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Effects of Fly Ash-Induced Textural Changes on Soil Water Retention and Soil Strength

BY

LAWRENCE DON WATSON ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

in

SOIL PHYSICS

DEPARTMENT OF SOIL SCIENCE

EDMONTON, ALBERTA

FALL, 1994

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L.D. Watson
8407-69 Avenue
Edmonton, Alberta
T6E 0R5

October 4, 1994

"This," he said, handling it, "is a stone, and within a certain length of time it will perhaps be soil and from the soil it will become plant, animal or man."

Hermann Hesse
Siddhartha, 1951

UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Effects of Fly Ash-Induced Textural Changes on Soil Water Retention and Soil Strength" submitted by Lawrence Don Watson in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE IN SOIL PHYSICS.

D.S. Chanasyk

Donald J. Pluth

D.J. Pluth

W J Hastie

J.W. Hastie

I.A. Campbell

September 29, 1991

DEDICATION

For Linda,
for Isaac and Tirzah.

To the memory of my father,
Robert Gordon Watson

Abstract

Fly ash (FA) is a byproduct of coal-fired power generating stations. FA is composed predominantly of silt-sized spherical particles. Several studies have been conducted into the potential use of FA as a soil amendment from a chemical point of view. However, since relatively few have accounted for changes in soil physical characteristics resulting from FA-induced textural change, this study was conducted to determine how such textural changes would alter soil water retention and soil strength.

Changes in soil water retention were monitored for two soil materials, a silty clay surface horizon disturbed by mining practices, and a sandy loam subsoil. FAs used were collected from two generating sites which were fired with coal from different mines, located approximately 80 km west of Edmonton, Alberta. Each soil material and each FA were mixed to rates of 5, 10, 20, 40, 60 and 80% FA per total volume. Soil water characteristic curves were determined for each soil material, FA and soil/FA mixtures using standard pressure plate methods. At any pressure, addition of FA to silty clay consistently decreased water retention, with differences between FA mixtures increasing as pressure increased. Sandy loam soil water retention increased as amendment rate increased up to pressures of 0.3 MPa and higher where water retention began to decrease. Resulting soil available water holding capacities (AWHC) for both soils increased dramatically as FA rate increased, indicating the relationship between water retention and artificially induced textural change.

Soil strength was determined using modulus of rupture on FA:soil mixtures described above, as well as mixtures using a third, coarser FA. Dramatic reductions in soil strength were evident for both soils when amended with FA from any source. FA additions of only 5% decreased soil strength from the inherent values of silty clay to an average of 77%

of its inherent strength, and of sandy loam to an average of 23%. Mixture strengths were least for rates between 20 and 40. It is concluded that textural change caused initial strength decreases, but other factors were likely responsible for subsequent strength increases. Soil tilth may be improved by adding FA, but factors such as trafficability, and potential toxicity and strength effects on plants must still be considered before FA is routinely used as a soil amendment.

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I recognize the contributions of many towards my successful completion of this thesis. Please allow me to openly thank a very few of them. Dr. David Chanasyk as a very patient and able supervisor, and as a friend. TransAlta Utilities for financial assistance. Ms. Kelly Ostermann and Chung Nguyen for their technical assistance. My fellow Soils graduate students, especially my friends Ms. Qualizza and Messrs. Dell and Harms, for constant spark. But most to my family, Linda, Isaac and Tirzah Watson; Mrs. June Watson; Ms. Ruthann Watson and Ms. Marnie Hill; and Mrs. Grace Kumm for standing close behind me, offering support as only a family can. Thank you, all.

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1. Introduction

1.1 Fly ash as a waste product

Fly ash is a byproduct of coal-fired power generation. It is typically collected by electrostatic precipitation from on-site stack gases. Annual FA production in the United States is estimated to be approximately 100 million tonnes (Straughan *et al.*, 1978; NRC, 1980). Alberta's annual production is estimated to be approximately 3 million tonnes. Inherent physical and chemical properties of this widely produced industrial byproduct indicate that it should not only be dismissed as waste, but could be possibly be used again as a raw material, for instance, as a soil amendment.

FA is a predominantly spherical, silt-sized ferro-alumino silicate material. Its chemical composition is influenced by the operating conditions of the power generating station, by the type and geographical location of the fuel coal and FA particle size (Adriano *et al.*, 1980). Elemental concentrations of FA reflect, although they are elevated above, those of the fuel coal, possibly due to carbon and nitrogen losses during combustion (Adriano *et al.*, 1980).

FA's silty texture, high silicate content, and Ca-induced pozzolanic properties have led to several construction-related uses (e.g. cement additive; asphalt filler; roadbed and non-agricultural soil stabilizer) (Thompson and Ness, 1983; Joshi and Nagaraj, 1987) as well as a possible role in the manufacture of ceramics (Kulkebov *et al.*, 1990; Barnes and Anderson, 1991). However, since such uses consume only a small fraction of the quantities of FA produced (approximately 10 to 20%), disposal by refilling open pits resulting from mining activities, or by stockpiling remain ongoing practices.

In their summary of existing research on the effect of FA on physical and chemical characteristics of agricultural soil, Adriano *et al.* (1980) reported that using unweathered FA would affect all common soil physical and chemical characteristics, with the exception of plant available water (Table 1.1). Application rates in cited studies generally did not exceed 25% by volume, although Chang *et al.* (1977) did report results up to and including 50% by volume. Summarized results were grouped without regard for initial soil texture. Adriano *et al.* (1980) ascribed unfavorable changes in the soil's chemical equilibrium as the most limiting factor regarding FAs utilization. A subsequent review article by Sharma *et al.* (1989) supplied several findings which opposed those cited by Adriano *et al.* (1980). However, information in such review articles indicate only perceived general trends; do not account for results opposing the proported trend; and provide limited insight into potential uses of FA, such as the use of FA as a textural amendment for soil. As a result specific questions pertaining to particular soil textures or precise amounts of fly ash to be added for a particular purpose remain unanswered.

In areas where precipitation is a limiting factor, any practice which would avail more water to plants could increase crop yields. Several authors (e.g. Salter and Williams, 1965; Rivers and Shipp, 1978) reported a direct relationship between percent silt in a soil and increases in available water holding capacity (AWHC). If the predominantly silt-sized FA acts as a soil textural amendment, then we should expect an AWHC response for the FA-amended soil similar to that as a silty soil.

1.2 Problem soils in Alberta

Approximately 2 million ha of Alberta soil are susceptible to crusting (Arshad and Mermut, 1988), often attributable to high percent silt and exchangeable Na and Mg levels, and low organic matter contents. The weak structure of such soils promotes surface sealing after rainfall, which in turn leads to poor seedling emergence. Surface sealing also promotes decreased infiltration and increased surface runoff, thereby increasing soil erosion. The elevated Ca levels of FA may inhibit soil aggregate collapse and subsequent crusting, if the effect of the Ca addition overcompensates the possible negative effect of an enhanced silt-sized fraction on crusting. Measuring soil strength should indicate which effect, that of CA or that of silt, dominates.

Even with positive results regarding the soil physical condition, such practices are not without risk. Several investigations into potential groundwater contamination by soluble FA constituents in runoff and leachate have been initiated (e.g. Theis *et al.*, 1989; Chapelle, 1980; Kopsick and Angino, 1981). And, although FA has been suggested as a supplier of micronutrients for plants, toxic effects of excessive FA amendment have been widely reported (e.g. Plank *et al.*, 1975; Aitken and Bell, 1985). Therefore any benefits must be weighed against recognized and potential hazards.

1.3 Study objectives

This study was undertaken to address two environmental concerns currently facing Alberta and other areas, namely the disposal of FA produced by coal-fired power generating stations; and problem soils, with the intent of resolving both issues with the use of FA as a soil amendment. Two select soil physical properties (soil water retention and soil strength) were chosen for study. The study of a full range of amendment rates will provide insight whether FA can improve these physical properties, whether these physical properties are affected by changing texture; and therefore whether there may be uses for FA in addition to those already existing. Any relationship that occurs between AWHC and soil strength as a result of texture could also be determined. In combination with the widely studied chemical effects of FA, this study will provide a broader basis upon which to make management decisions for use of FA as a soil amendment.

Table 1.1. Potential and observed effects of fly ash on physical, chemical and microbiological properties of soils compared with that of a non-treated typical agricultural soil (adapted from Adriano *et al.*, 1980).

Soil properties	Typical agricultural soil[1]	Soil treated with Weathered fly ash	Soil treated with Unweathered fly ash
Bulk density	1.3 Mg m^{-3}(avg.)	Lower	Lower
Aeration	High	Higher[2]	Higher[2]
Water holding capacity	High	Higher	Higher
Plant available water	High	None to little effect	None to little effect
Hydraulic conductivity	High	Increased by low rates; decreased by high rates	Increased by low rates; decreased by high rates
Modulus of rupture	High	Lower	Lower
Wind erosion	Resistant	More susceptible[2]	More susceptible[2]
Water erosion	Resistant	More susceptible[2]	More susceptible[2]
Nutrient content	All nutrients present	Very low N; others present	Very low N; others present
Nutrient availability	Balanced supply of all nutrients	Deficient in N; maybe deficient in P, Zn, Cu, Mn, etc.	Deficient in N; maybe deficient in P, Zn, Cu, Mn, etc.
pH	6.0-7.5	<6.0 to ≅ 8.0	<6.0 to ≅ 12.0
CEC	Medium to high	Lower[2]	Lower[2]
Toxic salts	None	None	B and soluble salts of Ca, Mg, Na, and K
Salinity	Low	Moderate	High but diminished after 2 to 3 years
Temperature	Adequate	Higher[2]	Higher[2]
Microbial activity	High	No effect[2]	Initially low[2]

[1] Mostly based on the knowledge of Adriano *et al.* (1980).

[2] Very limited or no reported data, but Adriano *et al.* (1980) feel very likely to happen.

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2. Alteration of soil water retention with fly ash addition.

2.1 Introduction

2.1.1 Fly ash as a power generation byproduct

Fly ash (FA), a byproduct of coal-fired power generating stations, is of sufficiently small particle size to be carried up the exhaust stack with the flue gas (Roy *et al.*, 1981). The particles are formed through the thermal decomposition or dehydration of inorganic minerals associated with the coal (Kopsick and Angino, 1981). FA consists of predominantly (70-90%) (Hodgson and Holliday, 1966) spherical silicate beads ranging in size from 0.01 to 100 µm (Davison *et al.*, 1974). It is typically collected by electrostatic precipitation from stack gases at the generating site and then sluiced to a settling pond, sluiced to smaller settling ponds where it is later excavated and landfilled, or transported in a slightly dampened state to some other disposal location (Hodgson and Holliday, 1966; Capp and Spencer, 1970). These disposal locations are usually an open pit resulting from mining activities, or a stockpile.

FA production in the United States in 1985 was estimated to be approximately 100 million tonnes (Straughan *et al.*, 1978; NRC, 1980). Present FA production in Alberta is approximately 3 million tonnes. The production of such large quantities of FA, and its inherent qualities (e.g. pozzolanic effects, high silicate content) has prompted its use in roadbed construction and non-agricultural soil stabilization, as a cement additive and asphalt filler (Thompson and Ness, 1983; Joshi and Nagaraj, 1987) and its possible use in the manufacture of ceramics (Kulkebov *et al.*, 1990; Barnes and Anderson, 1991).

FA can also have potential benefits as a soil amendment. Chang *et al.* (1977) noted that research into amendment potential of FA on agricultural soils had usually focused upon its chemical rather than physical characteristics. This bias has persisted.

2.1.2 Water Retention and Texture

The effect of changes in particle size distribution on soil water retention has been noted by several authors. In a survey of 27 English soils, Salter and Williams (1965) reported available water increases as soil texture changed from coarse to medium, and a general decrease in available water as texture changed from medium to fine. Similar results were presented for Alberta soils (Oosterveld and Chang, 1980), for Indian soils (Abrol *et al.*, 1969) and for Egyptian soils (Kandil *et al.*, 1976).

Available water holding capacity (AWHC) boundaries (upper: 0.01 MPa (sand) or 0.033 MPa (clay); and lower: (1.5 MPa)) indicate the suction range over which plants most readily obtain water from a soil. Kandil *et al.* (1976) reported sand and silt as the most significant fractions controlling AWHC. Shaykewich and Zwarich (1968) determined that clay and fine and very fine sand were significantly related to AWHC lower limits and that clay, organic matter and silt were significantly related to AWHC upper limits. Salter and Williams (1969) concluded that water held at the upper limit of available water was strongly negatively correlated with the percentage of coarse sand, but moisture retained at both upper and lower limits was correlated to percentage clay. Abrol *et al.* (1969) determined that the silt-size fraction was the major contributor to water held in the soil at 0.033 MPa, and that clay was positively correlated to that held at 1.5 MPa. However, Williams *et al.* (1982), using numerical and diagnostic methods, reported that although particle size distribution and field texture were consistently associated with the nature of the soil moisture characteristic curve, these properties must be considered in conjunction with the soil's pedality.

