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Developing Specifications for Waste Glass and Waste-to-Energy Bottom Ash as Highway Fill Materials

Volume 1 of 2 (Bottom Ash)

June 1, 1995

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WPA Item Number 0510650
Contract Number B-7754

Technical Report Documentation Page

1. Report No. FL/DOT/RMC/06650-7754	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

DEVOLOPING SPECIFICATIONS FOR
WASTE GLASS AND WASTE-TO-ENERGY
BOTTOM ASH AS HIGHWAY FILL MATERIALS
Volume 1 of 2 (BOTTOM ASH)

5. Report Date
June 1995

6. Performing Organization Code

7. Author's
P. J. Cosentino, E. H. Kalajian, C-S. Shieh and H. H. Heck

8. Performing Organization Report No.

9. Performing Organization Name and Address
Florida Institute of Technology
Civil Engineering Program
150 West University Blvd.
Melbourne, FL 32901-6988 407-768-8000 ext 8048

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
C-7754 WPA # 0510650

12. Sponsoring Agency Name and Address
Florida Department of Transportation
605 Suwannee Street
Tallahassee, Florida 32399-0450

13. Type of Report and Period Covered
Final Report
October 1992 to October 1994

14. Sponsoring Agency Code
99700-7587-119

15. Supplementary Notes

16. Abstract

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17. Key Words MWC Bottom Ash, Highway Applications Geotechnical Properties, Leaching Properties	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 145	22. Price

Form DOT 1700.7 (8-72)

Reproduction of completed page authorized

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

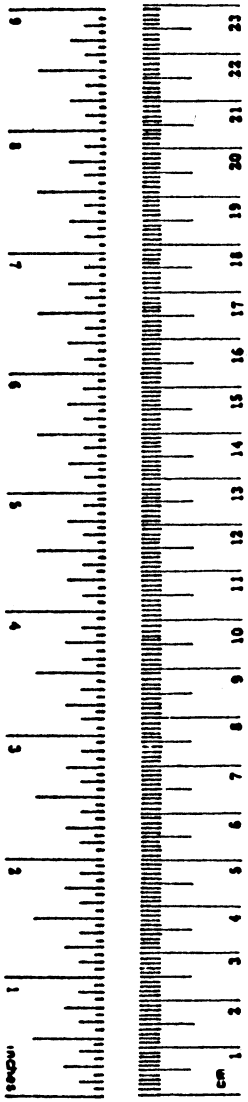
VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
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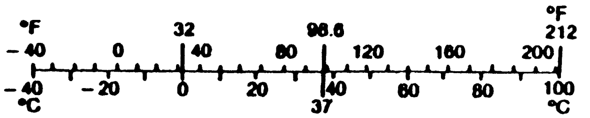

These factors conform to the requirement of FHWA Order 5190.1A.

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* SI is the symbol for the International System of Measurements

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ACKNOWLEDGMENTS

The researchers would like to thank the Florida Department of Transportation for funding this research under contract number C-7754. The assistance of Dr. Robert K. H. Ho throughout the study was invaluable. The diligent efforts of the following graduate and undergraduate students made timely completion of this project possible: Mario Chavez, Shakeel Syed, Shih-I Wang, Keith Guthrie, Gudny Palsdottir, Massimo Bosso, Rujroj Waiwudhi, Deborah Pandeline, Jenifer Benaman, Daniel Wintermeyer and Dorothy Rhine.

ABSTRACT

Municipal waste combustor (MWC) bottom ash from a Mass Burn (MB) and Refuse Derived Fuel (RDF) Waste-to-Energy facilities was evaluated for potential use as a highway fill material. MWC bottom ash has the physical and geotechnical properties necessary for many highway fill applications and meets existing environmental acceptability regulations. Bottom ash is classified as A-1a (0). The moisture-density, permeability and unconfined compressive strength of the bottom ash were a function of compassion energy and moisture content with behavior similar to many conventional fill materials. Compacted bottom ash has a negligible shrinkage and swell potential when saturated, however the ash swelled when allowed to air dry. The stress-strain characteristics of both ash types behave similarly to sand. Both ashes develop some cohesion that is attributed to pozzolanic cementing reactions occurring in the bottom ash. The angle of internal friction increases with the density of the compacted bottom ash. Values for these geotechnical properties as well as elastic and resilient moduli, CBR and LBR are presented.

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Based on the study findings, developmental specifications for incorporation into Florida DOT "Standard Specifications for Road and Bridge Construction" have been proposed for using bottom ash in highway fill applications.

1.0 INTRODUCTION

Municipal solid waste (MSW) consists of paper, cardboard, plastics, wood, metals, glass, food-wastes, and other combustible and non-combustible materials. Americans generate more than 4.4 billion tons of MSW each year, resulting in nearly six pounds of garbage being produced by each person per day (Stutzman, 1992). Until 1975, most of this waste was discarded as unusable. However, a study on alternative fuels conducted by The Organization of Petroleum Exporting Countries, turned attention towards the use of MSW as a fossil fuel (Alter and Dunn, 1980). Based on this and other studies, the combustion of MSW has become an economical source of energy for many states (EPA, 1975).

Converting the trash into energy in municipal waste combustor (MWC) facilities, significantly reduces the volume of our garbage by nearly 90%. These facilities also reclaim various metals from the waste stream for reuse. The remaining 10% is composed of fly ash, scrubber ash and bottom ash which can be disposed of in lined landfills or reused in various commercial applications (Wheelabrator, 1991). There are two types of MSW combustion plants: mass burn (MB) facilities and refused-derived-fuel (RDF) facilities. Mass burn facilities combust MSW without pre-combustion separation processing, while RDF facilities separate and recover resources prior to combustion.

At present, Florida burns more MSW than any other state except New York—about 25% of Florida's MSW is combusted in WTE plants. Florida will overtake New York's rate of waste incineration next month when the Lee County incinerator goes on line. This new WTE facility will have the capacity to burn 1,200 tons of waste per day (FDEP, 1993). Also on the horizon is a facility that will have the capacity to burn 1,500 tons of MSW per day—an existing facility is currently in the permitting process to achieve this capacity. By 1995, the estimated production of WTE ash residue in Florida will increase from the present rate of 1.9 million tons per year to 2 million tons per year.

1.1 Ash Management Practices

Until 1975, the most common methods of disposal of the ash residues was either land filling or daily cover. However, current and future research indicates that MWC ash has applications as a construction material (Collins, 1977). One important factor which hinders the accepted use of MWC ash as a construction material is its variability in physical and chemical properties due to different plants' processes. In addition, without consistent use of the ash in engineering applications, it would not be economical to pursue reuse of this material. For these reasons, the long range goals for ash management are: 1) to ensure a consistent and uniform production of ash by controlling the plant processes and the material which goes into the process, 2) to safely increase recycling or reuse of these products, and 3) to develop specific uses for MWC bottom ash as a construction material. In order to reach these goals, a general understanding of the engineering properties of MWC ash should be obtained.

1.2 Objectives

The objective of this investigation was to evaluate the geotechnical engineering properties and the environmental characteristics of MWC bottom ash for use in highway applications. Bottom ash from a mass-burn facility and a refuse-derived-fuel facility was examined to show any variability in the strength and deformation characteristics between the two most prevalent processes used in municipal waste combustion.

The following geotechnical properties of MWC ash were examined: visual classification, grain size analysis, specific gravity, absorption, mineralogy, pozzolanic activity, bulk rodded unit weight, moisture-density, and permeability. Shear and deformation characteristics of the bottom ash were evaluated as follows: unconfined compressive strength, consolidated drained triaxial shear test, determination of elastic modulus and resilient modulus, and California Bearing Ratio and Limerock Bearing Ratio values.

The following environmental characteristics of MWC ash were examined: elemental concentrations of selected metals in MWC bottom ash, leaching characteristics of ash column, and environmental acceptability of MWC bottom ash.

2.0 PREVIOUS MWC BOTTOM ASH STUDIES

2.1 Metals in WTE Ash

The metals present in WTE ash are either recyclable metal items or elemental metals. Combustion results in the enrichment of the elemental metals in the ash that is produced since metals may be neither created nor destroyed. However, different elemental metals are enriched in different amounts due to two factors: 1) thermal history during combustion and 2) the physical and chemical properties of each metal—such as their boiling point and their reactivity with other elements present in the combustion chamber (Clapp et al., 1988; Hocking, 1975). For example, Fe and Cu are enriched in bottom ash, whereas Hg and Cd are enriched in fly ash.

In addition to the naturally occurring metals present in the raw materials used in commercial products, the primary sources of metals in the combustible fraction of MSW are pigments, inks, stabilizers for plastics, clay filters, whiteners, photosensitizes, and miscellaneous chemical compounds (Campbell, 1976). When waste is combusted as mass burn—i.e., when waste is not separated prior to combustion—the existence of ferrous metals, cans, glass, and wires in the burning materials result in an increase of Fe, Si, Al, and Cu in the ash residues (Law and Gordon, 1979).

The distribution of the elemental metals within the ash matrix is determined by: the operating conditions during combustion, the composition of the municipal waste, the cooling and cleaning of emissions, and the physical-chemical behavior of the individual metals (Brunner and Monch, 1986). The temperature inside combustion chambers is normally above 760 - 980 °C—high enough to melt most metals and their compounds. Metals, such as Al, Fe, Cu, and their compounds, which have high boiling points are enriched in bottom ash after combustion. Cadmium and mercury, which have low boiling points, are vaporized during combustion and either condense and absorb onto the surface of fly ash or condense in the scrubbing system which results in higher concentrations in fly ash and scrubber residue (Brunner and Monch, 186; Campbell, 1976). Studies have shown that the concentrations of Cr, Mn, Pb, and Sn in fly ash and bottom ash are not significantly different (Brunner and Monch, 1986; Clapp et al., 1988; Lisk, 1988); these metals have more complex physical-chemical properties, and thus, combust differently at each plant.

