sand from an erodibility perspective .

There were also significant differences in particle-size distribution among minesoil materials (See Table 2). Minesoil under fly ash-treated plots was generally higher in sand and lower in clay, while minesoil in the control plots, which did not receive fly ash, generally contained less sand and more clay. There appeared to be a definite trend in decreasing amounts of sand and increasing amounts of clay

Table 2. Particle-size distribution of fly ash and minesoil materials.

TREATMENT	%SAND	%SILT	%CLAY
ALBRIGHT FLY ASH (0-8 cm)	17.72b*	77.44a	4.84d
FORT MARTIN FLY ASH (0-8 cm)	28.69a	66.67b	4.64d
HARRISON FLY ASH (0-8 cm)	18.77b	78.05a	3.18d
MINESOIL UNDER ALBRIGHT FLY ASH (20-28 cm)	20.91ab	36.27cd	42.82b
MINESOIL UNDER FORT MARTIN FLY ASH (20-28 cm)	29.27a	37.00cd	33.73c
MINESOIL UNDER HARRISON FLY ASH (20-28 cm)	28.15a	42.44c	29.42c
MINESOIL CONTROL (0-8 cm)	13.94b	33.85d	52.21a
MINESOIL CONTROL (8-16 cm)	15.68b	36.45cd	47.87ab

*means in columns with the same letter are not significantly different at the 0.05 level using analysis of variance statistical procedure.

corresponding to decreasing pH, suggesting acid sulfate weathering of minerals due to pyrite oxidation in the spoil. This same trend was 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 1991), and, as a result, increase in clay did not occur in minesoils under the alkaline fly ash-treated plots.

Aggregate Stability

Substantial differences in the water stability index were observed between fly ash and minesoil materials, as well as among the fly ash sources (See Table 3). 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 aggregating agent in the fly ash materials was calcium carbonate ($CaCO_3$), as determined by laboratory analysis. The highly alkaline fly ashes (Fort Martin and Harrison) exhibited very high percentages of aggregation and aggregate stability due to the abundance of calcium (Bhumbla et al 1991). Albright fly ash, in contrast, exhibited much lower percent aggregation and aggregate stability due to much lower levels of calcium. The primary aggregating agent of the minesoil materials was clay size particles. There was also evidence of organic contributions to aggregation in the surface layer of the minesoil

Table 3. Aggregate stability of fly ash and minesoil materials by wet sieving method.

TREATMENT	WATER STABILITY INDEX
ALBRIGHT FLY ASH (0-8 cm)	25.72c*
FORT MARTIN FLY ASH (0-8 cm)	94.00a
HARRISON FLY ASH (0-8 cm)	94.52a
MINESOIL UNDER ALBRIGHT FLY ASH (20-28 cm)	40.34bc
MINESOIL UNDER FORT MARTIN FLY ASH (20-28 cm)	40.15bc
MINESOIL UNDER HARRISON FLY ASH (20-28 cm)	42.69b
MINESOIL CONTROL (0-8 cm)	50.05b
MINESOIL CONTROL (8-16 cm)	46.13b

*means with the same letter are not significantly different at the .05 level using analysis of variance statistical procedure.

controls, as exhibited by granular structure and the results of sodium hydroxide (NaOH) treatment of the aggregates.

Bulk Density and Total Porosity

Bulk density also differed significantly among the fly ash and minesoil materials (See Table 4). Bulk density in the surface 8 cm was significantly lower in the fly ash compared to the minesoil control. This agrees with others (Adams et al 1971, Plass and Capp 1974, Chang et al 1977, Page et al 1979, Adriano et al 1980) who found 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 (See Table 1) and not related to the relative packing of the soil particles. This is supported in that all 3 fly ashes exhibited greater total porosity than the minesoil control (See Table 4). 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 among the minesoil materials (See Table 5) showed significantly lower bulk density in the surface 8 cm of the minesoil control plots than in either the 8-16 cm depth of the control or in minesoils under the fly ashes. This lower bulk density in the surface layer of the control plots was probably the result of organic residues, as well as the greater effect of freeze-thaw and wet-dry cycles at this depth. It should also be noted that the minesoil contained 10-20% rock fragments by volume, as reflected by the differences between total bulk density and the bulk density of the less than 2 mm fraction (See Table 5). Fly ash, on the other hand, while containing some water-stable aggregates greater than 2 mm in size, did not have any rock fragments.

Table 4. Bulk density and total porosity of fly ash and minesoil materials for the 0-8 cm fraction as determined from undisturbed soil cores.