2.1.3 Water Retention Alteration using Fly Ash

Bhumbla (1991) observed an increase in moisture retention of mine spoils amended with 400 and 800 t/ha FA. In an experiment conducted with five soils ranging in texture from silty clay to sandy loam, Chang *et al.* (1977) found fly ash-amended soils retained more water than those unamended, especially at applied FA rates of 25, 50, and 100% by volume. However, AWHC of loam and sandy loam soils did not change due to FA application. Aitken and Bell (1985), testing coal FA from five different Australian power generating stations, reported increased AWHC for a sandy loam soil (12% clay, 82% sand) when mixed with FA, irrespective of source.

Adriano *et al.* (1980) noted the importance of parent coal composition and conditions during its combustion, efficiency of emission control devices, fly ash storage and handling, and climate in determining fly ash properties. The dependence of these factors upon geographic location requires that fly ash studies be conducted on a local, rather than global, basis.

The objectives of this study were to determine if the addition of fly ash to soil would alter soil texture and soil water retention characteristics. It was postulated that additions of fly ash would cause a soil textural change which in turn would alter the soil's water retention characteristics, and the effects would depend on soil texture, and type and amount of fly ash added.

The value of this research is an increased understanding of the effects on soil water retention that fly ash as a textural modifier may promote, and an enhancement of our understanding of fly ash as a soil amendment.

2.2 Materials and Methods

2.2.1 Soils

Two soil materials were collected from areas disturbed by mining activities at the Highvale mine, 80 km west of Edmonton. Silty clay surface material from a reclaimed Wabamun soil (Black Solodized Solonetzic "A" horizon; 2.6% organic carbon) had been collected in 1990 as a control for previous research (Lussier, 1994). Subsoil material (mine spoil "C" horizon; 0.0% organic carbon) was collected in 1992 from the mine highwall. These two soils were chosen to provide extremes in texture. As well, these silty clay and sandy loam soils present management problems (cloddiness and crusting, respectively) and thus would likely benefit from amendments.

2.2.2 Fly Ashes

Fresh, unweathered sub-bituminous coal fly ashes from two TransAlta Utilities power generating stations (Sundance and Wabamun), approximately 80 km west of Edmonton, Alberta, were tested. The generating stations are fired by coal from two different mines which are situated approximately 3 km apart and differ in age by approximately 10 years. Samples were collected in 1992 directly from on-site storage facilities in a dry state.

Sundance fly ash had a bulk density of 0.95 Mg m^{-3}, did not indicate the presence of calcium carbonate when tested with dilute HCl, and had a pH value of 12.5 (water). Wabamun fly ash also had a bulk density of 0.95 Mg m^{-3}, and did not indicate the presence of carbonates, and had a pH of 12.5.

2.2.3 Mixture Preparation

Both soils and fly ashes were first passed through a 2-mm sieve. Most of the incoherent FA passed the sieve without grinding. The soils required grinding and sieving to break aggregates to the acceptable 2-mm maximum size.

Each fly ash was mixed with each soil to achieve 5, 10, 20, 40, 60 and 80% FA on a volume basis. Final batch volumes were approximately 3 L. Several separate batches were mixed during the course of this study. Particle size analysis (PSA) was conducted on 3 replicates of each of the mixtures using the hydrometer method (McKeague, 1978). More precise measurements were conducted on 3 replicates of both FAs, using the McKeague's (1978) hydrometer method, plus sonic dry sifting for sand fractionation.

2.2.4 Physical Analyses

Water retention was determined according to Klute (1986), with the following modifications. Samples were thoroughly mixed with a spoon and carefully apportioned into plastic rings (dia = 5 cm; h = 0.5 cm) which rested on ceramic pressure plates. To ensure that preferential particle size redistribution was minimized, samples were dropped, rather than poured, from the spoon. Pressure plates (n=6), each containing one replicate of each soil, FA and sample mixture, plus an internal standard, were filled with distilled water such that samples were saturated from the bottom. Samples were left to equilibrate for 24 hours, extra distilled water added as required. After 24 hours, excess water was aspirated from the plates, which were then placed inside multiple-plate pressure vessels, three plates per vessel. These were pressurized to 0.01, 0.033, 0.067, 0.1, 0.3 and 1.5 MPa for 48 hours. Samples were then removed from the vessels, weighed to determine wet weight, oven-dried at 105° C for 24 hours, and then weighed again. Water content was calculated on a gravimetric basis.

Field capacity (FC) was assumed to occur at a pressure of 0.033 MPa for all samples of texture finer than sandy loam. Samples which were sandy loam or coarser were assumed to achieve FC at a pressure of 0.01 MPa (Hausenbuiller, 1985). Permanent wilting point (PWP) was assumed to occur at 1.5 MPa for all samples. Available water holding capacity (AWHC) was calculated as

$$AWHC = FC - PWP$$

2.2.5 Data Analysis

Water retention data were plotted with corresponding PSA data on a textural triangle (ACECSS, 1987). Continuous prediction across the entire triangular area was derived by kriging using the corresponding water retention/PSA points as a base. Kriging was performed with Surfer™ software (Golden Software, Inc., Golden, Colorado).

2.2.6 Statistical Analysis

Differences among treatments were evaluated using two methods of analysis. The first method drew comparisons between soils for a given FA rate at a given pressure; and among FA rates for a given soil and a given pressure. These comparisons were performed using Duncan's Range Test of SAS software (SAS Institute, 1992) to $P \geq 0.05$ level of significance.

The second statistical method was a sequence of analyses which compared the best-fit linear slopes of the water retention characteristic data. Initial tests on 3 data preparation methods indicated that ln-ln transformation provided a superior linear best-fit to either normal-normal, or ln-normal methods, based on R^2 values. The Clapp and Hornberger (1978) equation

$$\ln(\psi_m) = \psi_e - b * \ln(\theta) \qquad (1)$$

where ψ_m is matric potential, ψ_e is air entry water potential, θ is volumetric water/porosity, and b is the slope, was modified to use gravimetric water content instead of volumetric water/porosity.

Initially, slopes (i.e. "b") of equation (1) were compared by linear regression ($P>0.05$) using the General Linear Model (GLM) of SAS software (SAS Institute, 1992). Slopes proven not significantly different were then compared by a least significant means test (LSMEANS) ($P>0.05$).

Where slopes proved significantly different by GLM, an analysis of covariance presented by Milliken (1991) determined over what range of FA addition rate, if any, treatments were not statistically different. Data obtained using the best fit line of equation (1) are hereafter referred to as "predicted".

2.3. Results and Discussion

2.3.1 Texture

The surface horizon soil was classified as a silty clay (Table 2.1a). However, with a clay content of only 0.8% less, it would have classified as a silty clay loam. The subsurface horizon soil was classified as a sandy loam. Fly ashes were texturally classified as silt loam (Tables 2.1a and b). The effect of Wabamun FA on mixture texture was similar to that of Sundance FA, although textures of only

Sundance FA:soil mixtures are illustrated in Figure 2.1. Both FAs were positioned near the centre of the silt loam class on the textural triangle.

Since it may be expected that soil physical characteristics would not change dramatically with a change in clay content of only (in this case) 0.8% regardless of change in textural classification, and that a wide range of sand/silt/clay mixtures may be classified in the same textural class, caution should be used before predicting soil performance on textural class alone.

Textural change in the silty clay soil as a result of fly ash addition involved a modest increase in both sand and silt but a dramatic decline in clay (Figure 2.1 and Table 2.1a). Increases in the silt fraction of the sandy loam mixtures as percent FA increased were predominantly at the expense of the sand fraction (Figure 2.1 and Table 2.1b). Regardless of initial soil texture, soil:FA mixtures spanned three textural categories. Textural class change for silty clay soil mixtures was more rapid at low FA rates, but greatest at high FA rates for the sandy loam mixture. Mixtures textures lie in roughly a straight line, evident for both soils (Figure 2.1).

More precise analysis indicates slight differences in particle size between Sundance and Wabamun FAs (Table 2.1c). Compared to Sundance FA, Wabamun FA had greater percentages of classes of medium silt to very fine sand, at the expense of both coarser and, especially, the finer particles (fine silt and clay).

2.3.2 Soil Water Characteristic Curves

Soil water characteristic curves for silty clay and sandy loam soils were different from each other and from both fly ashes (Figure 2.2). The silty clay soil retained more water than did the sandy loam at all pressures, as would be expected for these soils. The FAs, which were similar to each other in texture, displayed similar soil water characteristic curves (Figure 2.2).

Of special note is the water retention of both FAs at low pressures (e.g. ≤ 0.033 MPa) where their water retention approximated that of the silty clay, and at high pressures (e.g. ≥ 0.3 MPa) where both FAs behaved more like the sandy loam (Figure 2.2). The poor ability of the FAs to retain water at higher pressures cannot be described on the basis of particle mass alone, on which the hydrometer method relies. One possible explanation for this poor water retention is the spherical shape of the FA particles. This geometric form provides the least possible surface area, and therefore less water may be retained than by the irregular shapes of naturally occurring sand particles.

Adding FA to the silty clay soil consistently decreased water retention, regardless of pressure. Also, as pressure increased, difference in water content among FA mixtures increased (Tables 2.2a and 2.3a). Stronger surface adsorptive forces of the clay fraction as compared to those of the silt-sized FA may explain these increased differences.

Fly ash increased water retention of the sandy loam as amendment rate increased up to, but not including, the highest pressures (e.g. 0.3 MPa) (Tables 2.2b and 2.3b). This would be expected if FA acts as a textural amendment and provides the water holding characteristics of a silty soil (Salter and Williams, 1965; Ambrol *et al.*, 1969; Kandil *et al.*, 1976; Oosterveld and Chang, 1980). Unlike the silty clay, sandy loam displayed changes in water content due to increasing FA rate which tended to decrease as pressure approached 0.3 MPa where it then increased. At these high pressures, particle geometry may play the most important role.

Campbell (1985) cautioned against relying only on textural data for predicting water characteristics, stating that pore size distribution, not particle size distribution, determines water retention. Particle packing, shape and orientation must also be considered. Preparation of pressure plate replicates was likely accompanied by some unavoidable particle settling when soil portions were dispensed. Also, saturation from the bottom, required to ensure minimum trapped air, was observed to lift the mixture and promote differential settling. Resulting replicate-specific pore space distributions may explain variations between similar treatments (e.g. 100% FA at 1.5 MPa, Tables 2.2a to 2.3b). Values at low pressures may also vary due to the nature of pressure plate procedures (Campbell, 1985).

Actual data and predicted characteristic curves for Sundance FA are presented in Figure 2.3. Wabamun data are si,ilar to the Sundance data. At the four lowest pressures Sundance FA and the silty clay soil have similar water retention (Table 2.2). This is presumably due to smaller average pore spaces than the relatively coarser sandy loam soil. As pressure increases, the larger pores, and the lack of OM associated with FA precipitated a decline in its water retention characteristic curve. By approximately 0.3 MPa, the effects of pore size are no longer a factor in water retention, as FA and the sandy loam soil showed similar water retention capabilities. By 1.5 MPa some other factor, perhaps particle geometry, has come into prominence as FA retained less water than the sandy loam.

The closeness of fit for the predicted equations to the data is apparent. R^2 values for the predicted silty clay, sandy loam and Sundance FA were 0.92, 0.75 and 0.92, respectively. The R^2 value for the sandy loam was the lowest due to the poor fit at the two lowest pressures tested (0.01 and 0.33 MPa). R^2 values for most treatments were greater that 0.90. We conclude that the modified version of equation (1) can be expected to predict, with reasonable accuracy, the soil water characteristic curve.

Clapp and Hornberger (1978) found that 'b' from equation 2.2.6(1) is related to soil texture. A steeper slope is an indication of the increased difference between FC and PWP of that mixture. Such a relationship was evident in this study (Table 2.4) although it followed a different trend. Where Clapp and Hornberger (1978) described an increasing 'b' moving from coarse to fine soils, in the present study 'b' increased as the texture mixtures moved towards silt loam, regardless of initial soil texture. This is consistent with the findings of Shaykewich and Zwarich (1968). The predicted characteristic curves for the two soils and two FAs are given in Figure 2.4.

Results of GLM analyses indicated that the closest relationships between slopes occurred when rates differed the least (Tables 2.5a to d, non-diagonally shaded areas). With the exception of Sundance FA/silty clay, the ln-ln transformed water characteristic curve slopes of all FA/soil mixtures were not significantly different unless FA rates differed by more than 20%. An exception was the Sundance FA/silty clay mixture, where a close relationship existed between rates up to 60%. These results indicate that typically at least 20% FA is required before the changes in pore and particle sizes, shapes and geometeries influence the magnitude of water retention, regardless of pressure.

Subsequent LSMEANS analysis indicated that rate differences of up to 20% could commonly provide similar overall water release characteristics of a soil/FA mixture, not just similar magnitudes of change. Rate differences greater than 20% were significantly different for all FA/soil mixtures (Tables 2.5a to d, stippled area). Thus we expect that by adding 20% FA (v/v) to a soil (or soil/FA mixture) will significantly influence the amount of water which that soil (or mixture) will hold.