2.2 Engineering Investigations of Ash

Literature was reviewed for information about MWC bottom ash composition, treatment and utilization. Of the sources reviewed, most tend to confirm the belief that selected bottom ash material, especially bottom ash samples from facilities with ferrous metals removal systems, has a reasonable degree of physical uniformity; some studies have suggested that bottom ash has to be aged prior to utilization to modify the physical properties of the material (Hartlen, 1989). Aging bottom ash can reduce the moisture content, organic content, and unreacted lime content of ash; thereby making it more suitable for use (Collins, 1977). This practice has been used in Europe for several years (Hartlen, 1989).

According to Gidley and Sack (1984), there are a wide variety of wastes that are potentially useful in construction. These include wastes from the mining and metallurgical industries, municipal refuse, demolition wastes and ashes from combustion processes. These wastes can be used as embankments materials, highway base courses, landfill liners, concrete aggregates, and bituminous mixtures.

Ash utilization is not a new concept; industrial ashes and slags have been used as the basis of many concrete admixtures. Coal fly ash has been used as a pozzolanic material in concrete for several decades and in many applications such as road fill, as an aggregate in artificial reefs and, when pelletized, as a light weight construction aggregate (HDR Engineering, 1991). Blast furnace slags have been used both as aggregate and as fibers for reinforcement. Foster Wheeler Company (Charleston, S. C.) has been using MSW ash for the last decade as a partial substitute for up to approximately 71% of traditional Portland cement raw material (Darcy, 1991). The Foster Wheeler Company has conducted regular testing on incineration ash and has found the bottom ash to be a non toxic material (Darcy, 1991).

The use of bottom ash as a landfill daily cover or using ash as a bituminous or portland cement matrix for an impermeable cap has been proven to be very successful by the New York State Energy Research and Development Authority (Koppelman, 1990). In addition, Forrester and Goodwin (1990) confirmed that achieving liner-like permeability is attainable and cost effective. The highly compacted densities achieved for use as a landfill liner demonstrate the potential application of bottom ash as a highway fill material.

When considering ash material as an aggregate for construction material applications, four major issues are relevant: 1) economy, 2) compatibility with other materials, 3) concrete properties, and 4) environmental acceptability. The Foster Wheeler Company has conducted regular testing on incineration ash and has found bottom ash to be a non-toxic material (Darcy, 1991). Bottom ash is currently being used or considered for use as construction material in artificial reefs, roads, liners and daily covers for landfills, concrete masonry blocks, light-weight and coarse aggregate, and partial replacement of aggregate.

2.2.1 Highway Applications

WTE bottom ash has been used for the last two decades in many road applications around the world; the Netherlands and Germany use as road base and as an aggregate in asphalt applications (Van Der Sloot, 1990). Sweden uses processed bottom ash as structural fill; and tests of structural fill show that the bearing capacity of bottom ash is comparable to natural aggregate (Hartlen and Fallman,1990). Japan and Taiwan currently use WTE ash as an embankment or as structural fill materials on the coastline. Denmark uses bottom ash in embankment material (Van Der Sloot, 1990).

2.2.1.a Federal Highway Administration Ash Study

The Federal Highway Administration (FHWA) sponsored the first documented field studies of MWC bottom ash use in the United States. Ash from mass-burn facilities was used as an aggregate substitute in asphalt pavements. In addition, lime was added to the ash-asphalt blend as an anti-stripping agent. The ash fraction used ranged from 50% to 100% of the aggregate mix. This ash fraction is significantly higher than the ash fraction used today which, depending on the application, ranges between 10% and 50%. In any case, the FHWA concluded that the bottom ash was acceptable from an engineering perspective as a construction material (Chesner, 1993).

2.2.1.b SEMASS Ash Study

A company called, Energy Answers, constructed an access road to the SEMASS refuse-derived-fuel plant located in Rochester, Massachusetts using processed bottom ash. The top and base coarse of the pavement as well as the pavement sub-base consisted of 30% processed bottom ash. After 18 months of daily traffic to the plant, the roadway only showed signs of normal wear and tear. Chemical tests on soil samples adjacent to the road and water samples taken from the monitoring wells showed metal levels to be either non-detectable or well within the normal limits for Massachusetts (Chesner, 1993).

2.2.1.c CRRA and UCONN Ash Study

In August of 1992, the Connecticut Resources Recovery Authority (CRRA) and the University of Connecticut (UCONN) constructed an 1800 foot access road to the top of the Shelton landfill. The access road allowed the CRRA and UCONN to demonstrate the use of MWC bottom ash as a structural fill and as an aggregate for bituminous pavement in a controlled and well-monitored site. The laboratory results conducted prior to construction and the actual field results indicate that bottom ash performs well as both structural fill and bituminous concrete. The ash was found to be comparable to standard construction materials in use today. However, the bottom ash could not be recommended for use as a structural fill outside the landfill due to the quantities of leachable salts found in the ash. This issue appeared to be effectively controlled when the bottom ash was used in a bituminous mix (Demars *et al.*, 1994).

2.2.1.d Wheelabrator Ash Study

Wheelabrator has patented a Portland cement-based ash aggregate called McKaynite which is used to treat combined ash or bottom ash. Several field tests on McKaynite have been conducted by Wheelabrator in construction applications. These tests utilized ash from various WTE facilities in Florida that were located in Tampa, Pinellas County and Broward County. In 1987, a strip of pavement was installed in Tampa, Florida that utilized McKaynite in the asphalt mix. In 1991, a fill area was constructed in Ruskin, Florida with McKaynite aggregate fill material. The results from these studies indicated that there were no adverse effects on the groundwater, soil or air quality. The objective of these studies was to generate data needed to acquire state regulatory approval to use McKaynite aggregate in the field. Recently, Wheelabrator received the approval to use the McKay Bay facility's ash in the McKaynite as landfill cover and as road aggregate (Chesner, 1993).

2.2.1.e Denmark Ash Study

Since 1974, Denmark has been utilizing screened and sorted MSW bottom ash as subbase for parking lots, bicycle paths, and roads, both residential and major. Denmark's incentives for utilizing the bottom ash as a subbase are economical as well as derived from a concern for natural resources: as a subbase material, bottom ash can substitute for gravel which is expensive and limited in quantities. The use of bottom ash for civil engineering purposes has been regulated in Denmark since 1983. (Hjelmar, 1990).

2.2.1.f New York Studies

The New York City Sanitation Department (1988) investigated bottom ash as a partial aggregate supplement to determine if it could be used in asphaltic concrete in road paving applications. The testing program consisted of a series of Marshall mix tests that were designed to evaluate the effect that substituting processed residue for natural aggregate would have on wearing course and binder course mixes. This study concluded that 30% of the natural aggregate by weight could be substituted with bottom ash and still meet applicable gradation and Marshall mix design criteria. Asphaltic concrete made from bottom ash looked, handled, and behaved essentially the same as a conventional asphalt paving mix. Using a magnetic separator to remove the ferrous material from the ash did not produce any improvement in asphalt paving mix characteristics. Instead, the air voids of such mixes were considerably higher because some of the fine ash particles were removed during magnetic separation, resulting in a somewhat coarser mix gradation.

Studies performed by the New York State Energy Research and Development Authority (Koppelman, 1988) in Long Island, New York, have found the use of unbound bottom ash in road base material (under a bituminous pavement) to be successful and even suitable in areas that are insensitive to potential salt leaching (i.e., near the marine environment).

2.2.2 Building Construction Material

2.2.2.a Concrete Block Applications

The first building constructed of concrete masonry blocks made from MSW bottom ash residue was built at the SUNY Stony Brook by Roethel and Breslin (1990). The two-story 8,100 sq. ft. boathouse was made of 350 tons of ash concrete blocks. Bottom ash was used as an aggregate mixed with portland cement. The resulting product has been found to be stronger (1600-2570 psi) than traditional concrete blocks (1200-1800 psi) under similar circumstances.

The results of the SUNY-Stony Brook investigations indicate that incineration bottom ash possesses significant pozzolanic activity and is a suitable substitute for aggregate in the manufacture of concrete blocks for use by the construction industry. On-going research will monitor the boathouse for structural integrity and environmental impact during the next several years. In addition, the air quality within the building will be monitored, and the surrounding soil will be tested for ash constituents.

Chesner (1992) used bottom ash with 15% portland cement and 17 to 19% moisture content to produce blocks at the Besser company in Alpena, Michigan. An average 28 day compressive strength of 1521 psi was achieved for these bottom ash blocks. Control blocks produced using gravel, sand, 11% type II portland cement, and approximately 5.9% moisture achieved a 28 day compressive strength of 3976 psi.

2.2.2.b Light-Weight and Coarse Aggregate

A test program was conducted by Plumley and Boley (1990) at ABB Resource Recovery, Windsor, Connecticut, to produce light-weight stabilized ash from the combustion of MSW bottom ash. The incinerator residue was blended with lime and water in a mixer. The "green" mixture was then pelletized on a spinning-disk pelletizer and dusted with an embedding material to prevent caking. The resulting product was cured in a steam-filled silo. Controlled operation of the pelletizer and screening of the cured pellets resulted in a graded, light-weight aggregate that was found to be environmentally benign using the EPA's TCLP (toxic characteristics leaching procedure) leaching test. The pellets were suitable for utilization in various products or processes that incorporated gravel. These products were about 60% as dense as their natural gravel counterparts.