TREATMENT	TOTAL BULK -DENSITY (Mg/m^3)	< 2 mm BULK DENSITY (Mg/m^3)	TOTAL POROSITY (%)
ALBRIGHT FLY ASH	1.17a*	1.17a	52.43b
FT.MARTIN FLY ASH	1.12a	1.10a	57.00a
HARRISON FLY ASH	1.30b	1.20ab	54.46ab
MINESOIL CONTROL	1.36c	1.23b	46.83c

*means in columns with the same letter are not significantly different at the 0.05 level using analysis of variance statistical procedure.

Table 5. Bulk density and total porosity of minesoil materials as determined from undisturbed soil clods using non-polar liquid (Varsol) method.

TREATMENT	TOTAL BULK DENSITY (Mg/m^3)	<2 mm BULK DENSITY (Mg/m^3)	TOTAL POROSITY (%)
MINESOIL CONTROL (0-8 cm)	1.39a*	1.26a	45.77a
MINESOIL CONTROL (8-16 cm)	1.61c	1.37bc	38.76c
MINESOIL UNDER ALBRIGHT FLY ASH (20-28 cm)	1.58c	1.42c	39.27c
MINESOIL UNDER FT.MARTIN FLY ASH (20-28 cm)	1.62c	1.46c	38.49c
MINESOIL UNDER HARRISON FLY ASH (20-28 cm)	1.50b	1.32ab	42.85b

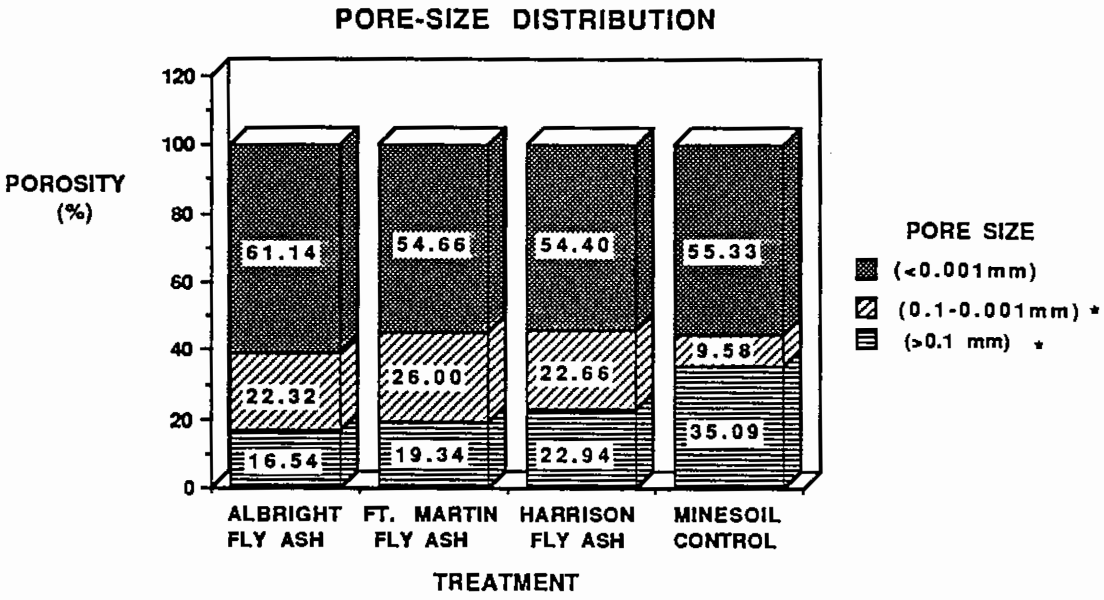
*means in columns with the same letter are not significantly different at the 0.05 level using analysis of variance statistical procedure.

Pore-size Distribution

Fly ashes had significantly less macropores (>0.1 mm) and significantly more mesopores (0.001-0.1 mm) than the minesoil control (See Figure 1). The amount of macropores in the fly ash 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. 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. The larger percentage of macropores in the minesoil control plots appeared to be the result of large, interaggregate pores and voids in the surface layer. The surface layer of the minesoil control plots could be described as loose and friable, as was exhibited by its relatively low bulk density (See Table 5). The amount of mesopores (0.001-0.1 mm) was more than 2 times greater in the fly ashes than in the minesoil (See Figure 1). The amount of micropores (<0.001 mm), however, was not significantly different among any of the treatments.