2.3.2.1 Field Capacity

Both FAs displayed similar trends in FC for both soils as FA rate increased (Figures 2.5a and b). Lowest FCs were associated with highest sand content, moderate values with highest silt content, and highest values with highest clay content. Despite similarities in the effects on FC for a given soil between FAs, FC trends between soils for increasing FA was opposite for the two soils. As FA rate increased, FC of the silty clay soil mixtures decreased slightly, from mid-30% to low-30% values (Table 2.3). This accompanied the textural shift of increased sand and silt fractions at the expense of the clay (Table 2.1). In contrast, field capacity for the sandy loam treatment increased dramatically from mid-teen values near 0% FA, to low 30% values at 100% FA (Table 2.6b), associated with an increased silt content nearly totally at the expense of the sand fraction (Table 2.1).

2.3.2.2 Permanent Wilting Point

The trend in PWP (1.5 MPa) caused by changing percent FA was similar for both soils. However, there were differences between the soils in the magnitude of the soil water contents at that pressure. Measured values (Table 2.6a and b) and values predicted by kriging (Figures 2.6a and b) were similar regardless of fly ash. Both soils retained least water, approximately 3 to 4% (gravimetric), for loam textured mixtures (ACECSS, 1987), or approximately 50% sand and 10% clay. Moving towards this textural class, PWP decreased from approximately 18% for high clay mixtures, and from approximately 8% for high sand mixtures. These trends are in agreement with Chang *et al.* (1977).

PWP for the silty clay soil decreased dramatically as the FA rate increased from 80% to 100% (Table 2.6a). Up to 80% fly ash, the average water content percent decrease for every unit increase in percent Sundance FA was 0.52, and the incremental changes in PWP were relatively constant. From 80% to 100% the decrease was 3.1% per unit percent Sundance FA increase. For Wabamun FA, the average water content decrease was 0.36% per unit percent FA increase for the 0% to 80% FA range, but a 3.5% percent decrease per unit percent FA increase from 80% to 100%.

Incremental decreases in PWP for sandy loam mixtures were initially large for 5% FA (Sundance: 2.4%; Wabamun: 1.5%), then decreased to lowest incremental changes at mid-FA rates (Table 2.6b). Highest Sundance FA rates caused PWP to decrease by large increments (-1.7%), while Wabamun FA increased water retained (0.4%). Average water retention change for the 80 to 100% range was 0.84% and 0.77% per unit percent FA change for Sundance and Wabamun FA, respectively.

2.3.2.3 Available Water Holding Capacity

The AWHC of the FAs were similar, ranging from approximately 28% to 31%. The effects of both FAs on the AWHC of silty clay soil were also similar (Table 2.6a). Up to 80% FA, nearly equal decreases in FC and PWP led to similar AWHCs of approximately 17.5%, regardless of FA or addition rate. However, pronounced AWHC increases promoted by FA addition were evident for the sandy loam, and AWHCs were lower for the Wabamun FA (Table 2.6b). Over the entire range of tested rates, Sundance FA increased water retention a total of 16.4%, and Wabamun increased a total of 20.9%. These trends are the result of increased water retention at FC due to increased FA rate, increases which over-compensated the effects of FA at PWP. Although the magnitude and pattern was different for the two FAs, the continual increases for sandy loam/FA mixtures demonstrates the ability of FA to increase AWHC.

2.3.3 The Relationship of Texture and Water Retention

Highest AWHCs correspond to soil:FA mixtures with highest amounts of FA (Figures 2.7a and b). Highest values of AWHC tend to reflect low clay and sand contents. This follows the predictions for soil by Ambrol *et al.* (1969), Kandil *et al.* (1976), Oosterveld and Chang (1980) and Salter and Williams (1965). The close relationship of silt-sized fraction and AWHC is in agreement with Shaykewich and Zwarich (1968).

For textures coarser than silt loam (100% FA, Table 2.1) a negative relationship between AWHC and percent sand existed, as did a positive relationship between AWHC and percent silt. For textures finer than silt loam, AWHC was positively related to both sand and silt, but negatively related to clay.

That the incremental water content differences in silt loam soil were most highly pronounced from 80% to 100% FA, and then only at high pressures, may be explained by the effect of organic matter (OM) content. The dramatic decrease in water retained at the highest rate suggests that texture is not the only relevant parameter. Several authors (Shaykewich and Zwarich, 1968; Salter and Williams, 1969; Williams *et al.*, 1983) included OM into their discussions on soil water retention characteristics of soil. Salter and Williams (1969) stated that the inclusion of OM in their regression analysis generally improved the fit to the data, but offered no explanation for the observed effects. Shaykewich and Zwarich (1968) determined that OM was, along with percent clay, the most important factor in determining FC and PWP under field conditions. In the present study using disturbed samples, OM may not contribute noticeably to water retention if the combined mineral/FA fraction can adequately attract water to its surface at low pressures (e.g. FC). This supposition is supported by Hudson (1994) who found that rates of change in water retention due to OM content differed markedly between FC and PWP. Although increased OM content promoted increased water retention at both FC and PWP, the rate of increase for PWP was smaller than that of FC. In this study, one would expect FC, PWP and AWHC to decline as FA rate increased due to OM decrease.

A silty clay soil will retain more water than a sandy loam, regardless of the FA with which it is mixed (Tables 2.2 and 2.3). Sundance FA promoted greater water retention than Wabamun FA, regardless of the soil with which it is mixed, likely due to its higher fine silt and clay contents. FA-amended silty clay soils held more water than FA amended sandy loam soils. Only when FA rates reached or exceeded 60% did the AWHCs of sandy loam mixtures approach those of those of the silty clay mixtures.

Water retention of silty clay soil mixed with Sundance and Wabamun FA (Tables 2.2a and 2.3a, respectively) diminished at all pressures as FA rate increased. In contrast, the sandy loam soil mixed with either Sundance and Wabamun FA had increased water retention at all pressures as FA rate increased.

Silty clay soil did not exhibit any obvious changes in pressure-specific water retention as a function of FA used (Table 2.7a). Of ninety-six Sundance/Wabamun FA comparisons at 8 rates and 6 pressures, only twenty were significantly different. Sundance FA soil mixtures tended to hold less water at low pressure (0.01 MPa) at mid to high FA rates. Wabamun FA soil mixtures held less water at mid pressure (0.1 to 0.3 MPa) and mid to high rate. Only two of eight rates displayed any significant differences among AWHCs, the lower values found as a result of Sundance FA (Table 2.7a).

Sandy loam mixtures (Table 2.7b) on the other hand, tended to retain more water if mixed with Sundance rather than Wabamun FA, especially at mid pressure (0.033 to 0.3 MPa) and mid to high FA rate. AWHC was also greater for Sundance FA, the differences most pronounced at lower FA rates. Both effects are likely due to the slightly finer texture of the Sundance FA than the Wabamun FA.

Considering Sundance FA mixed with two soils (Tables 2.7a and b), soil type is the predominant factor in water retention, as water retention was consistently higher at all pressures and FA rates in silty clay mixtures as compared to sandy loam ones. Similar results are indicated for soil mixtures with Wabamun FA (Tables 2.7a and b). Only at highest FA rates did the AWHCs of the sandy loam soil approach or exceed the AWHCs values of the silty clay at equivalent FA rates.

2.4 Conclusions

Texture and water retention, which depends upon texture, of silty clay and sandy loam soils were changed by FA addition. Increasing the quantity of FA in a soil effectively shifted soil texture to silt loam, regardless of the initial soil texture. Therefore the applicability of fly ash as a textural modifier was proven.

Accompanying this textural shift were statistically significant changes in water retention at all imposed pressures. AWHC tended to increase as texture approached that of FA, silty loam. however, amendment rates of 20% or greater were required before increases began to differ statistically.

Statistical differences between the effects of the two FAs on FC, PWP and AWHC occurred occasionally, but followed no discernible trend. The physical magnitude of these differences, however, was small. Even small differences in texture between FAs resulted in significant differences in water retention. We conclude that fly ash can be used as an AWHC enhancement, with the greatest enhancement for the sandy loam, and that the FA types used in this study can determine to what extent AWHC will increase.

Recognizing dependence of water retention on not only texture (particle size distribution) but also pore size distribution, variability between treatments may be due in part to unavoidable particle differntial distribution during the laboratory analysis. However, predominant trends can be explained as being due to physical changes resulting from FA addition.

2.5 Practical Implications

The practical implications of this study include the increases in soil water retention characteristics that can be attained by adding FA to some soils. However, there are other soil properties which may be altered by a fly ash amendment. Besides water holding characteristics, soil strength and soil fertility may also be altered. Prior to large scale FA application, practitioners should ensure that the desired FA rate will not adversely affect soil erodibilty and crusting potential, nor plant germination and growth.

Table 2.1a. Particle size distribution of fly ash (Sundance, Wabamun)/silty clay mixtures.

Fly ash	Fly ash (vol. %)	Mean (n=3) size fraction (%)			Classification (CSSS, 1978)
		Sand	Silt	Clay	
Sundance	0	14.6	44.6	40.8	silty clay
	5	18.1	45.1	36.8	silty clay loam
	10	18.3	46.0	35.7	silty clay loam
	20	16.8	47.1	36.1	silty clay loam
	40	22.2	50.0	27.8	silt loam
	60	23.6	52.6	23.8	silt loam
	80	27.5	54.8	17.7	silt loam
	100	28.2	59.8	12.0	silt loam
Wabamun	0	14.6	44.6	40.3	silty clay
	5	15.3	45.6	39.1	silty clay loam
	10	16.0	46.6	37.4	silty clay loam
	20	17.5	48.6	33.9	silty clay loam
	40	20.4	52.6	27.0	clay loam/silt loam
	60	23.2	56.7	20.1	silt loam
	80	26.1	60.7	13.2	silt loam
	100	27.7	66.6	5.8	silt loam

Table 2.1b. Particle size distribution of fly ash (Sundance, Wabamun)/sandy loam mixtures.

Fly ash	Fly ash (vol. %)	Mean (n=3) size fraction (%)			Classification (CSSS, 1978)
		Sand	Silt	Clay	
Sundance	0	77.4	10.1	12.5	sandy loam
	5	76.5	12.4	11.1	sandy loam
	10	75.7	13.4	10.9	sandy loam
	20	70.1	19.1	10.8	sandy loam
	40	60.5	27.6	11.9	sandy loam
	60	52.0	35.3	12.7	loam/sandy loam
	80	42.7	46.0	11.3	loam
	100	28.2	59.8	12.0	silt loam
Wabamun	0	77.4	10.1	12.5	sandy loam
	5	75.0	12.8	12.2	sandy loam
	10	72.6	15.6	11.9	sandy loam
	20	67.7	21.0	11.3	sandy loam
	40	58.0	31.9	10.0	sandy loam
	60	48.4	42.9	8.8	loam
	80	38.7	53.8	7.5	silt loam
	100	27.7	66.6	5.8	silt loam

Table 2.1c. Particle size distribution of Sundance and Wabamun fly ashes.

Particle class	Particle diameter range (μm)	Mean (n=3) particle size distribution (%)	
		Sundance	Wabamun
very coarse sand	> 1000	0.0	0.0
coarse sand	500-1000	0.2	0.1
medium sand	250-500	1.2	0.6
fine sand	100-250	10.4	9.1
very fine sand	50-100	16.4	17.9
coarse silt	20-50	18.5	21.6
medium silt	5-20	27.4	33.8
fine silt	2-5	13.9	11.2
clay	< 2	12.0	5.8

Table 2.2. Water retention (g/g * 100) of Sundance FA/soil mixtures as affected by FA rate.

(a) silty clay mixture

FA (%)	Pressure (MPa)						
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	42.0 a	34.7 a	25.3 b	24.2 a	19.8 a	18.2 a	16.8 bc
5	39.7 b	34.2 a	27.9 a	25.0 a	20.1 a	17.8 a	16.5 bc
10	39.0 b	33.7 a	27.7 a	24.9 a	18.6 a	17.1 ab	16.8 bc
20	39.0 b	32.8 ab	27.7 a	24.7 a	19.7 b	16.0 b	17.1 bc
40	35.8 c	31.2 bc	25.6 b	22.9 b	13.3 d	15.7 b	15.5 c
60	34.1 d	30.4 c	24.6 b	22.1 b	15.6 c	12.3 c	18.3 b
80	34.6 d	29.8 c	24.8 b	22.1 b	10.7 e	11.4 c	18.5 b
100	34.5 d	31.1 bc	22.9 c	22.0 b	7.3 f	3.3 d	27.8 a

(b) sandy loam mixture

FA (%)	Pressure (MPa)						
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	16.9 g	20.4 d	-	8.4 g	8.2 ab	6.7 a	13.6 e
5	17.8 fg	18.7 d	10.1 f	9.2 f	7.1 c	5.7 b	13.7 e
10	18.8 f	18.9 d	10.0 f	9.7 f	7.2 c	5.6 bc	13.7 e
20	20.7 e	19.7 d	12.0 e	10.8 e	7.2 c	5.4 bc	14.8 de
40	22.0 d	21.3 cd	14.5 d	12.9 d	7.3 c	4.8 cd	16.6 d
60	25.5 c	23.5 c	18.7 c	16.3 c	8.4 a	4.9 cd	20.6 c
80	29.7 b	26.7 b	21.8 b	18.7 b	8.3 a	4.2 de	25.5 b
100	34.5 a	29.9 a	24.8 a	19.9 a	7.9 b	3.7 e	31.0 a

Statistical comparisons by Duncan's Multiple Range test. Similar letters in a column for a given pressure indicate no significant difference among fly ash rates ($P>0.05$).