Lauer (1979) used the nonmagnetic fraction of the residue sized between the 25 mm and 75 mm mesh as a fine and coarse aggregate in concrete. Similarly, Aleshin, and Bortz (1976) used waste glass as coarse aggregate. Neutralysis Industries Inc. of Brisbane, Australia, has been using bottom ash to produce light-weight aggregate by mixing clay or shale to produce pelletized feedstock, which is then pyro-processed in a series of kilns. This process produces light-weight ceramic aggregate for use in structural concrete, masonry block manufacturing, and precast concrete shapes. Light-weight aggregate makes the block or finished concrete shapes one-third lighter than heavy aggregate and provides superior insulating and acoustical characteristics (Merdes, 1990).

2.2.2.c Partial Replacement of Aggregate

Thomas Nevin (1992) investigated the properties of concrete where a percentage of the aggregate (gravel, pearock, and sand) has been partially replaced with bottom ash. The concrete specimens were cured in lime water for 28 days and exposed to sea water for 28 days. The control concrete was designed for a compressive strength of 5000 psi. This study concluded that: 1) the technique of using a constant fineness modulus as a criterion to replace conventional concrete aggregate with bottom ash was an effective means of minimizing changes in the grain size distribution; 2) the workability and unit weight of concrete that contained ash showed a slight decrease as WTE bottom ash was increased from 0 to 16%, while the voids and absorption of the concrete increased; the air content was unaffected by the ash content of the concrete; and 3) WTE bottom ash can be used as a partial replacement of up to 12% of conventional concrete aggregate without causing major changes in the compressive and tensile properties of the concrete when exposed to either lime water or sea water.

2.3 Geotechnical Properties

Bottom ash displays a high degree of variability in both physical and engineering properties. In order to identify this variability, a literature review on the physical and engineering properties of WTE bottom ash applicable for use as a highway fill material are describe in the following sections.

2.3.1 Grain Size Distribution

According to Forrester and Goodwin (1990), bottom ash reflects a granular material of mostly gravel consistency. In addition, Huang and Lovell (1990), indicated that bottom ash is a relatively well graded, sand-sized material. A well graded material can be readily compacted to a dense condition and will generally develop greater shear strength and lower permeability than a poorly graded material (GAI Consultants, 1979).

2.3.2. Moisture Content

Water can also be absorbed into the body of the bottom ash particles or retained on their surfaces as a film of moisture. Thus, the moisture content of bottom ash will affect such engineering properties as compaction behavior and compressive strength. Chesner (1989) found that the moisture content of bottom ash can range from 20 to 70 percent of the dry weight of the ash while natural aggregate has a moisture content between 3 and 10 percent. For construction applications, the moisture content should be within 2 percent of the moisture content at which the aggregate has its maximum density.

Chesner (1989), concluded that bottom ash samples from facilities with ferrous metals removal capabilities, generally display higher moisture content than ash samples from facilities without ferrous metal removal systems. Previous research on bottom ash conducted at Florida Tech reported a moisture content range from 5 to 18 percent during different sampling periods (Wu, 1990, Nevin, 1991 and Jain, 1992).

2.3.3 Specific Gravity

The specific gravity is the ratio of the particle mass to the mass of an equal volume of water. The specific gravity of bottom ash reported by Seals, Moulton and Ruth (1972), ranged from 2.35 to 2.78. Huang and Lovell (1990) later stated it ranged from 1.94 to 3.46. Both studies also indicated that the specific gravity of bottom ash is a function of chemical composition. Bottom ash with a high carbon content will typically have a low specific gravity, while bottom ash with a high iron content will typically have a high specific gravity. Other factors that may cause variation in the specific gravity of bottom ash are: the method of incineration, the season and the management procedures employed at the WTE plant (HDR Engineering, 1991).

2.3.4 Absorption

The absorption capacity of an aggregate represents the maximum amount of water that can be absorbed into its pore spaces. Natural aggregate absorption typically ranges between 0.5 and 2 percent by weight (Chesner, 1989). Chesner also performed absorption tests on fine (<4.75 mm) and coarse fractions (>4.75 mm) of bottom ash. He reported that absorption values ranged from 3 to 5 percent by weight for the fine material and from 11 to 17 percent by weight for the coarse material. The pores at the surface of the particles affect the adherence among the aggregate particles and might exert some influence on the strength of a construction material (SCS Engineers, 1991).

2.3.5 Bulk Rodded Unit Weight

The bulk unit weight of a soil sample is the weight of graded aggregate required to fill a container of specified volume. The term *bulk* is used because the volume is occupied by both aggregate and voids. The bulk unit weight of natural aggregate material generally ranges from 80 to 130 pcf (SCS Engineers, 1991). Chesner (1989), reported that the bulk unit weight for bottom ash samples ranged between 59 and 77 pcf—indicating that bottom ash is classified as a lightweight aggregate.

2.3.6 Moisture-Density Relationship

Two compactive methods which have been followed to compact bottom ash are: ASTM D-698 standard proctor compaction and ASTM D-1557 modified proctor compaction. The results of six investigations conducted on bottom ash from various sources are summarized in Table 2.1. Natural soil aggregates have OMC's ranging from 10 to 30 percent and maximum dry densities ranging from 90 to 135 pcf (Chesner, 1989). Bottom ashes have optimum moisture contents that are similar to natural aggregate; however, maximum dry densities are typically at the lower range of natural aggregate material.

2.3.7 Permeability

In a literature review, the coefficient of the permeability of bottom ash displayed a high degree of variability. Forrester and Goodwin (1990), conducted several laboratory permeability tests on raw bottom ash achieving a coefficient of permeability of 1.8×10^{-5} cm/sec; however, the moisture content or density used in the laboratory specimens for the permeability tests were not reported. Seals, Moulton and Ruth (1972), indicated that bottom ash permeability, at a relative density of 50 percent, falls into a medium permeability range that has values similar to that of sand. Their research reported that the minimum permeability value of 5.0×10^{-3} cm/sec for bottom ash is due to a high percentage of fine sand size particles (approximately 62%) and fines (approximately 8%). According to Huang and Lovell (1990), the result of permeability tests conducted on the bottom ash compacted to 95 percent of the maximum dry density (109 pcf at 16 % moisture content, with 10 % fines content by weight) was 2.0×10^{-3} cm/sec. Huang and Lovell (1990) verified that the permeability of bottom ash is a function of the percentage of fines.

2.3.8 Swelling

Previous investigations made by various researchers (e.g. Roethel, 1986; Forrester, 1988; Chesner, 1989; Forrester and Goodwin, 1990; SCS Engineers, 1991) indicate that MSW ash possesses a potential for pozzolanic behavior due to the presence of high free-lime content and cement-like mineralogy. This pozzolanic behavior or reactivity refers to the tendency for ash to react with excess lime. Lime reacts with combined ash (bottom ash and fly ash) and water to form cementitious products (calcium silicate hydrates and calcium aluminate hydrates) which cause volume expansion and cracks in the ash product's structure (Chesner, 1989). Since bottom ash has a negligible lime content, it is "*expected*" that cementitious reactions that could stabilize a bottom ash road base would not be generated (SCS Engineers, 1991).

The swelling of bottom ash results from the reaction of water vapor with salts found in ash residue (Chesner, 1989). The resultant hydrated salts expand the volume of ash. Swell tests on bottom ash resulted in the noticeable expansion of the sample dimensions; however, there is no record of the exact volume increases in the bottom ash samples, because the samples began to crumble after a week of testing (Chesner, 1989). To reduce the chance of swelling during use, bottom ash is typically allowed to age or is "*pretreated*" prior to use in construction applications. Swelling could be a potential limitation for road base or structural use, because swelling could weaken the road or the structure. Aging allows time for the swelling reactions to occur before the ash is used in construction applications (Hartlen, 1989).

2.3.9 Unconfined Compressive Strength

Previous studies on the unconfined compressive strength of bottom ash were not cited in the literature.

2.3.10 Consolidated Drained Triaxial Shear

The consolidated drained triaxial shear test is used to determine the shear strength parameters: cohesion (c) and angle of internal friction (ø) (Bowles, 1992). Huang and Lovell (1990) reported ø values ranging between 45° and 60° for relative densities between 90% and 100% on material passing through a 3/8" sieve. Demars, *et al* (1994) reported ø values of 40° to 45° for MSW ash samples passing the #4 sieve. Seals, Moulton and Ruth (1972) reported ø values of 38° to approximately 43° for loosely compacted ash samples passing the 3/8" sieve. The friction angles reported by Huang and Lovell (1990), Demars, *et al* (1994) and Seals, Moulton and Ruth (1972) were found using the direct shear test. These friction angles generally increased by 2° over values obtained using the triaxial test. Seals, Moulton and Ruth (1972) also reported that bottom ashes in dense states would generally yield increases in friction angles of 6° to 8°.

2.3.11 Elastic and Resilient Moduli

Typical elastic moduli ranges for various materials are as follows: stabilized base materials: 5×10^4 - 6×10^6 psi, stiff clay: 7,600 - 17,000 psi, medium clay: 4,700 - 12,300 psi, soft clay: 1,800 - 7,700 psi, and very soft clay: 1,000 - 5,700 psi (Huang, 1993).

The resilient modulus is the elastic modulus based on the recoverable strain under repeated loads.