Infiltration Rate

Infiltration rate was significantly greater on the minesoil control plots than on the fly ash plots (See Table 6). Higher infiltration rates on the control plots may be a reflection of the larger percentage of macropores in these



* Fly ashes vs Minesoil control are significantly different at the .05 level using analysis of variance statistical procedure.

Figure 1. Effective pore-size distribution of fly ash and minesoil as determined by water desorption method.

Table 6. Infiltration rates determined using single-ring infiltrometer.

TREATMENT	INFILTRATION RATE (cm/hr)
ALBRIGHT FLY ASH	2.4b*
FT.MARTIN FLY ASH	11.4b
HARRISON FLY ASH	6.0b
MINESOIL CONTROL	44.4a

*means with the same letter are not significantly different at the .05 level using analysis of variance statistical procedure.

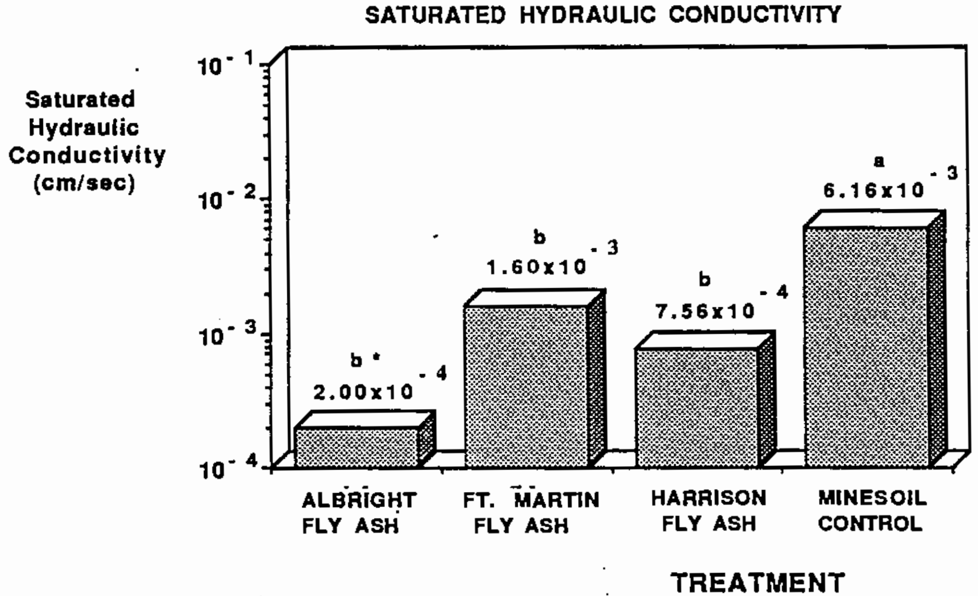
plots. The much higher intake rate on the minesoil plots also indicates that there must be substantial continuity among the larger macropores. The low infiltration rate on the Albright plots (See Table 6) corresponds to the low percentage of macropores in the Albright fly ash (See Figure 1). The infiltration rates for Harrison and Fort Martin plots were intermediate (See Table 6), as were the percentages of macropores on these plots (See Figure 1).

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity (Ksat) values (See Figure 2) show the same trend as infiltration rates (See Table 6). The minesoil control plots had significantly greater Ksat values than any of the fly ash treatments. These higher values may also be related to the differences in pore-size distribution between the fly ashes and minesoil (See Figure 1). Ksat values, although showing some degree of variability, were not significantly different among the fly ash treatments. Differences in Ksat and infiltration values were not statistically significant among the fly ash sources due to large variability among the samples and to the low number of samples analyzed (16 cores/treatment). Soil hydraulic properties are often notorious for high variability among measurements, thus requiring a large number of samples to reveal statistically significant differences.