Field capacity is water retention at 0.033 MPa; 0.01 MPa for sandy loam or coarser textures ($FA \geq 60\%$). Permanent wilting point is water retention at 1.5 MPa for all textures.

Table 2.3. Water retention (g/g * 100) of Wabamun FA/soil mixtures as affected by FA rate.

(a) silty clay mixture

FA (%)	Pressure (MPa)						
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	42.5 a	35.4 a	26.8 ab	24.8 ab	24.8 a	16.3 a	18.6 e
5	41.4 b	34.9 a	27.3 a	25.0 a	20.8 b	16.1 a	18.3 e
10	41.2 b	34.3 a	27.4 a	24.3 bc	19.7 b	15.8 a	18.0 e
20	40.6 b	33.5 ab	25.9 bc	23.6 c	18.3 c	15.8 a	17.4 ed
40	39.0 c	31.5 bc	25.2 cd	21.5 d	14.9 d	12.8 c	18.9 d
60	37.9 d	32.7 c	25.2 cd	19.7 e	11.8 e	13.7 b	16.9 c
80	35.4 e	31.2 c	26.4 ab	19.4 ef	9.4 f	12.0 d	17.9 b
100	38.4 cd	33.5 bc	24.5 d	18.9 f	6.3 g	3.2 e	27.9 a

(b) sandy loam mixture

FA (%)	Pressure (MPa)						
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	16.5 d	13.3 e	10.6 e	10.5 d	9.5 a	6.5 a	6.8 f
5	18.1 cd	13.2 e	9.5 f	8.9 f	7.5 a	6.1 ab	7.1 f
10	18.1 cd	13.5 e	9.7 ef	9.1 ef	7.0 b	5.8 ab	7.5 f
20	19.6 cd	14.8 e	10.7 e	9.8 de	7.0 b	5.4 abc	9.3 e
40	22.1 bc	19.3 d	13.6 d	11.4 c	6.7 c	5.2 abcd	14.1 d
60	25.9 b	22.0 c	16.8 c	12.9 b	6.6 c	4.0 d	18.0 c
80	32.5 a	27.7 b	20.2 b	15.8 a	6.6 c	4.8 bcd	22.8 b
100	32.0 a	34.1 a	22.0 a	16.3 a	5.9 d	4.3 cd	29.8 a

Statistical comparisons by Duncan's Multiple Range test. Similar letters in a column for a given pressure and soil indicate no significant difference among fly ash rates ($P>0.05$).

Field capacity is water retention at 0.033 MPa except for 0.01 MPa for sandy loam or coarser textures (FA ≥ 60%). Permanent wilting point is water retention at 1.5 MPa for all textures.

Table 2.4. Comparison of slopes of ln-ln transformed water characteristic curves for silty clay and sandy loam soils amended with Sundance and Wabamun fly ashes.

Fly ash rate (%)	Silty clay soil			Sandy loam soil		
	Textural class	Sundance FA	Wabamun FA	Textural class	Sundance FA	Wabamun FA
0	SiC	5.12	5.19	SL	3.61	4.90
5	SiCL	5.49	5.66	SL	3.47	4.21
10	SiCL	5.41	5.19	SL	3.37	4.01
20	SiCL	4.97	4.92	SL	3.17	3.60
40	SiL	4.06	3.85	SL	2.77	2.94
60	SiL	4.39	3.35	L/SL	2.62	2.06
80	SiL	3.09	2.81	L	2.21	2.12
100	SiL	1.78	1.68	SiL	1.91	1.84

Table 2.5a. Probability values from General Linear Model comparison of the effect of fly ash rate (%) on water retention for Sundance FA/silty clay mixture.

FA (%)	0	5	10	20	40	60	80	100
0	.	0.7257	0.8909	0.6217	0.4719	0.0861	0.0002	0.0001
5		.	0.8277	0.3895	0.2727	0.0357	0.0001	0.0001
10			.	0.5206	0.3814	0.0594	0.0001	0.0001
20				.	0.8235	0.2092	0.0008	0.0001
40					.	0.2906	0.0014	0.0001
60						.	0.0328	0.0001
80							.	0.0001
100								.

Statistical comparisons by General Linear Model on ln-ln transformed data. Values considered significant if P>0.05. For a given fly ash rate in the left column compare across for a given rate e.g. comparing 5% and 10% P-value = 0.8277. Diagonal shading indicates comparisons in which slopes were significantly different. Stippled shading indicates comparisons for which slopes were similar, but which subsequently failed LSMEANS test.

Table 2.5b. Probability values from General Linear Model comparison of the effect of fly ash rate (%) on water retention for Sundance FA/sandy loam mixture.

FA (%)	0	5	10	20	40	60	80	100
0	.	0.0976	0.0343	0.0015	0.0001	0.0001	0.0001	0.0001
5		.	0.6488	0.1239	0.0042	0.0003	0.0001	0.0001
10			.	0.2741	0.0161	0.0017	0.0001	0.0001
20				.	0.2085	0.0442	0.0001	0.0001
40					.	0.4149	0.0027	0.0001
60						.	0.0320	0.0001
80							.	0.0238
100								.

Statistical comparisons by General Linear Model on ln-ln transformed data. Values considered significant if $P>0.05$. For a given fly ash rate in the left column compare across under required rate e.g. comparing 5% and 10% P-value = 0.6488. Diagonal shading indicates comparisons in which slopes were significantly different. Stippled shading indicates comparisons for which slopes were similar, but which subsequently failed LSMEANS test.

Table 2.5c. Probability values from General Linear Model comparison of the effect of fly ash rate (%) on water retention for Wabamun FA/silty clay mixture.

FA (%)	0	5	10	20	40	60	80	100
0	.	0.4950	0.9310	0.6269	0.0036	0.0017	0.0001	0.0001
5		.	0.4347	0.2356	0.0003	0.0001	0.0001	0.0001
10			.	0.6847	0.0040	0.0019	0.0001	0.0001
20				.	0.0132	0.0068	0.0001	0.0001
40					.	0.8189	0.0578	0.0001
60						.	0.0948	0.0001
80							.	0.0001
100								.

Statistical comparisons by General Linear Model on ln-ln transformed data. Values considered significant if P>0.05. For a given fly ash rate in the left column compare across under required rate e.g. comparing 5% and 10% P-value = 0.4347. Diagonal shading indicates comparisons in which slopes were significantly different. Stippled shading indicates comparisons for which slopes were similar, but which subsequently failed LSMEANS test.

Table 2.5d. Probability values from General Linear Model comparison of the effect of fly ash rate (%) on water retention for Wabamun FA/sandy loam mixture.

FA (%)	0	5	10	20	40	60	80	100
0	.	0.2493	0.1037	0.0001	0.0001	0.0001	0.0001	0.0001
5		.	0.6200	0.0937	0.0001	0.0001	0.0001	0.0001
10			.	0.2334	0.0018	0.0001	0.0001	0.0001
20				.	0.0578	0.0001	0.0001	0.0001
40					.	0.0003	0.0002	0.0001
60						.	0.8504	0.1259
80							.	0.1792
100								.

Statistical comparisons by General Linear Model on ln-ln transformed data. Values considered significant if P>0.05. For a given fly ash rate in the left column compare across under required rate e.g. comparing 5% and 10% P-value = 0.6200. Diagonal shading indicates comparisons in which slopes were significantly different. Stippled shading indicates comparisons for which slopes were similar, but which subsequently failed LSMEANS test.

Table 2.6a. Select water retention characteristics of the silty clay soil amended by Sundance and Wabamun fly ash.

Fly ash	Fly ash (vol. %)	FC water ((g/g)*100)	FC change per unit FA change[1] (%)	PWP water ((g/g)*100)	PWP change per unit FA change[1] (%)	AWHC (g/g)*100	AWHC change per unit FA change[1] (%)
Sundance	0	34.7 a	-	18.2 a	-	16.8 bc	-
	5	34.2 a	-10.0	17.8 a	-8.0	16.6 bc	-4.0
	10	33.7 a	-10.0	17.1 ab	-14.0	16.8 bc	4.0
	20	32.8 ab	-9.0	16.0 b	-11.0	17.1 bc	3.0
	40	31.2 bc	-8.0	15.7 b	-1.5	15.5 c	-6.5
	60	30.4 c	-4.0	12.3 c	-17.0	18.3 b	3.0
	80	29.8 c	-3.0	11.4 c	-4.5	18.5 b	1.0
	100	31.1 bc	6.5	3.3 d	-40.5	27.8 a	46.5
Wabamun	0	35.4 a	-	16.3 a	-	18.6 bc	-
	5	34.9 a	-10.0	16.1 a	-4.0	18.3 bc	-6.0
	10	34.3 a	-12.0	15.8 a	-6.0	18.0 bc	-6.0
	20	33.5 ab	-8.0	15.8 a	0.0	17.4 bc	-8.0
	40	31.5 bc	-10.0	12.8 c	-15.0	18.9 b	5.0
	60	32.7 b	6.0	13.7 b	4.5	16.9 c	1.5
	80	31.2 c	-7.5	12.0 d	-8.5	17.8 bc	1.0
	100	33.5 ab	11.5	3.2 e	-44.0	27.9 a	55.5

[1] Water retention change per unit change in FA has been calculated as the difference between two sequential water retention values divided by the change in per cent fly ash. For example, using the Sundance FA/silty clay soil mixture, the difference in water retention between 0% and 5% FA at field capacity (0.033 MPa) equals -0.5%. This value divided by the change in FA content (5%) expressed as a per cent equals -10.0%. FC = field capacity (0.033 MPa); PWP = permanent wilting point (1.5 MPa); AWHC = available water holding capacity = FC - PWP

Table 2.6b. Select water retention characteristics of the sandy loam soil amended by Sundance and Wabamun fly ash.

Fly ash	Fly ash (vol. %)	FC water ((g/g)*100)	FC change per unit FA change[1] (%)	PWP water ((g/g)*100)	PWP change per unit FA change[1] (%)	AWHC (g/g)*100	AWHC change per unit FA change (%)
Sundance	0	20.4 d	-	6.7 a	-	13.6 e	-
	5	18.7 d	-34.0	5.7 b	-20.0	13.7 e	-12.0
	10	18.9 d	4.0	5.6 bc	-2.0	13.7 e	0.0
	20	19.7 d	8.0	5.4 bc	-2.0	14.8 de	11.0
	40	21.3 cd	1.6	4.9 cd	-2.5	16.6 d	9.0
	60	25.5 c	21.0	4.9 cd	0.0	20.6 c	20.0
	80	29.7 b	21.0	4.2 de	-3.5	25.5 b	24.5
	100	34.7 a	25.0	3.7 e	-2.5	31.0 a	27.5
Wabamun	0	13.3 d	-	6.5 a		6.8 e	
	5	13.2 d	-2.0	6.1 ab	-8.0	7.1 e	6.0
	10	13.5 d	6.0	5.8 ab	-6.0	7.5 e	8.0
	20	14.8 d	13.0	5.4 abc	-4.0	9.3 d	18.0
	40	19.3 c	22.5	5.2 abcd	-1.0	14.1 c	24.0
	60	25.9 b	33.0	4.0 d	-6.0	21.9 b	39.0
	80	32.5 a	33.0	4.8 bcd	4.0	27.7 a	29.0
	100	32.0 a	-2.5	4.3 cd	-2.5	27.7 a	0.0

[1] Water retention change per unit change in FA has been calculated as the difference between two sequential water retention values divided by the change in per cent fly ash. For example, using the Sundance FA/sandy loam soil mixture, the difference in water retention between 0% and 5% FA at field capacity (0.01 MPa) equals -1.7%. This value divided by the change in FA content (5%) expressed as a per cent equals -34.0%.

FC = field capacity (0.033 MPa; 0.01 MPa where FA ≥ 60%); PWP = permanent wilting point (1.5 MPa); AWHC = available water holding capacity

Table 2.7a. Water retention of silty clay mixtures comparing Sundance and Wabamun fly ashes.