2.3.12 California Bearing Ratio (CBR) and Limerock Bearing Ratio (LBR)

The CBR test measures the shearing resistance of a soil or aggregate material in relation to a standard test material. Typically, natural aggregates have CBR values ranging between 30 and 80 percent. A typical minimum specification for a road base is 100 percent (SCS, 1991). Chesner (1989) reports CBR values between approximately 85 and 155 percent for bottom ash utilizing the compactive energy described in ASTM D-1557.

The LBR test is used for evaluating limerock and other soils for base, stabilized subgrade and subgrade or embankment material found in Florida (FDOT, 1993). The LBR number can be calculated directly from the data from the CBR test where the LBR number is equivalent to the ratio of corrected stress at 0.1" penetration over 800.

2.4 Existing Regulations

2.4.1 Current MWC Ash Regulations

Florida's regulation on MWC ash management (Florida Administration Code 17-702, 1991) requires that an application for a permit to construct and operate solid waste combustors shall include an ash residue management plan. The plan shall (1) describe the methods, equipment, and structures necessary to control the dispersion of ash residue during handling, processing, storage, loading, transportation, unloading, and disposal; (2) identify disposal sites;

(3) include an estimate of the quantities of bottom and fly ash to be generated; (4) include a quality assurance plan; (5) include procedures to assure that hazardous wastes are not received at or burned in the facility; and (6) be updated as necessary to reflect changing conditions. In addition to the requirement for an ash management plan, the regulation also includes specific requirements for the storage, off-site transportation, disposal, and recycling of ash residue. According to the regulation, WTE ash can be either disposed of in a lined MSW landfill or utilized if the processed ash residue does not cause discharges of pollutants to the environment.

2.4.2 Environmental Issues

Studies have shown MWC ash has promising engineering applications, although heavy metal content has raised a concern that it might cause contamination to groundwater if put into fill material. According to a recent study conducted for the Environmental Protection Agency, all the metals found in the leachates of fly ash and bottom ash combinations were below the EP toxicity maximum allowable limits. In addition, the majority of the metal concentrations found met primary and secondary drinking water standards set by the Safe Drinking Water Act (NUS, 1990).

Another study conducted at the University of Connecticut showed high amounts of chlorides and sulfates leaching out of MB bottom ash. Toxicity Characteristic Leaching Procedure (TCLP) tests were conducted on ash mixes consisting of 50% ash and 50% aggregate. The results indicated that the concentration of metals in the leachate was less than the concentrations of pure ash and the combined ash mixes passed the toxicity tests. The final conclusion was that the leachable elements in the ash were effectively controlled when the ash was mixed with a bituminous material (Demars, *et al.*, 1994).

On May 3, 1994, the Supreme Court ruled that any residue created by MSW incinerators must be tested for hazards using TCLP tests prior to disposal or treatment. The TCLP procedure is cited as the standard test for determining if a material is deemed hazardous. Typically, the leachate concentrations of calcium, cadmium, arsenic, chromium, lead and silver are tested using the TCLP procedure. Wang (1994) showed that typically less than 0.1% of these metals leached out of the bottom ash under simulated real world conditions. The concentrations of Pb (1700 mg/g) and Cd (24 mg/g) in the total bottom ash leachate were both below the EPA toxicity standard of 5000 μg/L. Therefore, the bottom ash alone would not be considered a hazardous waste and could be disposed of in ordinary landfills if needed.

Table 2.1 Previous investigations of moisture-density relationship for MWC ash

Reference	Ash	Compactive	Particle Size Passing		OMC	Maximum Dry Density	
	Source or Type	Energy - ASTM	(in)	(mm)	(%)	(pcf)	(kN/m^3)
Seals, Moulton and Ruth (1972)	Mitchell	D-698	3/8	9.5	14.6	116.6	18.3
	Fort Martin	D-698	3/8	9.5	24.8	85.0	13.4
	Kanawha River	D-698	3/8	9.5	26.2	72.6	11.4
Collins (1977)	Well Burned	D-698	NA	NA	12	95.6	15.0
		D-698	NA	NA	18	110.6	17.4
	Intermediately Burned	D-698	NA	NA	14	90.6	14.2
		D-698	NA	NA	20	105.6	16.6
	Poorly Burned	D-698	NA	NA	16	75.5	11.9
		D-698	NA	NA	24	90.6	14.2
Huang and Lovell (1990)	Gallagher	D-698	NA	NA	16	109.0	17.2
	Gibson	D-698	NA	NA	18	101.7	16.0
	Schafer	D-698	NA	NA	22	95.4	15.0
Demars, et al (1994)	Bridgeport	D-1557	0.75	19.0	13	125.8	19.8
		D-1557	0.75	19.0	10	114.4	18.0
Chesner (1989)	Bottom Ash	D-1557	NA	NA	11	80.0	12.6
		D-1557	NA	NA	22	100.0	15.7
Forrester and Goodwin (1990)	Bottom Ash	D-1557	NA	NA	15	116.4	18.3

OMC - Optimum Moisture Content

NA - Not Available

3.0 METHODOLOGY AND EXPERIMENTAL PROCEDURE

3.1 Description of MWC Facilities

The geotechnical properties of MWC bottom ash were examined in order to evaluate its performance in highway applications. The MWC bottom ash used in this study was provided by a mass-burn (MB) combustion facility and a refuse-derived-fuel (RDF) combustion facility. Descriptions of the operation of these facilities and the production of ash are provided in the following sections.

3.1.1 Refuse Derived Fuel (RDF) Facilities

The RDF process starts when collection vehicles and transfer trailers deposit solid waste onto the tipping room floor. White goods, (i.e., refrigerators, water heaters, etc.) are separated from the solid waste stream and processed on the oversize-bulky-waste (OBW) line while tires are processed on a separate line. Front end loaders are then used to transfer the remaining waste from the tipping room floor to conveyors that feed the flail shredder. The flail shredder breaks the waste down into a manageable size. A grapple crane is then used to extract items which are non-processible such as rugs, mattresses and cables. Once removed, these items are sent directly to the landfill. The shredded waste is conveyed beneath a large magnet for ferrous metal removal. The shredded waste is then screened in a trommel where glass and grit are removed. Further along the trammel, a picking conveyor recovers the aluminum for recycling. The remaining waste is transported to a storage bin for use as fuel (Project Profile, 1990). The fuel is now ready for combustion and is fed uniformly onto the boiler's traveling-grate stoker (Keith *et al.*, 1990). Here, the heat generated by the combustion of the waste is converted into steam to power the turbines to produce electricity which is then sold back to the local power industry for distribution to the power grid (Project Profile, 1990). The bottom ash from the combustion chamber is discharged through a diverter valve into a water-bath deasher. The bottom ash then moves up the inclined end of the deasher for dewatering and discharges onto the bottom ash transfer conveyor. The conveyor transports the bottom ash to the ash building where fly ash is combined with it. The combined ash is then hauled to the landfill as daily cover (Keith *et al.*, 1990).

3.1.2 Mass Burn (MB) Facilities

At MB facilities, sorting takes place after combustion. The ash that falls through the grate as well as that which remains on it is quenched in water. The fly ash which is collected with precipators is then mixed with the bottom ash to form a combined ash. This combined ash undergoes metal separation to remove ferrous and non-ferrous materials for recycling (Wheelabrator, 1991). The ferrous materials are extracted using magnets while the non-ferrous materials are sorted by size and weight using trommel screens. The aluminum is separated along an inclined conveyor belt by means of eddy currents. (Pfeffer, 1992). Once the valuable metals have been recovered and shipped for recycling, the remaining combined ash is deposited in a landfill (Wheelabrator, 1991).

3.1.3 WTE Survey Development

To determine the location, contact person(s), availability, processes and costs of WTE the survey form shown in Figure 3.1 was developed. Copies of this form were sent to the WTE facility plant managers in Florida.

3.2 Ash Sampling

The MB bottom ash used for this research was provided by the Pinellas County Resource Recovery Facility, located in Pinellas County, FL. This WTE facility consumes an average of 3150 tons of MSW per day. The plant is publicly owned but privately operated by Wheelabrator Pinellas, Inc. and currently delivers approximately 75 megawatts of power per day to the Florida Power Corporation.

The RDF bottom ash used for this research was provided by Palm Beach Solid Waste Authority, located in Palm Beach County, Florida. This WTE facility consumes an average of 2250 tons of MSW per day. The plant is operated through a 20-year contractual agreement with Babcock & Wilcox (a McDermott Company) and currently delivers approximately 61.3 megawatts of power per day to Florida Power & Light Corporation (Project Profile, 1990).

3.3 Bottom Ash Engineering Properties

The physical properties of the bottom ash were determined from several different samples in order to minimize variations in measured characteristics between the test sample selected and the 55 gallons drums received at Florida Tech. The test samples were taken in accordance with ASTM Standard C 702-87, Method A. This method consists of reducing the sample using a mechanical splitter. Table 3-2 presents a summary of the test methods and procedures used to evaluate the engineering properties of the MB and RDF ashes. These procedures are briefly presented in the following sections.

3.3.1 Physical Composition

A visual classification was performed on the MWC bottom ash samples that were received from the MB and RDF facilities. The visual classification was conducted to determine the percentage of recoverable materials such as metals and glass contained in the ash. A representative sample retained on the #8 sieve and passing the #4 sieve was air dried, weighed, and then washed. Once washed, the material was air dried and weighed again. The material that was lost due to washing was classified as fines. The remaining bottom ash was separated into three categories: glass, metals and clinker. The glass and metals are recyclable materials while the clinker consisted of any objects that were unidentifiable or miscellaneous, such as; rocks, ceramics, wood and paper. The ferrous materials were separated from the sample using a magnet while the non-ferrous materials and glass were removed by visual inspection. The remaining unidentifiable material was grouped into the clinker category. Once the sample was completely divided into categories, a percentage by weight of each category was recorded.