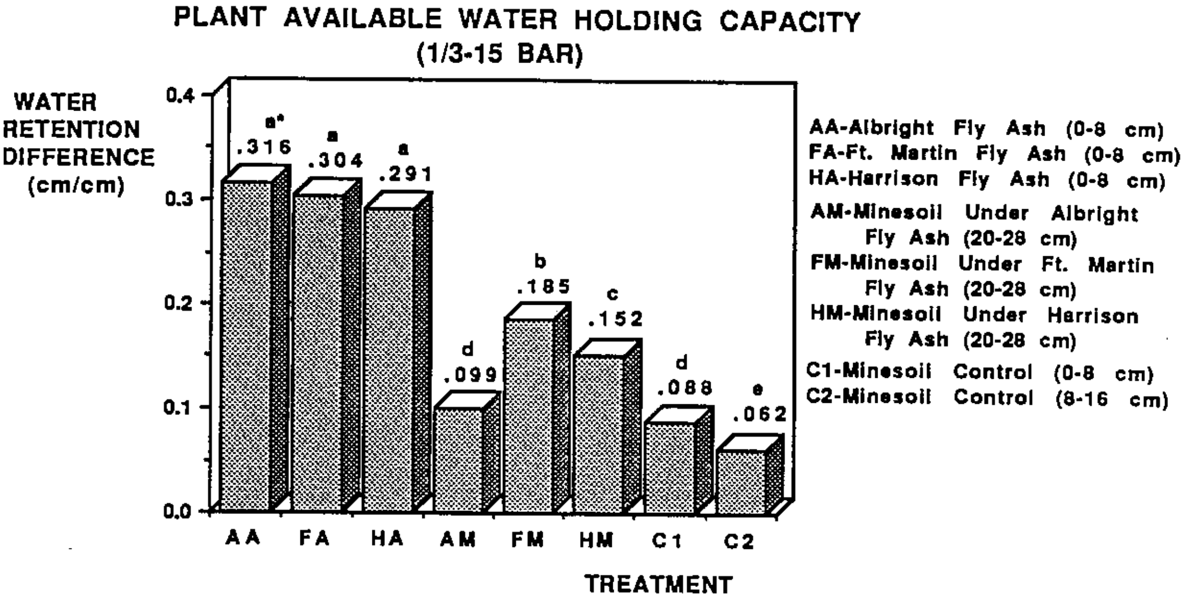
Moisture Retention

Plant-available water holding capacity was significantly different between the fly ashes and minesoil control (See Figure 3). Plant-available water holding capacity averaged more than 3 times higher in the surface 8 cm of the fly ash plots than in the minesoil control plots. 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. Plant-available water holding capacity has most commonly been defined as the moisture retained by the soil at tensions between 33 and 1,500 kPa (1/3 to 15 bar). The moisture retention characteristics of a soil are largely a function of the pore-



*means with the same letter are not significantly different at the 0.05 level using analysis of variance procedure.

Figure 2. Saturated hydraulic conductivity of the 0-8 cm fraction using undisturbed soil cores.



*means with the same letter are not significantly different at the .05 level using analysis of variance procedure.

Figure 3. Plant available water holding capacity of fly ash and minesoil materials.

size distribution with plant-available water retention being mainly a function of the total porosity found in the 0.0001 to 0.1 mm pore-size range. With the pore-size classifications used in this study, plant-available water would be roughly proportional to the percentage of pores ranging from large mesopores (0.1 mm) to large micropores (0.0001 mm) in size. The minesoil control plots had a very small percentage of pores occurring in this size range, and thus had very low moisture retention values (See Figure 3). On the other hand, the fly ashes had a large proportion of pores occurring in the meso and large micropore range, and therefore had much higher moisture retention values.

Moisture retention values were also significantly different among the minesoil materials (See Figure 3). The highest moisture retention was in the minesoils directly under the alkaline fly ashes (Fort Martin and Harrison). These higher values may have resulted from 2 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^{++} and Mg^{++}, which were being leached out of the fly ash layer (Bhumbla et al 1991). Both 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 little, if any, roots were observed to enter the minesoils under the Albright plots. 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 (1991). 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 minesoil to aid in flocculation. Thus, moisture retention of the minesoil under the Albright fly ash was not much different than that of the minesoil control plots.

Summary

The results of this study revealed substantial differences between fly ash and minesoil for most of the physical properties examined. Overall, fly ash appeared to be superior to minesoil for most of the physical properties which affect plant growth. Bulk density of the fly ash was significantly lower than that of the 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 pores in the 0.0001 to 0.1 mm size range, which are very important in determining water holding capacity. Based on this, it was not surprising that plant-available moisture retention was more than 3 times higher in the fly ashes than in the minesoil. This suggests that vegetation growing on fly ash would be much less susceptable to drought stress.

The fly ashes examined in this study exhibited lower infiltration rates and lower saturated hydraulic conductivity than the minesoil. Lower water-conductivity values, along with fine particle size and low particle density, suggest that fly ash, when surface applied, 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 that 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 land reclamation. These advantages include greatly increased water holding capacity, greater total porosity, medium soil texture, and lower bulk density. All of these are very important factors affecting plant growth. Although fly ash can greatly improve these physical properties, it may also require more careful planning and management practices due to the potential problems of boron toxicity and high soluble salts as well as due to its inherent erosion potential.

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