FA (%)	(a) Sundance fly ash							(b) Wabamun fly ash						
	Pressure (MPa)													
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	42.0 a	34.7 a	25.3 a	24.2 a	19.8 a	18.2 a	16.5 b	38.4 b	35.4 a	26.8 a	24.8 a	20.0 a	16.3 b	19.1 a
5	39.7 a	34.2 a	27.9 a	25.0 a	20.1 b	17.8 a	16.4 b	35.4 b	34.9 a	27.3 a	25.0 a	20.8 a	16.1 b	18.8 a
10	39.0 a	33.7 a	27.7 a	24.9 a	19.7 a	17.1 a	16.6 a	37.9 a	34.3 a	27.4 a	24.3 a	19.7 a	15.8 b	18.5 a
20	39.0 a	32.8 a	27.7 a	24.7 a	18.6 a	16.0 a	16.8 a	39.0 a	33.5 a	25.9 b	23.6 b	18.3 a	15.8 a	17.7 a
40	35.8 b	31.2 a	25.6 a	22.9 a	13.3 b	15.7 a	15.5 b	41.2 a	31.5 a	25.2 a	21.5 b	14.9 a	12.8 a	18.7 a
60	34.1 b	30.4 b	24.6 a	22.1 a	15.6 a	12.3 b	18.1 a	41.4 a	32.7 a	25.2 a	19.7 b	11.8 b	13.7 a	19.0 a
80	34.6 b	29.8 a	24.9 a	22.1 a	10.7 a	11.4 b	18.4 a	40.6 a	31.2 a	26.4 a	19.4 b	9.4 a	12.0 a	19.2 a
100	34.5 b	31.1 a	22.8 a	22.0 a	7.3 a	3.3 a	27.8 a	42.5 a	33.5 a	24.5 a	19.9 b	6.3 b	3.2 a	30.3 a

Statistical comparisons by Duncan's Multiple Range test. Similar letters indicate no significant difference between fly ashes ($P \geq 0.05$). For a given fly ash (%) and a given pressure (or AWHC), compare water retention values between fly ashes: e.g. at 0% and at 0.01 MPa, compare 42.0% and 38.4%.

Table 2.7b. Water retention of sandy loam mixtures: comparing Sundance and Wabamun fly ashes.

FA (%)	(a) Sundance fly ash							(b) Wabamun fly ash						
	Pressure (MPa)													
	0.01	0.033	0.067	0.1	0.3	1.5	AWHC	0.01	0.033	0.067	0.1	0.3	1.5	AWHC
0	16.9 a	20.4 a	10.6 a	8.4 b	8.2 b	6.7 a	10.2 a	16.5 a	13.3 b	10.6 a	10.5 a	9.5 a	6.5 a	10.0 a
5	17.8 a	18.7 a	10.1 a	9.2 a	7.1 b	5.7 a	12.1 a	18.1 a	13.2 b	9.5 a	8.9 a	7.5 a	6.1 a	12.0 a
10	18.8 a	18.9 b	10.0 a	9.7 a	7.2 a	5.6 a	13.2 a	18.1 a	13.5 b	9.7 a	9.1 b	7.0 a	5.8 a	12.3 a
20	20.7 a	19.7 a	12.0 a	10.8 a	7.2 a	5.4 a	15.3 a	19.6 a	14.8 b	10.7 a	9.8 b	7.0 a	5.4 a	14.2 a
40	22.0 a	21.3 a	14.5 a	12.9 a	7.3 a	4.9 a	17.1 a	22.1 a	19.3 b	13.6 a	11.4 b	6.7 b	5.2 a	16.9 a
60	25.5 a	23.5 a	18.7 a	16.3 a	8.4 a	4.9 a	20.6 a	25.9 a	22.0 b	16.8 b	12.9 b	6.6 b	4.0 a	18.0 a
80	29.7 a	26.7 b	21.8 a	18.7 a	8.3 a	4.2 a	22.5 a	32.5 a	27.7 a	20.2 b	15.8 b	6.6 b	4.8 a	22.9 a
100	34.7 a	29.9 b	24.8 a	19.9 a	7.9 a	3.7 a	26.2 b	32.0 a	34.1 a	22.0 b	16.3 b	5.9 b	4.3 a	29.8 a

Field capacity is calculated as 0.033 MPa for all mixtures, except for the sandy loam mixtures where FA ≤ 40%, and then FC calculated as 0.01 MPa.

Statistical comparisons by Duncan's Multiple Range test. Similar letters indicate no significant difference between fly ashes (P≥0.05). For a given fly ash (%) and a given pressure (or AWHC), compare water retention values between fly ashes: e.g. at 0% and at 0.01 MPa, compare 16.9% and 16.5%.

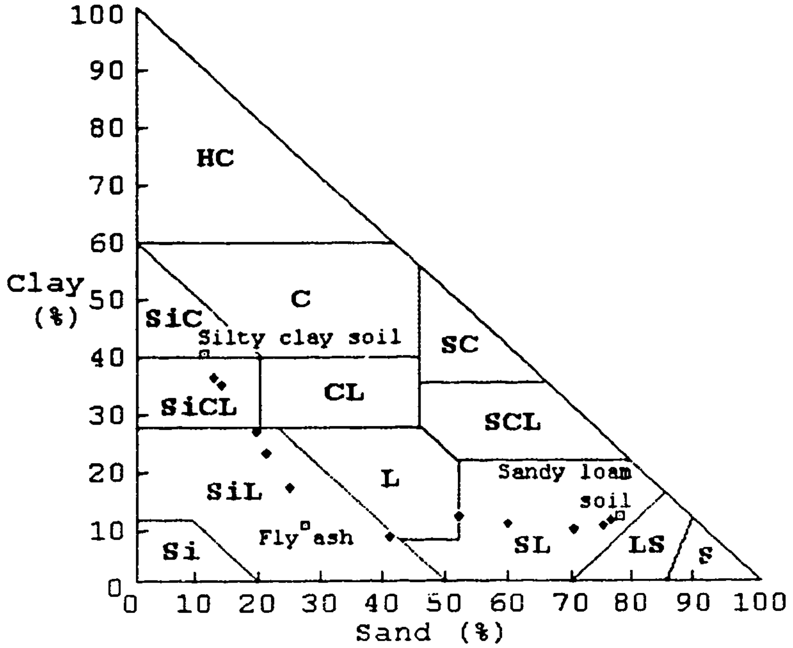


Figure 2.1. Textural position of the test soils, Sundance fly ash and soil/fly ash mixtures.

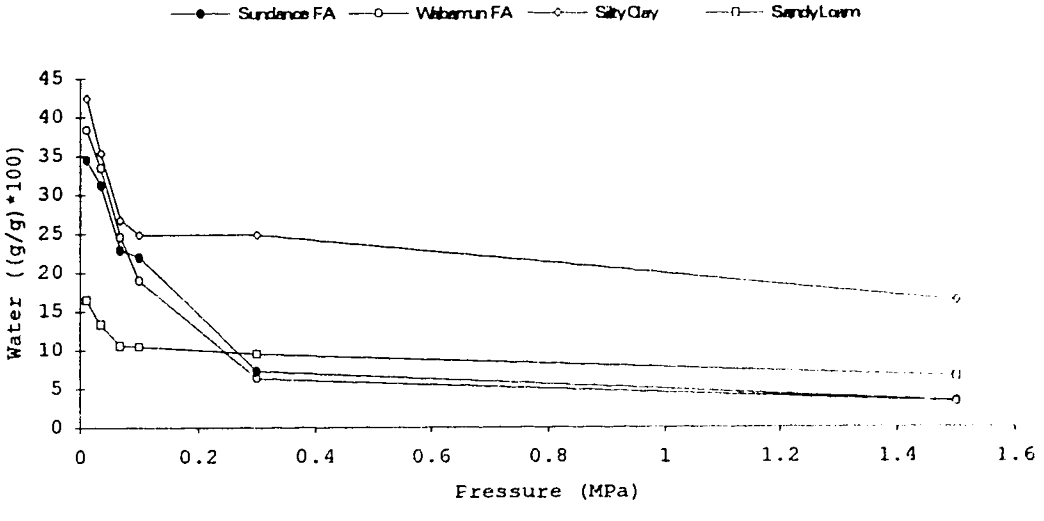


Figure 2.2. Soil water characteristic curves comparison of silty clay and sandy loam soils and Sundance and Wabamun fly ashes.

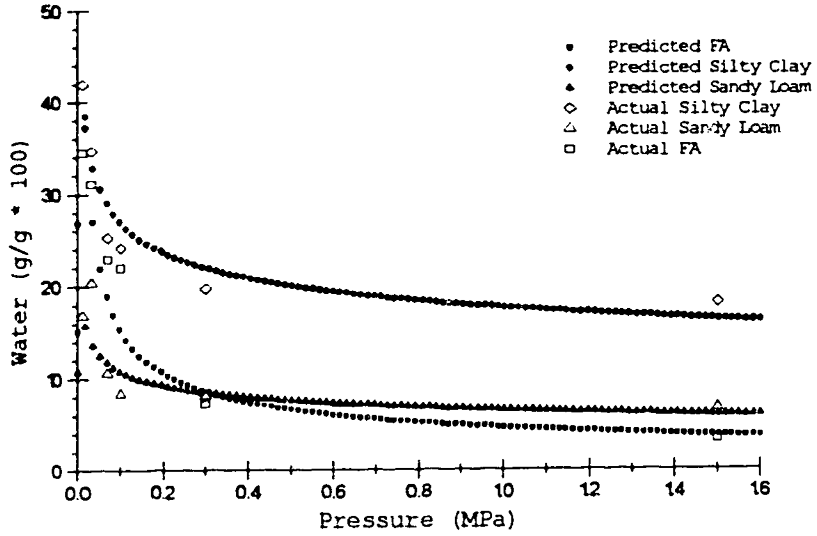


Figure 2.3. Actual and predicted values for the soil water characteristics of silty clay, sandy loam and Sundance FA.

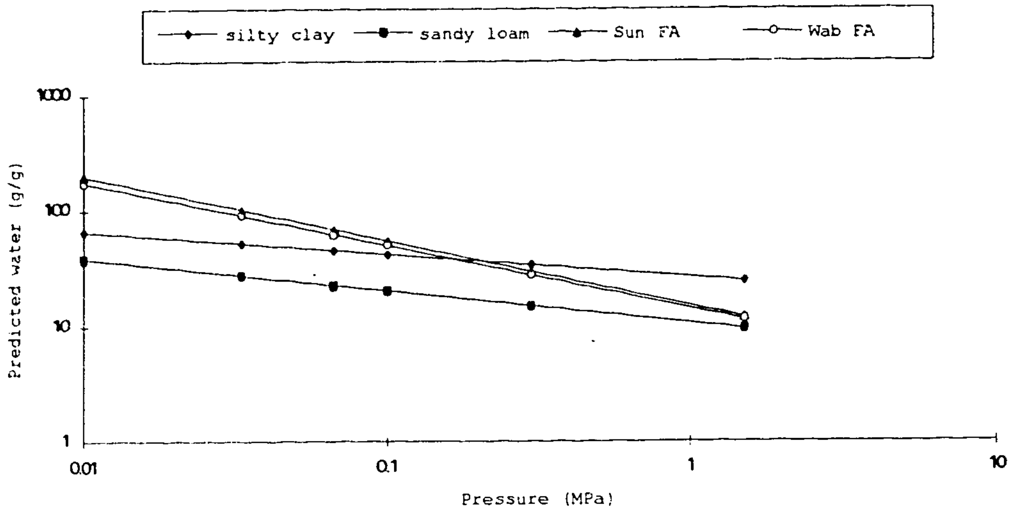
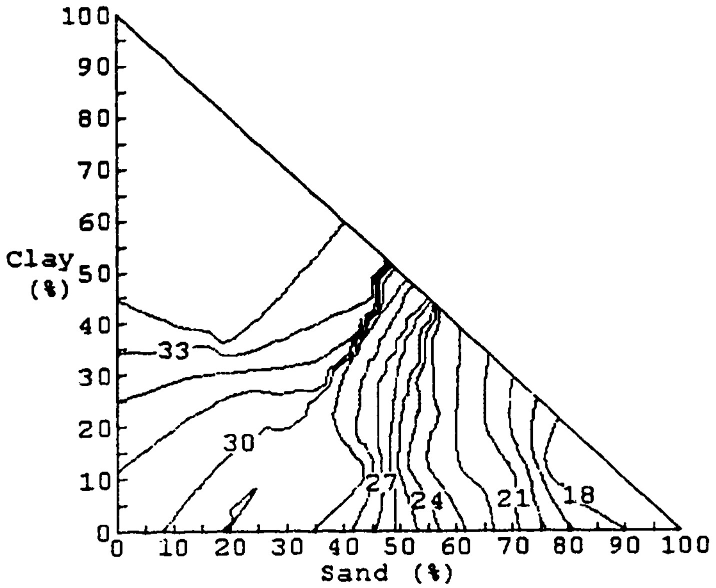


Figure 2.4. Predicted soil water retention characteristic curves using a modified Clapp and Hornberger (1978) equation, based on ln-ln transformed data.