3.3.2 Grain Size Distribution

The grain size distribution of the MB and RDF ashes was conducted in accordance with ASTM C 136-84a, "Standard Method for Sieve Analysis of Fine and Coarse Aggregate" (ASTM, 1991). The bottom ash was oven dried at 110 ± 5° C for 24 hours before being sieved in a mechanical sieve shaker for 15 minutes. A series of US standard sieves were used: 1 in.(25.40 mm), 3/4 in., 3/8 in., #4

(4.75 mm), #10 (2.00 mm), #20 (0.85 mm), #50 (0.30 mm), #100 (0.15 mm), #200 (0.08 mm).

The parameters to be determined from the grain-size distribution of the WTE bottom ash are: the uniformity coefficient (C_u) and the coefficient of gradation, or coefficient of curvature (C_c), and the effective diameter (D_{10}), (Unified Soil Classification System, USCS). These coefficients are defined as follows:

$$C_u = \frac{D_{60}}{D_{10}} \tag{3.1}$$

$$C_c = \frac{D_{30}^2}{(D_{60})(D_{10})} \tag{3.2}$$

where:

D_{10} = diameter corresponding to 10 percent passing by weight, in mm.,
D_{30} = diameter corresponding to 30 percent passing by weight, in mm.,

and

D_{60} = diameter corresponding to 60 percent passing by weight, in mm.

3.3.3 Moisture Content

The moisture content of MB and RDF bottom ashes was conducted in accordance with ASTM C 566-89 " Standard Test Method for Total Moisture Content of Aggregate by Drying" (ASTM, 1991). A ventilated oven was used to dry the sample at a temperature of 110 ± 5° C. Two samples were used to determine the average moisture content. Moisture content tests were also conducted throughout the testing program.

3.3.4 Specific Gravity

Specific gravity tests were performed on two different MWC bottom ash grain size samples; one consisted of material passing the #4 sieve and the other consisted of material passing the #8 sieve. These tests were conducted in accordance with ASTM D-854-92, "Standard Test Method for Specific Gravity of Soils."

3.3.5 Absorption

The absorption of MB and RDF bottom ashes was conducted in accordance with ASTM C 128-88 (ASTM, 1991) "Specific Gravity and Absorption of Fine Aggregate". The absorption capacity of the aggregate represents the maximum amount of water that the aggregate can absorb. The bottom ash was oven dried at 110 ± 5° C for 24 hours and then submerged in water for another 24 hours before testing and divided into two size fractions using the # 4 (4.75 mm) sieve. For purpose of comparison with previous investigations conducted at Florida Tech, only the smaller size fraction passing the # 4 (4.75 mm) sieve was used.

3.3.6 Bulk Rodded Unit Weight

The bulk unit weight of MB and RDF bottom ashes was determined in accordance with ASTM C29/C29M-90 "Standard Test Method for Unit Weight and Voids in Aggregate" (ASTM, 1991). The sample was oven dried at 110 ± 5° C for about 24 hours before the test and then placed in a Proctor mold of 1/30 ft^3. The sample of bottom ash was compacted in three equal layers with a 5/8 in. diameter steel rod with a hemispherical tip, each layer was rodded 25 times with the rod. Once the mold was filled, the weight of the material was determined.

3.3.7 Moisture-Density Relationship

Moisture-density relationships were performed on MWC bottom ash from MB and RDF facilities. Two different grain size samples of each ash were used; one consisted of material passing the #4 sieve and the other consisted of material passing the #8 sieve. These tests were conducted in accordance with ASTM D-698-91, "Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort" and ASTM D1557-91, "Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort." A total of 42 specimens were fabricated and tested as shown in Table 3.1 for comparison to data reported by Chavez (1993).

Prior to sample fabrication, the sieved ash was air dried for approximately 72 hours. In order to achieve the desired moisture content range of 10 % to 24%, water was added to the ash. The samples were then mixed thoroughly in a mechanical mixer for approximately ten minutes and stored in air tight plastic bags for 48 hours to produce a uniform moisture distribution and to allow for any absorption to occur. After 24 hours, the moisture content of each sample was determined. If the moisture content revealed that the sample was on the dry side of the desired moisture content, water was added to the sample to obtain the desired moisture content. Samples which were found to be on the wet side of the desired moisture content were discarded and new samples were prepared. In either case, the samples would not be tested for 48 hours from the time of their preparation.

The samples of bottom ash were compacted to the desired energy level using either a manually operated or mechanical compactor. The compacted bottom ash was trimmed even with the top of the mold. From the excess material of each sample, approximately three 50 gram samples were collected for moisture content determination.

3.3.8 Permeability

To develop relationships between permeability and molding water content, multiple samples of MB and RDF bottom ashes were tested for permeability. The tests were conducted in accordance with AASHTO T-215-70. Falling head tests were conducted using compaction permeameters model K-610A designed by Soiltest. This unit consists of a standard steel compaction mold of 1/30 ft^3 which was replaced with a polyvinyl chloride plastic PVC mold of 1/30 ft^3, a cast aluminum base with a built-in porous stone that had an average pore size of 225 microns, and a cast aluminum top with overflow valve assembly. The samples were compacted following ASTM D-698. The two reasons for using the PVC mold were: 1) avoidance of corrosion of the steel mold due to extended exposure to water; and 2) prevention of chemical reactions which may occur between the ions in the ash and the metal. The apparatus shown in Photo 3.1, depicts five molds with specimens for falling head testing.

Factors which may influence the reliability of the permeability test in the laboratory, include: (a) air bubbles trapped in the test specimen (b) the degree of saturation of the test specimen and (c) temperature variation during the test. To minimize errors, the water temperature was recorded before and after each test, and the water was allowed to flow for about two hours until no air bubbles were observed before data collection.

For the specimens compacted wet of optimum, minimum flows were observed during the two hours of the deairing phase. A vacuum pump was used to remove the air bubbles for about 45 minutes before the specimen was saturated from the bottom upward under vacuum to free any remaining air bubbles in the specimens.

After the specimens had been saturated and the permeameters were full of water, the vacuum was disconnected. After saturation each specimen was subjected to steady state flow. Falling head tests were then conducted on each specimen. Five to ten trials were conducted on each specimen to determine an average permeability.

The following falling head formula was used to calculate the coefficient of permeability (k) of the test specimens.

$$k = 2.303\frac{aL}{At}\log\frac{h_1}{h_2} \tag{3.3}$$

where:

k = coefficient of permeability in cm/sec,
L = length of specimen in cm,
h_1 = initial head in cm,
h_2 = final head in cm,
t = total time elapsed during measurements in seconds,
A = cross-sectional area of specimen in cm^2, and
a = cross-sectional area of the tube used as a burette in cm^2.

The permeability was corrected using the equation:

$$k_{20^\circ C} = k_{T^\circ C}\frac{\eta_T}{\eta_{20}}. \tag{3.4}$$

where:

k_{20^oC} = coefficient of permeability at 20 ^{o}Celsius (68^{o}F) in cm/sec,
k_{T^oC} = coefficient of permeability at test temperature in cm/sec,
$_{20}$ = viscosity ratio of the water at 20 ^{o}Celsius (68^o F), and
$_T$ = viscosity ratio of the water at test temperature.

3.3.9 Swelling and Shrinkage Potential

Swelling potential is either the percent swell, or the swelling pressures generated by the expansion of soils. A method to determine swell pressures has not been standardized or accepted universally at this time (Sridharan *et al.*, 1986). The experiments conducted in this investigation are based on the percent swell of soils as suggested by Seed and Chan (1959). To evaluate the swelling and shrinkage potential of MB and RDF bottom ashes, compacted specimens at five different moisture contents were evaluated in both saturated and air dry conditions. Five of the remaining 10 specimens that were produced at the same time as the specimens used in the permeability test of WTE bottom ash were placed in plastic containers. A perforated 4 inch diameter clear acrylic plate with a centered 1/4 inch diameter 2 inch high clear acrylic rod extension was located on the upper surface of each specimen. A dial indicator of one full inch overall range with 0.001 inch continuous graduation divisions was seated on the upper portion of each stand (Photo 3.2). Water was added to the plastic containers and the axial expansion was recorded daily for data collection.

An additional five specimens were set up the same manner as described above with the exception that these five specimens were not submerged in water, and therefore allowed to air dry. This second set-up enabled the cementitious reactivity on soaked specimens to be compared with air dried specimens. After the submerged specimens reached an apparent equilibrium, the water was removed and the volume reduction or expansion measured while the specimens were drying.

3.3.10 Unconfined Compressive Strength

Unconfined compression tests were performed on MWC bottom ash from MB and RDF facilities. Two different grain size samples of each ash were used; one consisted of material passing the #4 sieve and the other consisted of material passing the #8 sieve. These tests were conducted in accordance with ASTM D-2166-91, "Standard Test Method for Unconfined Compressive Strength of Cohesive Soil." Samples were prepared both wet and dry of optimum. A total of six to eight samples were prepared for each bottom ash grain size ranging in moisture contents from 6% to 26%. The samples were then compacted to a relative density of 100% of either standard or modified proctor maximum.

The samples were extracted from the compaction molds using a Carver hydraulic press model C. Approximately 40 psi of pressure was applied to extract the specimens. Once the specimens were extracted from the molds, each one, in turn, was placed between the loading plates of a compression test machine. A metal cap and a rubber seat were used at each sample end to provide a uniform distribution of pressure on both surfaces. The unconfined compressive strength test was conducted using a GEO Brainard-Kilman model S-610 CBR/UCC compression test machine. A compressive load was applied to the surface of the sample and steadily increased at a loading rate of 0.005 inches per minute, until failure occurred. The compressive strength was calculated by dividing the ultimate load at failure by the cross-sectional area of the specimen.