(a) Sundance fly ash



(b) Wabamun fly ash

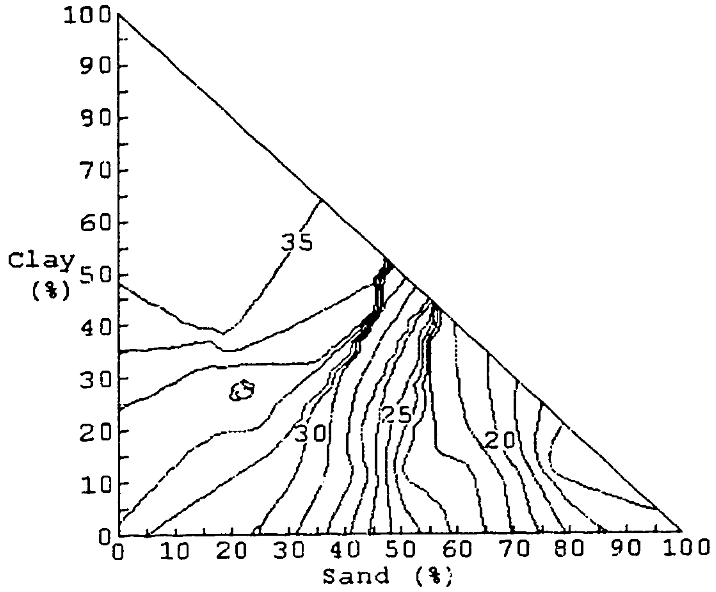
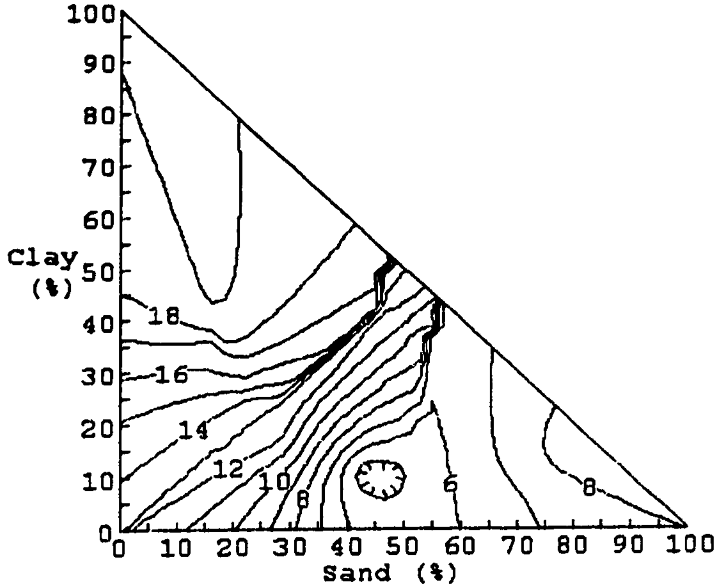


Figure 2.5. Predicted effect of FA addition on water retention at 0.033 MPa. Missing data derived by kriging.

(a) Sundance fly ash



(b) Wabamun fly ash

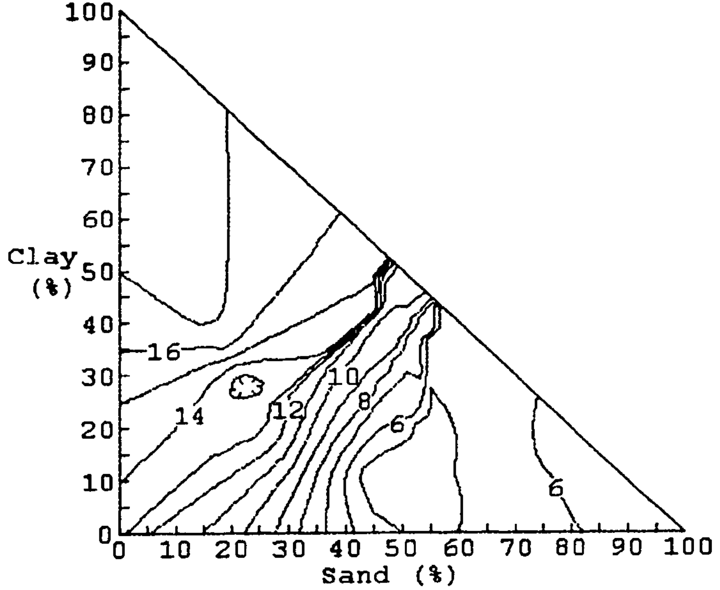
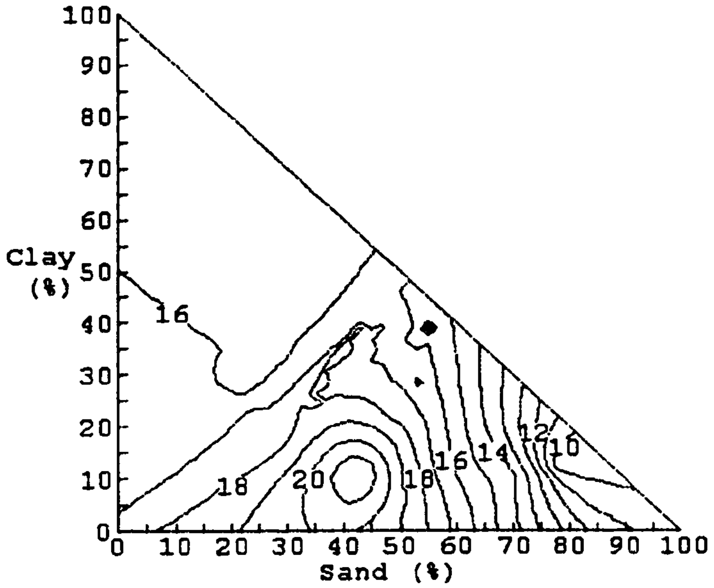


Figure 2.6. Predicted effect of FA addition on water retention at 1.5 MPa. Missing data derived by kriging.

(a) Sundance fly ash



(b) Wabamun fly ash

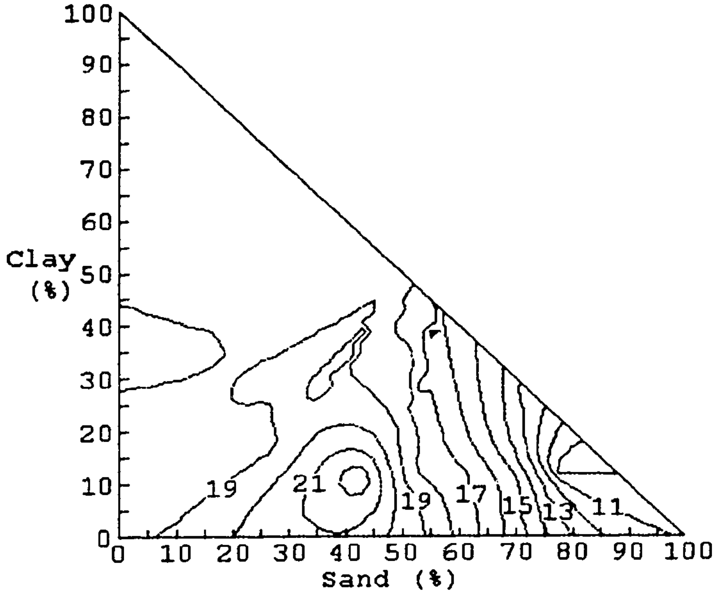


Figure 2.7. Predicted effect of FA addition on AWHC. Missing data derived by kriging.

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3. Reduction of soil strength through addition of fly ash.

3.1. Introduction

Soil strength refers to the ability of a soil to resist deformation. Lack of sufficient strength against externally imposed destructive forces can lead to soil aggregate breakdown and susceptibility to dispersion, surface sealing and ultimately surface crusting. Surface crusts will decrease seedling viability, and increase surface runoff and erosion potential. Therefore, decreasing the likelihood of soil crusting should lead to improved agronomic conditions.

The prevalent view expressed in the literature is that an increase in silt content will decrease aggregate strength (e.g. Arshad and Mermut, 1988; Bradford and Huang, 1992), but that crust strength will increase (Spivey *et al.*, 1986). Following aggregate collapse, the translocation of clays via infiltrating water into the uppermost few mm of the soil profile usually promotes crust formation as the soil dries. However, Bresson and Cadot (1992) found crusting to be related to silt illuviation. Regardless of translocated particle size, the collapse of soil aggregates is apparently due to an elevated silt content. Additionally, the soil may be expected to exhibit an increase in strength when subsequently dried if sufficient clay is present.

3.1.1 Fly ash as a soil strength amendment

Richards (1953) noted the importance of low soil strength to successful seedling emergence. The requirement for soil crust strength quantification led to his development of a modulus of rupture (MOR) method\` for soil strength.

Tackett and Pearson (1965) reported sharp increases in crust strength when a small fraction of clay (5-10%) was added with 22.6% silt to sand. Whitmeyer and Blake (1989) found that shear strength decreased dramatically when the silt:clay ratio of washed sand (minimum 80% sand) was less than 2. Sharma and Agrawal (1980), studying 27 Indian soils, reported that of the three particle size classes, clay was most closely, and positively, correlated with MOR. The magnitude of the correlation for percent sand was nearly equal to that of the clay, but the correlation was negative. Percent silt was a much less reliable predictor of MOR. The effects of the combined clay and silt fractions did not appear to be cumulative, and the authors suggested that the effects of the clay fraction overshadowed those of the silt fraction. In related work, Sharma (1985), reporting a field study on Indian sandy loam to clay loam soils with high crusting potential, concluded that 67.9% of the variation in MOR could be explained by clay and silt fractions. Increased clay and silt content in the study soils tended to increase MOR. Both Sharma and Agrawal (1980) and Sharma (1985) suggested that as particles increased in size, and coincidentally became more irregularly shaped, the relative surface areas for surface-to-surface attraction decreased. This decreased surface-to-surface attraction, and thus reduced soil strength, was attributed to be one result of more random particle arrangement, and of less dense packing.

Using a modification of Richards' (1953) method on five California soils with various textures, Chang *et al.* (1977) concluded that adding even a small amount ($\geq$ 2.5% by vol) of fly ash significantly reduced MOR values. However, FA is also recognized as possessing pozzolanic properties. A pozzolan is defined as "a siliceous or aluminous material, which in itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (Committee C-9 on Concrete and Concrete Aggregates, 1960). For this and other reasons (abundance, inexpense) FA has been utilized as an additive in various construction materials (e.g. road bedding, cinder blocks, etc.). It may be these pozzolanic properties, accompanied by the tendency for silt-size particles to compact (Bradfield and Jamison, 1938), which are evident when one observes the extremely hard surfaces at FA disposal site stockpiles. However, the effect on FA's pozzolanic properties by diluting the FA with soil has not been widely reported.

Adriano *et al.* (1980) noted the importance of parent coal composition and conditions during its combustion, efficiency of emission control devices, fly ash storage and handling, and climate in determining fly ash properties. The dependence of these factors upon geographic location requires that fly ash studies be conducted on a local, rather than global, basis.

The objectives of this study were to determine if the addition of fly ash to soil would alter soil strength. It was postulated that additions of fly ash would cause a soil textural change which in turn would alter the soil's strength, and the effects would depend on soil texture, and type and amount of fly ash added. Increasing the silt-sized fraction of a soil with low clay contents through FA addition may be expected to decrease the strength of a soil. Should the initial soil be clay-based, an increase in strength with increased FA addition should be expected as a result of crust formation.

The value of this research is an increased understanding of the effects on soil strength that fly ash as a textural modifier may cause, and enhance our understanding of fly ash as a soil amendment.

3.2 Materials and Methods

3.2.1 Soil/Fly Ash Briquettes

Two soils were used in this study, namely reclaimed silty clay surface horizon material and sandy loam subsurface material. Both soils had been disturbed by surface mining. Three FAs were tested, collected from three power generating stations (Wabamun, Sundance and Keephills). Two of the FAs (Sundance and Keephills) originated from coal in the same mine. These soils, and the FAs from the Sundance and Wabamun stations, were described previously (Sections 2.2.1 and 2.2.2, respectively). Keephills FA had a bulk density of 1.01 Mg m-3, indicated no presence of carbonates, and had a pH of 12.6. The techniques used for particle size analysis for Keephills FA were identical to those used for Sundance and Wabamun, as described in Section 2.2.3.

Individual FAs were mixed manually with each soil in single batches according to the following ratios: 5, 10, 20, 40, 60 and 80% FA by volume. Samples of each mixture were used to fill briquette molds (0.95 x 3.5 x 7.0 cm) with care taken to ensure that preferential settling did not occur. Mixtures were leveled within the briquettes. The briquettes were then saturated with distilled water from the bottom to ensure maximum opportunity for soil air to escape. Briquettes were left saturated for one hour before excess water was aspirated, and then ovendried at 50 °C overnight (approximately 18 hours).

Richards (1953) suggested putting a film of petroleum jelly on the interior of the molds prior to filling to facilitate briquette removal after drying. This method was attempted, but abandoned as jelly residue contaminated the edges of the briquettes in an uncontrollable and unpredictable fashion. In general, briquettes were easily removed without the film.

3.2.2 Modulus of Rupture

The MOR method followed in this study was a modification of that proposed by Richards (1953). The strength-testing apparatus consisted of a balance beam upon a platform on which rested a briquette support and knife edge assembly; an immovable beam; a receiving vessel on the weight pan; and a supply of water discharging at 2 L/min.

To test the strength of each briquette, the following procedure was used. The briquette was placed across the two vertical bars of the briquette support on the balance platform. The knife edge was then adjusted so that it rested on, but exerted no force upon, the briquette. The balance beam was adjusted so that any upward movement of the assembly would force the knife edge, due to the immovable beam, onto the briquette. Water was then caused to flow (2 L/min) into the receiving vessel on the weight pan. The weight of the water caused the assembly to move upward. When the pressure exerted by the knife edge caused the briquette to fail, the water source overshot the receiving vessel. The weight of water in the vessel was then recorded for each briquette.

The force required to break each briquette was calculated by:

$$s = (3 * FL)/(2000 * bd^2)$$

where s is the MOR (mbar), F is the breaking force in dynes (grams of water * 980), L is the distance between the two briquette support bars (cm), b is briquette width (cm), and d is briquette thickness (cm).

3.2.3 Statistics

In addition to the statistical methods described previously for the water retention characteristics of FA:soil mixtures, non-linear comparisons of the results were completed using a method described by Izauralde *et al.* (1986). Each comparison included two FA:soil treatments, sharing a common soil or FA, for the full range of FA rates. Using a non-linear least squares SAS subroutine (SAS Institute, 1992), data for each FA:soil mixture, and also for pooled data of compared mixtures, were individually fit to an equation of the form

$$\ln(MOR) = A - (FA / t)$$

where A and t are coefficients. The F-values, calculated from the sum of square residual for each individual mixture, and for the pooled data, were compared. The model described by the pooled data was deemed representative if both individual and pooled F-values were not significantly different.

Rates within a FA:soil mixture were compared using Duncan's Multiple Range Test ($p \geq 0.05$).

3.3 Results and Discussion

Particle size distributions of the soils, FAs and mixtures are listed in Tables 3.1a and b. Keephills FA was notably coarser than both the Wabamun and Sundance FAs, especially in the fine sand and very fine sand categories (Table 3.1c), in spite of coming from coal from the same mine as Sundance FA. The predominance of nearly equal fractions of medium silt to fine sand for Keephills contrasted with a medium silt peak in a predominantly medium silt to very fine sand range for Sundance and Wabamun FA (Table 3.1c).

The lowest MOR of any intact replicate was 179 Pa.

Briquettes with FA rates greater than 20% often broke when handled, and were assigned an MOR of 0.0 mbar. However, some limited soil strength was evident in spite of briquette failure. This was especially true for the briquettes with the highest rates of Keephills FA. These briquettes often were observed as the strongest of the three FAs, but an inherent brittleness did not allow their successful removal from the molds. A film of petroleum jelly on the mold may have prevented this breakage but since such breakage was obvious only with Keephills FA, and since the petroleum jelly was known to seep into the briquette itself, breakage due to brittleness was considered unavoidable.

Richards' (1953) MOR technique was adequate for briquette strengths greater than approximately 200 mbar. MORs less than 200 mbar could not easily be measured. Values of 0 were assigned to briquettes that broke prior to measurement. Since the 0.0 mbar values were incorporated into average treatment MOR, artificially low MOR resulted for mixtures of limited strength. Thus average values less than 200 mbar should be considered with caution.

Average inherent MOR for silty clay was 1332 mbar (standard deviation = 644 mbar) and 1522 (standard deviation = 330 mbar) for the sandy loam for all experimental runs (n = 18). The Sundance, Wabamun and Keephills FAs had average inherent MORs of 157, 127 and 0 mbar with standard deviations of 119, 113 and 0 mbar (n=6) (Tables 3.2a and b). The inability of Richards' (1953) MOR technique to quantify low soil/FA mixture strengths is well demonstrated in the Keephills data. Sundance and Wabamun FAs had MORs approximately 10-20% those of the inherent soil strength, with mean values near the lowest determinable MOR.

The high standard deviations are characteristic of the heterogeneity of these soils in the field, and are perhaps due to some extent to wetting the samples from the bottom.

However, it is important to note that regardless of the initial MOR values for a given soil, amending that soil with equal rates of any FA resulted in comparable MOR relative reductions (Tables 3.2a and b).

Dramatic reductions in soil strength were evident for both soils when amended with FA from any source. Only 5% FA addition decreased the strength of the silty clay to 77% of its inherent strength, averaged across three FAs (Table 3.2a). An addition of 5% FA to the sandy loam reduced its strength to an average of 23% of its inherent value (Table 3.2b). Mixture strengths were least for all FAs and both soils at the 40% rate, with MORs at or near 0 mbar. At rates greater than 40%, soil strength increased moderately for both soils except for Keephills FA.

No single equation completely represented the MOR trend with increasing FA. The trend appeared to combine an exponential decline to some FA addition rate, followed by a gently sloping linear increase (Figures 3.1-3.3, a, b and c). The rate value appears to be soil dependent, approximately equal to 40% FA for silty clay, and approximately 20% for sandy loam. The linear portion of the trend suggests a process dominated by FA's cohesive properties.

The consequence of this apparent combination of textural and pozzolanic effects posed a problem as to the nature of model to be used for statistical comparison. The exponential decline was finally considered as most indicative since it most closely represented the dramatic loss of soil strength at low FA rates.

Non-linear comparison (Izauralde *et al.*, 1986) indicated that of treatments where either a soil or a FA was shared, and over the entire range of rates, all but one (Wabamun FA:sandy loam vs. Keephills FA:sandy loam) were significantly different (Table 3.3). With this exception, it was not possible for one equation to describe the effect of two or more FA:soil mixtures.

The results of this study substantiate the work of Chang *et al.* (1977) in that very small amounts of any FA were required to reduce soil strength, in spite of FA's reputed pozzolanic nature. Additionally, the results of this study substantiate in part the work of Sharma and Agrawal (1980) and Sharma (1985) in that as soils became coarser, MOR decreased. However, this was not the case with sandy loam as MOR values increased as coarseness increased. Thus we may not attribute decreasing MOR to particle coarseness alone, but to the addition of FA, and perhaps also to some interaction between the cementitious compounds of the sandy loam and of the FA. If cementation did take place between the silty clay particles and FA, it appears that the effect was overcompensated for by the coarseness effect of the silt-sized particles of the FA.

3.4 Conclusions

The modulus of rupture method should be considered suitable for predicting the effect of FA addition on soil strength. The limited capability of this test to measure the lowest levels of soil strength (approximately 200 mbar) could be viewed as too limiting to accommodate the full range of FA rates tested in this study.

Even quantities as low as 5% FA per volume soil drastically reduced soil strength, regardless of soil or FA. This finding is consistent with those reported by Chang *et al.* (1977). If we may assume that FA acts as a textural amendment, then this result was predicted by the work of Arshad and Mermut (1988) and Bradford and Huang (1992) who reported that silt-sized particles promoted instability in soil aggregates.

The findings of this study appear to be in contradiction with those of several authors (Bradfield and Jamison, 1939; Tackett and Pearson, 1965; Spivey *et al.*, 1986). Where this study suggests that increased silt content reduces soil strength, the literature generally reports that soil crusts are strongest when developed from high silt-content soils. The contradiction may be explained by considering the method of soil preparation when one follows Richards' (1953) modulus of rupture technique. Soil crusts develop not only because of particle size distribution, but also and perhaps more importantly due to the effects of raindrop impact, and of particle translocation into the uppermost soil during infiltration. In contrast, the method followed in this study requires that the briquettes be carefully saturated from the bottom up to exclude trapped air from within. Thus particle translocation will be virtually eliminated. The MOR technique described in this study will approximate only the first portion of aggregate breakdown and surface sealing which will normally occur under natural conditions.

3.5 Practical Implications

Minor amounts of FA would be required to ameliorate problem soils. Based on the ongoing work of A.M. Hammermeister (pers. comm.) and of L.Y. Salé (pers. comm.), amounts required would not likely exceed toxicity tolerance levels of barley grown in north-central Alberta.

In addition to toxicity concerns, however, trafficability must also be maintained. The loss of strength at FA addition rates of 20-40% by vol was evident by its powdery condition, and though not specifically addressed in this study, high rates may impede equipment operation.

A concern associated with, but not addressed in, this study is that of surface sealing and erosion potential. Should the loss of strength cause soil aggregate collapse, the remaining weakened surface would be at a high risk of both water and wind erosion. Visual observation suggests that rates greater than approximately 40% FA per volume may pose high erosion risk.

Table 3.1a. Mean (n=3) particle size analysis of fly ash (Sundance, Wabamun, Keephills)/silty clay mixtures.

Fly ash	Fly ash (vol. %)	Size fraction (%)			Classification (CSSS, 1978)
		Sand	Silt	Clay	
Sundance	0	14.6	44.6	40.8	silty clay
	5	18.1	45.1	36.8	silty clay loam
	10	18.3	46.0	35.7	silty clay loam
	20	16.8	47.1	36.1	silty clay loam
	40	22.2	50.0	27.8	silt loam
	60	23.6	52.6	23.8	silt loam
	80	27.5	54.8	17.7	silt loam
	100	28.2	59.8	12.0	silt loam
Wabamun	0	14.6	44.6	40.8	silty clay
	5	15.3	45.6	39.1	silty clay loam
	10	16.0	46.6	37.4	silty clay loam
	20	17.5	48.6	33.9	silty clay loam
	40	20.4	52.6	27.0	clay loam/silt loam
	60	23.2	56.7	20.1	silt loam
	80	26.1	60.7	13.2	silt loam
	100	27.7	66.6	5.8	silt loam
Keephills	0	14.6	44.6	40.8	silty clay
	5	16.2	44.7	39.1	silty clay loam
	10	17.8	44.7	37.5	silty clay loam
	20	21.0	44.9	34.2	clay loam
	40	27.3	45.2	27.5	clay loam
	60	33.7	45.4	20.9	loam
	80	40.0	45.7	14.2	loam
	100	43.8	51.1	5.0	silt loam

Table 3.1b. Mean (n=3) particle size analysis of fly ash (Sundance, Wabamun, Keephills)/sandy loam mixtures.

Fly ash	Fly ash (vol. %)	Size fraction (%)			Classification (CSSS, 1978)
		Sand	Silt	Clay	
Sundance	0	77.4	10.1	12.5	sandy loam
	5	76.5	12.4	11.1	sandy loam
	10	75.7	13.4	10.9	sandy loam
	20	70.1	19.1	10.8	sandy loam
	40	60.5	27.6	11.9	sandy loam
	60	52.0	35.3	12.7	loam/sandy loam
	80	42.7	46.0	11.3	loam
	100	28.2	59.8	12.0	silt loam
Wabamun	0	77.4	10.1	12.5	sandy loam
	5	75.0	12.8	12.2	sandy loam
	10	72.6	15.6	11.9	sandy loam
	20	67.7	21.0	11.3	sandy loam
	40	58.0	31.9	10.0	sandy loam
	60	48.4	42.9	8.8	loam
	80	38.7	53.8	7.5	silt loam
	100	27.7	66.6	5.8	silt loam
Keephills	0	77.4	10.1	12.5	sandy loam
	5	75.9	11.9	12.3	sandy loam
	10	74.3	13.7	12.0	sandy loam
	20	71.2	17.3	11.5	sandy loam
	40	65.0	24.5	10.5	sandy loam
	60	58.8	31.6	9.6	sandy loam
	80	52.6	38.8	8.6	sandy loam
	100	43.8	51.1	5.0	silt loam

Table 3.1c. Mean (n=3) particle size distributions of Sundance, Wabamun and Keephills fly ashes.

Particle class	Particle size range (μm)	Particle size distribution (%)		
		Keephills	Sundance	Wabamun
very coarse sand	> 1000	0.0	0.0	0.0
coarse sand	500-1000	0.1	0.2	0.1
medium sand	250-500	1.5	1.2	0.5
fine sand	100-250	19.5	10.4	9.1
very fine sand	50-100	22.7	16.4	17.9
coarse silt	20-50	22.5	18.5	21.6
medium silt	5-20	22.1	27.4	33.8
fine silt	2-5	6.6	13.9	11.2
clay	< 2	5.0	12.0	5.8

Table 3.2a. Mean (n=6) MOR for three fly ashes separately mixed with silty clay soil.