3.3.11 Consolidated Drained (CD) Triaxial Shear

The testing program consisted of 72 CD triaxial shear tests. The tests were conducted with MB and RDF bottom ashes. Two different grain size samples of each ash were used; one consisted of material passing the #4 sieve and the other consisted of material passing the #8 sieve. The samples were prepared at relative densities varying from 90% to 100% of either standard or modified proctor maximum. The samples were then tested at various confining pressures from 5 psi to 15 psi. Table 3.2 presents a summary of the testing program in more detail.

The CD triaxial shear testing procedure outlined by Bishop and Henkel (1964) was used in this study. The CD triaxial shear test was conducted as an axial compression test in which the sample was consolidated under isotropic conditions, and subjected to shear stress by increasing the axial load with drainage. A very slow rate of loading is used to prevent excess pore pressures from being introduced into the system during the application of the axial load. For this study, a loading rate of 0.005 inches per minute was applied to the sample, until failure occurred. Since the pore pressures are negligible, the principal stresses become the effective stresses (Bishop and Henkel, 1964). The majority of the triaxial samples were prepared using a Harvard Miniature compaction procedure outlined by Wilson (1964). These samples were compacted to the desired density in a split mold by varying the number of layers, the number of tamps per layer and the spring used. The number of layers ranged from 3 to 6, the number of tamps per layer ranged from 10 to 30 and either a 20 lb or 40 lb spring was used. In addition, the porous stones were covered with filter paper to prevent clogging and strips of filter paper were draped across each sample to aid in the saturation process. However, some of the samples exhibiting low relative densities crumbled while being removed from the mold. These low relative density samples were prepared following the procedure outlined by Bishop and Henkel (1964). A brief summary of this procedure follows: 1) samples are constructed by placing a split mold around the membrane; 2) the prepared ash is weighed to get an initial weight; 3) the ash is placed inside the membrane and gently compacted using a wooden tamper until a height of 2.8" is attained; 4) the remainder of the prepared ash is weighed again to determine the weight of the sample; and 5) the density of the constructed sample is also calculated, since an approximate moisture content of the prepared sample is known.

3.3.12 Elastic Modulus

The elastic modulus was calculated from the stress-strain data for each CD triaxial shear test. This was accomplished by calculating the slope of the elastic portion of the stress-strain curve. The elastic modulus equals the stress divided by the strain as shown in equation 3.5.

$$E = \frac{\sigma}{\varepsilon} \qquad (3.5)$$

where: E = modulus of elasticity
σ = stress
ε = strain

3.3.13 Resilient Modulus

The resilient modulus is defined as the change in stress divided by the change in strain as shown in equation 3.6.

$$Mr = \frac{\Delta\sigma}{\Delta\varepsilon} \qquad (3.6)$$

where: Mr = resilient modulus
$\Delta\sigma$ = change in stress @ given strain
$\Delta\varepsilon = 0.001$ in/in

The resilient modulus was determined for the majority of the CD triaxial tests. This was accomplished by unloading and reloading the specimen. The specimen was unloaded at 0.030" displacement (1.1% strain) and reloaded at 0.027" displacement (1.0% strain). This allowed a resilient modulus at 1% strain to be calculated. In addition, the specimen was also unloaded at 0.050" displacement (1.8% strain) and reloaded at 0.047" displacement (1.7% strain).

3.3.14 California Bearing Ratio (CBR)

California Bearing Ratio (CBR) tests were performed on MB and RDF bottom ash passing the #4 sieve. These tests were conducted in accordance with ASTM D-1883-92, "Standard Test Method for CBR (California Bearing Ratio) of Laboratory Compacted Soils" using the compactive energy as described in ASTM D-1557-91. A surcharge of 15 lbs. was applied to simulate the overburden pressure. Four MB bottom ash samples were prepared with moisture contents ranging from approximately 11% to 16% and four RDF bottom ash samples were also prepared with moisture contents ranging from 14% to 19%. Each set of four ash samples were tested unsoaked.

In addition to the unsoaked CBR test, one MB bottom ash sample and one RDF bottom ash sample were tested soaked. These samples were at their maximum dry density before being immersed in water for 96 hours prior to testing. This was done: 1) to provide the engineer with both expansion and strength loss information on the ash when it becomes saturated in the field 2) and for comparison to the unsoaked values (Bowles, 1992).

The ASTM specification defines the CBR number as, "the ratio of the unit stress required to effect a certain depth of penetration of the standard into a compacted specimen of soil at some water content and density to the standard unit stress required to obtain the same depth of penetration on a standard sample of crushed stone." The CBR number is usually based on the ratio for a penetration of 0.1". However, if the CBR number at a penetration of 0.2" is greater than that at 0.1", the test must be redone. If the second test yields the same results, the CBR number at 0.2" penetration is used.

These relationships are shown in equations 3.7 and 3.8.

$$\text{CBR @ } 0.1'' = \frac{\sigma_{0.1''}}{1000 \text{ psi}} * 100 \tag{3.7}$$

$$\text{CBR @ } 0.2'' = \frac{\sigma_{0.2''}}{1500 \text{ psi}} * 100 \tag{3.8}$$

where: CBR = California Bearing Ratio in percent
$\sigma_{0.1''}$ = Corrected stress @ piston penetration

3.3.15 Limerock Bearing Ratio (LBR)

The Limerock Bearing Ratio (LBR) values were calculated for MB and RDF bottom ash samples passing the #4 sieve using the data collected from the CBR tests. The previously collected data was used since the procedure for the CBR tests (ASTM D-1883-92) is in accordance with the procedure for the LBR tests (FDOT FM-5-515). The LBR was determined to evaluate the MWC bottom ash in various highway applications encountered in Florida.

The LBR number equals the stress at 0.1" penetration divided by 800 as shown in equation 3.9.

$$\text{LBR} = \frac{\sigma 0.1''}{800 \text{psi}} * 100 \tag{3.9}$$

where: LBR = Limerock Bearing Ratio in percent
$\sigma_{0.1''}$ = Corrected stress @ 0.1"

3.4 WTE Bottom Ash Environmental Tests

3.4.1 Loss on Ignition

The procedure outlined by ASTM C311 "Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete" (ASTM, 1990) was used to determine the loss-on-ignition of WTE bottom ash. Samples were oven dried at 105°C for 24 hours and then combusted within a furnace at 550° C for at least 2 hours to a consistent weight.

3.4.2 Elemental Analysis

Ash samples for the study were sieved through a No. 4 sieve (4.76 mm in opening size) and stored in plastic containers until used. Two batches of bottom ash were retrieved at different times. Six samples that were 1,000 g each were taken for an analysis of Ag, As, Ca, Cd, Cr, and Pb. Ash samples were oven-dried at 105±5° C for 4 hours and then crushed until a minimum of 500 g could be collected through a 500-µm sieve. The crushed samples were weighed and dried in 24 hour increments at 105±5° C until the change in the weight of the sample was less than 0.5%. All oven-dried samples were cooled in a desiccator prior to digestion. The plasticware used for the study was cleaned and soaked in a 10% HNO_3-10% HCl acid bath for at least 24 hours and then rinsed at least three times with distilled-deionized water (DDW). All acid-cleaned apparatus was stored in plastic bags until used.

The Silberman and Fisher (1979) technique, which uses hydrofluoric-boric acids (HF-H_3BO_3), was utilized in this study. Approximately 0.5 g of each dried sample was weighed and transferred to a 125-ml polyethylene bottle. Next, 5 ml of DDW and 5 ml of HF were added to each sample. The samples were then shaken in a reciprocating shaker for 24 hours. Afterwards, 90 ml of 3% H_3BO_3 was added to the samples, and the samples were shaken again for another 24 hours. Samples with undissolved residue were vacuum-filtered through a 0.40 µm Millipore® membrane filter. The filtrate was then diluted to 100 ml of final solution.

The filtrates were analyzed for concentrations of selected metals— which included Ag, As, Ca, Cd, Cr, and Pb—using a Perkin-Elmer Zeeman 5100 Atomic Absorption Spectrophotometer (AAS) equipped with a graphite furnace. Calcium was analyzed using the flame AAS, and Ag, As, Cd, Cr, and Pb were analyzed using the graphite furnace AAS. A well-characterized ash sample—Standard Reference Material fly ash (SRM-1633a) from the National Institute of Standards and Technology (NIST)—was used as a reference material. This was acid-digested using exactly the same procedure as that used for the ash samples to determine the completeness of the digestion of the ash and to provide the accuracy and quality assurance of analytical methods.

A 1% La^{3+} (w/v) solution was used for the analysis of calcium in the AAS operation using an air-acetylene flame to suppress the interference caused by the presence of the stable oxysalts: aluminum, beryllium, phosphorus, silicon, titanium, vanadium, and zirconium. The stable oxysalt phosphorus, for example, was formed by the reaction below:

$$2Ca^{2+} + 2PO_4^{3-} + 2H^+ \rightarrow Ca_2P_2O_7 + H_2O$$

With the addition of La^{3+} (w/v) solution, Ca^{2+} was able to be analyzed more effectively by minimizing the phosphate effect according to following equation:

$$La^{3+} + PO_4^{3-} \rightarrow LaPO_4$$

The La^{3+} solution was prepared by adding 11.728 g of lanthanum oxide (La_2O_3) to 10 ml of DDW and by next adding 50 ml of concentrated HCl to dissolve the La_2O_3. The solution was then diluted to 1 liter with DDW.