Fly ash	Fly ash addition rate (% tot vol)	MOR (mbar)	Standard deviation (mbar)	Strength relative to 0% FA rate
Sundance	0	865	237	1.00
	5	689	103	0.80
	10	336	64	0.39
	20	172	85	0.24
	40	32	78	0.04
	60	66	103	0.15
	80	69	107	0.24
	100	100	110	0.23
Wabamun	0	1134	69	1.00
	5	954	154	0.84
	10	646	111	0.57
	20	258	74	0.23
	40	0	0	0.00
	60	0	0	0.00
	80	124	114	0.11
	100	220	9	0.19
Keephills	0	2176	202	1.00
	5	1482	132	0.68
	10	847	458	0.47
	20	0	0	0.00
	40	0	0	0.00
	60	0	0	0.00
	80	0	0	0.00
	100	0	0	0.00

Table 3.2b. Mean (n = 6) MOR values for three fly ashes separately mixed with sandy loam soil.

Fly ash	Fly ash addition rate (% tot vol)	MOR (mbar)	Standard deviation (mbar)	Strength relative to 0% FA rate
Sundance	0	1067	15	1.00
	5	210	15	0.20
	10	198	2	0.19
	20	0	0	0.00
	40	0	0	0.00
	60	210	24	0.20
	80	188	12	0.18
	100	242	79	0.23
Wabamun	0	1730	264	1.00
	5	373	91	0.22
	10	195	0	0.11
	20	0	0	0.00
	40	0	0	0.00
	60	0	0	0.00
	80	198	0	0.11
	100	212	0	0.12
Keephills	0	1542	239	1.00
	5	380	106	0.25
	10	208	0	0.13
	20	0	0	0.00
	40	0	0	0.00
	60	0	0	0.00
	80	183	0	0.12
	100	0	0	0.00

Table 3.3. Statistical comparisons of non-linear responses due to FA addition. Addition rates were 0-100% FA per total volume for all treatments. Compared treatments shared either a common FA or a common soil.

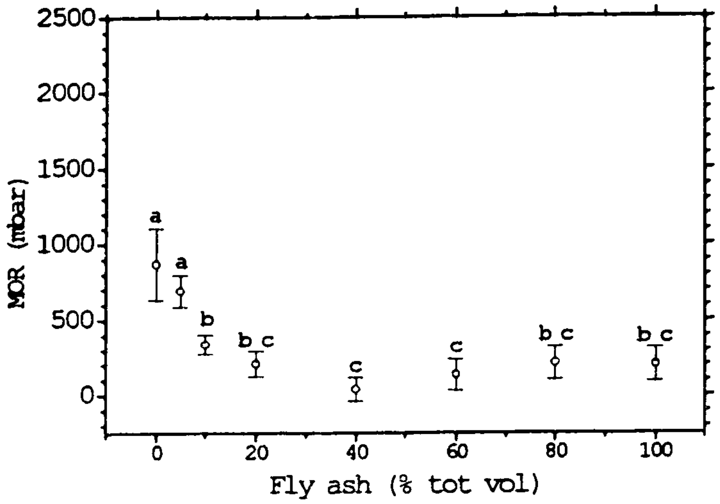
FA:soil mixture[1] comparisons	F_c-value[2]	Significance	
		$p \geq 0.050$	$p \geq 0.025$
trt 1 vs. trt 2	12.36	different	different
trt 1 vs. trt 3	4.62	different	not different
trt 1 vs. trt 5	149.75	different	different
trt 2 vs. trt 4	22.06	different	different
trt 2 vs. trt 6	12.93	different	different
trt 3 vs. trt 4	74.81	different	different
trt 3 vs. trt 5	79.74	different	different
trt 4 vs. trt 6	2.99	not different	not different
trt 5 vs. trt 6	111.55	different	different
trt 1 vs. trt 3 vs. trt 5	78.79	different	different
trt 2 vs. trt 4 vs. trt 6	12.15	different	different

[1] FA:soil mixtures have been assigned treatment numbers for brevity. They are:

trt 1 - Sundance FA:silty clay
trt 2 - Sundance FA:sandy loam
trt 3 - Wabamun FA:silty clay
trt 4 - Wabamun FA:sandy loam
trt 5 - Keephills FA:silty clay
trt 6 - Keephills FA:sandy loam

[2] F_c-value = calculated F-value.

a) silty clay



b) sandy loam

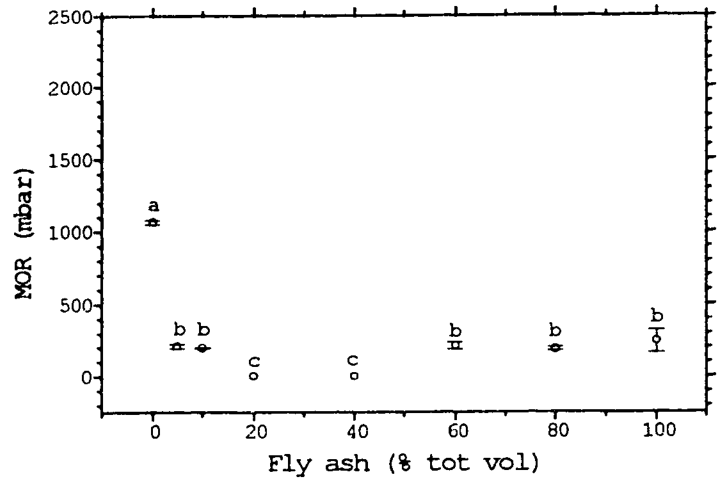
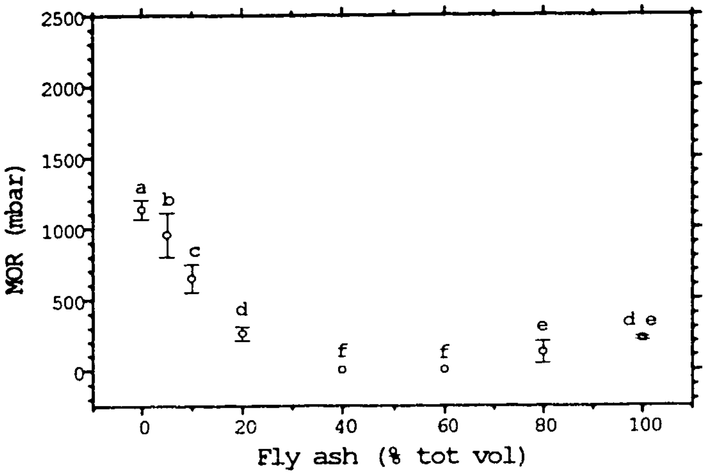


Figure 3.1. The effect of Sundance fly ash addition on the modulus of rupture of a) silty clay and b) sandy loam. Means with the same letter are not significantly different, by Duncan's Multiple Range test ($P \geq 0.05$). Error bars indicate standard deviation.

a) silty clay



b) sandy loam

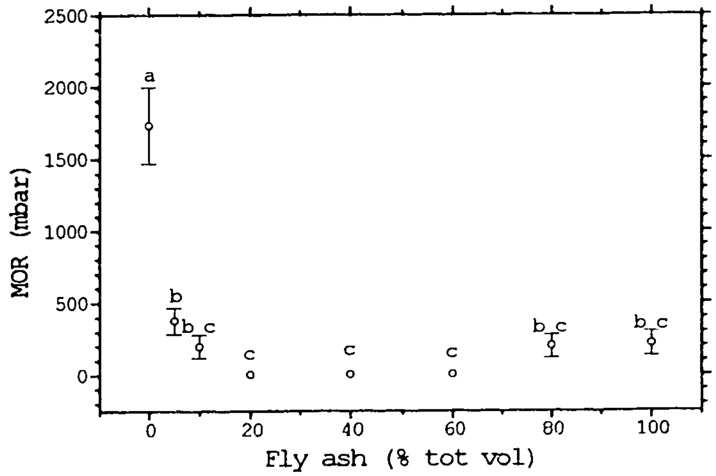
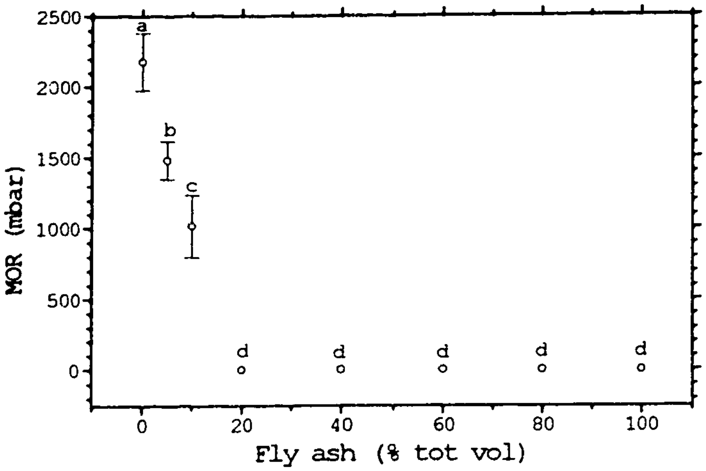


Figure 3.2. The effect of Wabamun fly ash addition on the modulus of rupture of a) silty clay and b) sandy loam. Means with the same letter are not significantly different, by Duncan's Multiple Range test ($P \geq 0.05$). Error bars indicate standard deviation.

a) silty clay



b) sandy loam

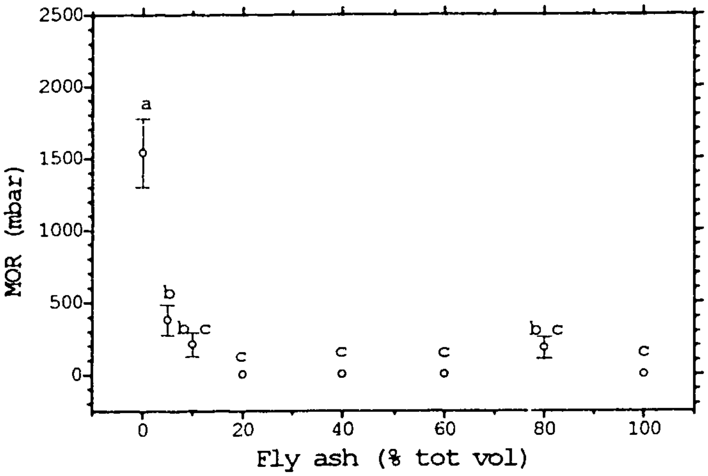


Figure 3.3. The effect of Keephills fly ash addition on the modulus of rupture of a) silty clay and b) sandy loam. Means with the same letter are not significantly different, by Duncan's Multiple Range test ($P \geq 0.05$). Error bars indicate standard deviation.

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4. Synthesis

This study was undertaken to study the effects of FA on water retention and strength characteristics of soil. The initial textures of the two test soils, and the full spectrum of FA rates (0 to 100% volume basis, inclusive) permitted the study of a textural continuum ranging from silty clay soil, via silty loam FA, to sandy loam soil. Adding FA to soil enhanced FC, PWP and AWHC in a linear fashion, regardless of initial soil texture. Soil strength, measured by MOR, decreased exponentially as FA rate increased until about 40% FA, then increased modestly. The trends of effect among ashes were generally similar, with some differences in the magnitude of effect between FAs, likely due differences in the textures of the FAs. The greatest influence of FA on both soil water retention and soil strength occurred for coarse textured soils. Altering soil texture with FA will likely improve conditions for plant growth. Enhanced soil water retention is important for all soils and beneficial for all plants, and decreased strength should improve germination in soils which are prone to crusting.

From an water retention point of view, the recommended FA application rate could be as high as could be physically incorporated into the soil. However, continual reduction of soil strength with FA rates up to 20-40% depending on texture suggests that perhaps the 20-40% addition range would represent an upper limit of addition based on these two physical characteristics. These rates would likely maintain trafficability as well as reduce surface sealing and erosion potential which may result from an overly "loose" FA:soil mixture.

During the course of the study the applicability of MOR as a predictor of soil crusting potential was brought into question. While Richards' (1953) method was developed to study crust strength and its effects on plant germination, the method does not promote particle translocation often associated with crusting. However, since this study was primarily concerned with the effect of texture on strength, not crusting, the MOR technique is suitable. Crusting may possibly be viewed as a special case where the textural effect on strength is complicated by preferentially enhancing a particle size fraction. Further research comparing sprinkling of water on the briquettes with gentle soaking from below is required to resolve the issue as to whether MOR truly represents a measure of crusting.

Our work has demonstrated that FA increases AWHC, and decreases soil strength. In combination with evidence that has been provided in the literature, the effect of FA (a silt sized medium) on the water holding characteristics of soil are similar to the effect of increasing silt content in the soil. Some areas of agronomic concern, such as surface sealing, erosion potential and trafficability, are more obvious in the field than in a laboratory. These and other possible problem issues have not been addressed in this study and should be investigated before large scale FA application is attempted.

Improved agronomic success is likely due to the effects of FA on some physical parameters, but more research is required before FA can be routinely used as a soil amendment. High FA application rates may be toxic to plants and/or the animals feeding upon them. Research in areas such as soil fertility, chemistry, microbiology, etc. are needed to quantify the upper bounds of acceptable application rates, which may be dependent upon soil texture. Benefits from the standpoint of other disciplines would likely be enhanced by the improved physical condition of the soil.

4.1 References

Richards, L.A. 1953. Modulus of rupture as an index of crusting of soil. Soil Sci. Soc. Am. Proc. 17:321-323.