During the time the AAS graphite furnace was used, selected modifier solutions were utilized to improve the performance of metal analysis. The optimum parameters for furnace operation are presented in Table 3.3.

A standard calibration curve using three standards was carried out in each AAS operation. A solution of NIST 3171 or 1633a coal fly ash with a known concentration was analyzed to ensure the accuracy of the standard calibration curve.

3.4.3 Mineralogy

Samples were examined for the morphology of individual particles and for mineral formation within the ash matrix using a scanning electron microscope (SEM) equipped with an energy dispersive x-ray spectrometer (EDS). Prior to SEM/EDS analysis, samples were dried and sieved manually to collect particles in the range smaller than 0.5 mm or in the range smaller than 1 mm but greater than 0.5 mm. Both fraction sizes of ash samples were examined for mineral formation. Selectively, based on SEM observation, some samples were applied to EDS analysis to determine the predominant elements of ash particles or identified mineral.

3.4.4 Pozzolanic Activity

The pozzolanic activity index of MWC ash was determined according to ASTM C311-90 "Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland-Cement Concrete" (ASTM, 1991). Cubes 5 x 5 x 5 cm were used as molds for curing specimens up to 28 days in a water-lime bath. This was followed by testing for compressive strength. The control mixture for the test was a combination of graded sand, type I portland cement, and water. The test mixture was prepared by replacing 20% of the cement with ground ash and passed through a #100 US standard sieve. The index was determined by the ratio of the strength of the test samples over the strength of the control samples multiplied by 100. An index of 100 indicates that ash has pozzolanic qualities equal to that of portland cement. An index greater than 100 indicates that ash has better pozzolanic qualities than portland cement, while an index less than 100 indicates that ash has poor pozzolanic qualities when compared with portland cement.

3.4.5 Column Leaching Test

The column leaching test, modified from the ASTM D4874 "Standard Test Method for Leaching Solid Waste in a Column Apparatus" (ASTM, 1989), was conducted to investigate the leaching characteristics of compacted MWC bottom ash. A segment of PVC pipe, with an inside diameter of 10.2 cm (4 in) and a height of 45.7 cm (18 in), was used in the study as a column apparatus. The PVC cylinder was mounted on a perforated clear acrylic plate and a rubber gasket was placed between the plate and the bottom of the cylinder. Before preparing a sample column, all parts of the test apparatus that would contact the ash material, leaching fluid, or product leachate were cleaned by submersion in an acid bath for 24 hours, rinsed with DDW at least three times and dried in a ventilating hood.

A previous study reports that the compactive effort of the modified Proctor test is suitable to simulate heavy field equipment used in construction (Forrester and Goodwin, 1990). Ash columns for leaching tests in the study were fabricated using the compaction technique according to the ASTM D698, "The Standard Methods of Test for Moisture-Density Relations of Soils Using 2.5-kg Hammer and 304.8-mm Drop" (ASTM, 1989). The PVC cylinder and a metal collar were fastened firmly to a detachable base plate to ensure that the compaction energy was not absorbed by the vibration or shifting of the column cylinder during compacting. The compaction mold was weighed before and after compaction. The weight difference was used to determine the density of the compacted ash column.

To fabricate the ash column, ash material (less than 4.76 mm) was compacted into the cleaned PVC cylinder to a height of 15.2 cm or 45.7 cm in 4 and 12 layers, respectively, with 25 uniformly distributed blows per layer. The compaction was performed using a 24.5 Newton compaction hammer which dropped 0.305 m onto the ash material.

After compaction the whole apparatus, with the ash material inside it, was weighed again to determine the compacted weight of the MWC bottom ash. Approximately 300 g of ash from the same container was dried in the oven at 105±5° C until the weight difference after two successive periods of drying was less than 0.5% (ASTM D2216, 1989). The weight was then used to determine the moisture content of the wet sample—obtained by dividing the weight of the water in the ash by the dry weight of the ash.

The compacted ash column was carefully assembled in the laboratory. To avoid the potential error of presaturating an ash column before the leaching test was begun, a sprinkler system was developed in the study to simulate the mean annual maximum rainfall of 5.1 cm/hour (U.S. Geological Survey, 1970), which was converted to the flow rate of 7 ml/min. by multiplying 5.1 cm/hour by the surface area of the ash column (i.e., 81 cm^2).

To determine the effects of flow rate on the leaching characteristics of MWC bottom ash, leaching fluids at a rate of 4, 7, and 10 ml/min. were used, respectively, in the study. Leaching fluid was pumped to the top of the column and through the sprinkler system by an electrically driven peristaltic pump to simulate the rainfall event. The flow rate of the leaching fluid was determined before and after the leaching test by measuring the volume of the leaching fluid collected over a specific period of time. The sprinkler system was assembled by fitting 17 tubes with an inside diameter of 0.58-mm into a larger tube with a 3.18-mm inside diameter. The space between the 0.58-mm tubes was sealed with polyurethane glue (3M Marine Adhesive/Sealant, Part No. 05203). Leachate was collected from the bottom of the column.

For tests at a flow rate of 4 ml/min., leachate samples were collected every 20 minutes for 6 hours. At flow rates of 7 and 10 ml/min., leachate samples were collected every 10 minutes for the first 2 hours, and every 20 minutes for the next 4 hours. The volume of individual leachate samples taken at each interval was measured and recorded. An aliquot of 10 ml of leachate was taken from each sample for pH determination before filtration. The rest of the sample was filtered to remove suspended solids. The filtered samples were then treated with 0.5-ml ultra pure HNO_3 to reduce pH to less than 2. The filtrates were then analyzed for concentrations of Ag, As, Ca, Cd, Cr, and Pb.

In addition to the change of flow rate, the effects of the contact time of leaching fluid with the ash column were determined by changing the height of the compacted MWC ash column. There was no criteria for selecting the height of the ash column to meet the objective of the study. Generally, a 30.5- cm column is used for column leaching study. To create a significant range of difference in height and to cover the general height of 30.5 cm, the column heights of 15.2 and 45.7 cm were investigated.

The leaching fluids used in the study were a pH 4.5 distilled-deionized water (DDW) and a pH 4.2 synthetic acid rain (SAR) solution. The effect of acid rain was determined by using an SAR solution as the leaching fluid. The SAR was prepared according to the National Atmosphere Deposition Program (NADP) quality reference to simulate acid rain common to the Northeastern United States (U.S. EPA, 1990). A primary solution was prepared by the addition of the chemicals shown in Table 3.4 to four liters of DDW. The primary solution was then diluted ten fold. A 1 N NaOH solution was used, when necessary, to adjust the pH to approximately 4.2.

Table 3.1 Specifications followed to evaluate physical composition

- Grain Size Distribution (ASTM C 136-84a)
- Moisture Content (ASTM C-566-89)
- Specific Gravity (ASTM D-854-92)
- Moisture-Density Relationship (ASTM D-698-91 & ASTM D-1557-91)
- Permeability (AASHTO T-215-70)
- Swell Potential (Seed and Chan, 1959)
- Shrinkage Potential (Seed and Chan, 1959)
- Unconfined Compressive Strength (ASTM D-2166-91)
- Consolidated Drained Triaxial Shear Test
- Determination of Elastic Modulus
- Determination of Resilient Modulus
- California Bearing Ratio (CBR) Test (ASTM D-1883-92)
- Limerock Bearing Ratio (CBR) Test

Table 3.2 CD triaxial shear testing program on bottom ash

ASTM D-698-91				ASTM D-1557-91			
MB < #4		RDF < #4		MB < #4		RDF < #4	
Dr	σ_3	Dr	σ_3	Dr	σ_3	Dr	σ_3
100%	5 psi	100%	5 psi	100%	5 psi	100%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi
95%	5 psi	95%	5 psi	95%	5 psi	95%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi
90%	5 psi	90%	5 psi	90%	5 psi	90%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi
MB < #8		RDF < #8		MB < #8		RDF < #8	
Dr	σ_3	Dr	σ_3	Dr	σ_3	Dr	σ_3
100%	5 psi	100%	5 psi	100%	5 psi	100%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi
95%	5 psi	95%	5 psi	95%	5 psi	95%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi
90%	5 psi	90%	5 psi	90%	5 psi	90%	5 psi
	10 psi		10 psi		10 psi		10 psi
	15 psi		15 psi		15 psi		15 psi

Dr = Relative Density σ_3= confining pressure 1 psi = 6.895 kPa

Table 3.3. Conditions for graphite furnace AAS with Zeeman background correction

Element	Wavelength (nm)	Slit (nm)	Pretreatment temp./time[a]	Atomize temp./time	Modifier Solution
Ag	328.1	0.7	800/20	1800/5	1/2 $(NH_4)_2HPO_4$ [b]+ 1/2 NH_4NO_3[c]
As	193.7	0.7	1200/35	2300/5	$Ni(NO_3)_2$[d]
Cd	228.8	0.7	600/35	1600/5	NH_4NO_3
Cr	357.9	0.7	1650/30	2500/5	1/2 $(NH_4)_2HPO_4$ + 1/2 NH_4NO_3
Pb	283.3	0.7	700/35	1800/5	1/2 $(NH_4)_2HPO_4$ + 1/2 NH_4NO_3

[a] Temperature was given in °C and time in second.

[b] 3 % $(NH_4)_2HPO_4$

[c] 10 % NH_4NO_3

[d] 2 % $Ni(NO_3)_2$

Table 3.4 Chemicals used to prepare a primary solution for a 4-liter synthetic acid rain

Chemical	Weight (g)
$NaNO_3$	0.1150
KNO_3	0.2196
NH_4NO_3	0.6480
$MgCl_2$	0.0821
H_2SO_4	0.1755[a]
$CaSO_4$	0.1057

[a] The H_2SO_4 had a concentration of 98 percent by weight.

Figure 3.1 Survey of Statewide Waste-to-Energy Plants
A Study for the Florida Department of Transportation to Enable the Development of FDOT Specifications for WTE Bottom Ash

1. Facility name, address, phone number and contact person(s) ______________________________

2. Name and phone number of the contractor (or plant operator) that operates the plant ______________________________

3. Is the facility a mass-burn( ), or a refuse derived fuel plant ( )?

4. Plant operation information:
   - a. MSW burn rate ______________________________
   - b. Furnace temperature ______________________________
   - c. Production rate of MSW ashes:
     - fly ash ______________________________
     - bottom ash ______________________________
     - scrubber ash ______________________________

5. Are the incinerator ashes combined ( ) or kept separate ( ) before landfilling?
   - If combined what are the approximate percentages of fly ash ( ), scrubber residue ( ), and bottom ash( )?

6. Is there any additional treatment performed on the incinerator ashes before landfilling? Yes ( ) No ( ).
If yes please check the appropriate items below.
   - a. removal of metals ( ) ______________________________
   - b. removal of certain metals ( ) ______________________________
   - c. removal of other materials ( ) ______________________________

7. Who is responsible for your resource recovery (name, address, phone number)? ______________________________

8. How are you currently using the bottom ash? ______________________________
   - a. percent landfilled ______________________________
   - b. percent daily cover ______________________________
   - c. percent other, please specify ______________________________

9. Please include any additional information or reports on your facilities and bottom ash which may be available.

10. If available, please provide printed materials (i.e. brochures) about your facility to:
Paul J. Cosentino, Ph.D., P.E.
Civil Engineering Department
Florida Institute of Technology
Melbourne Florida, 32901-6988
(407) 768-8000 (ext. 7555)

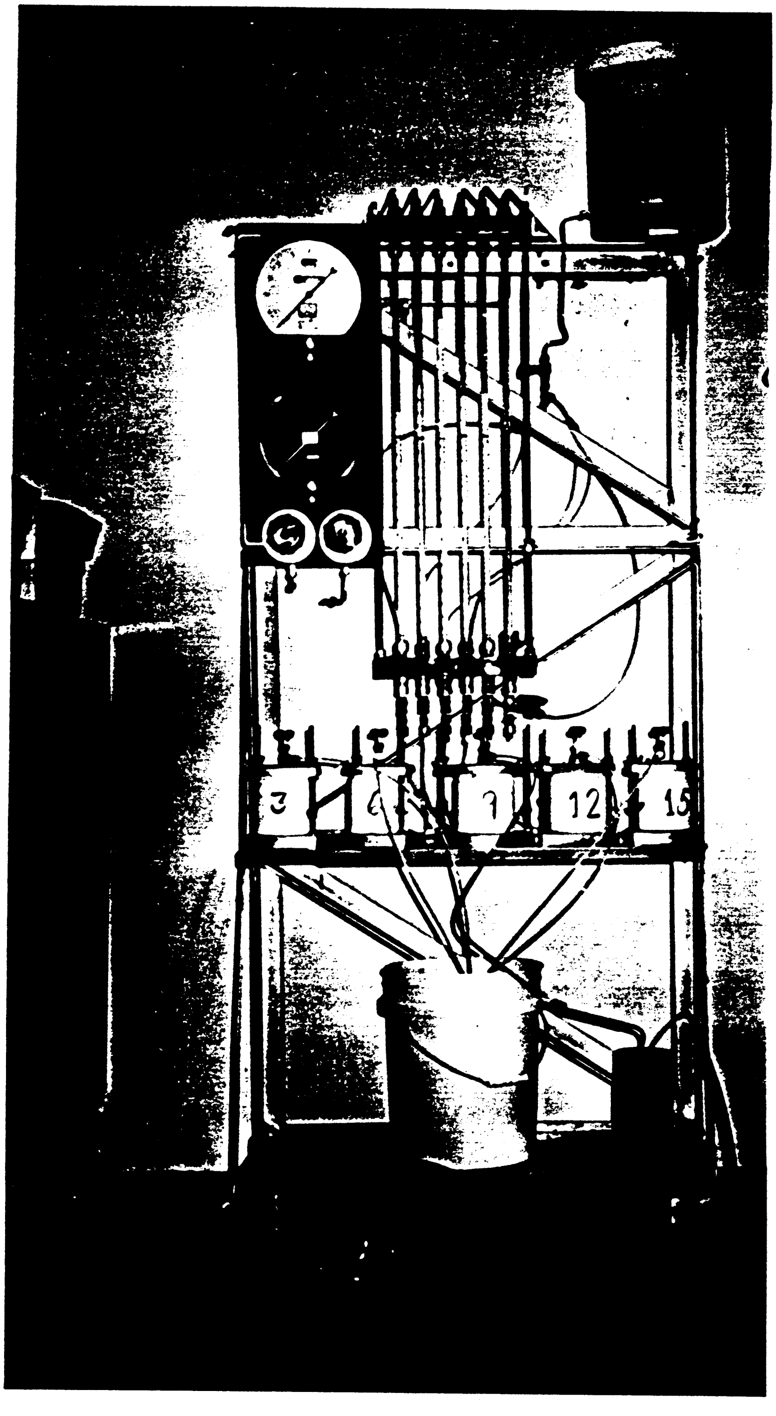

Photo 3.1. Permeability test set-up

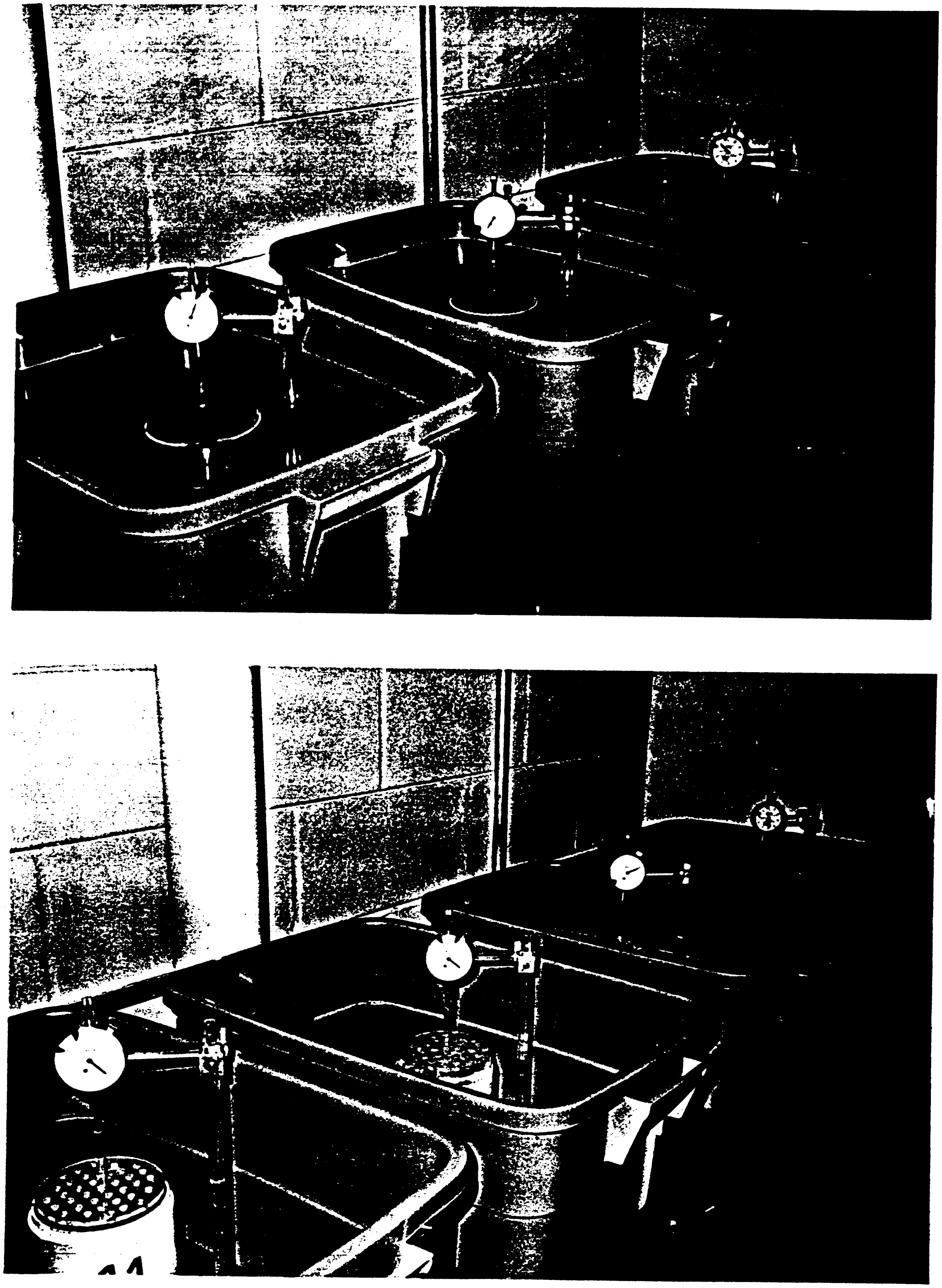

Photo 3.2. Swell and shrinkage tests, saturated and dry

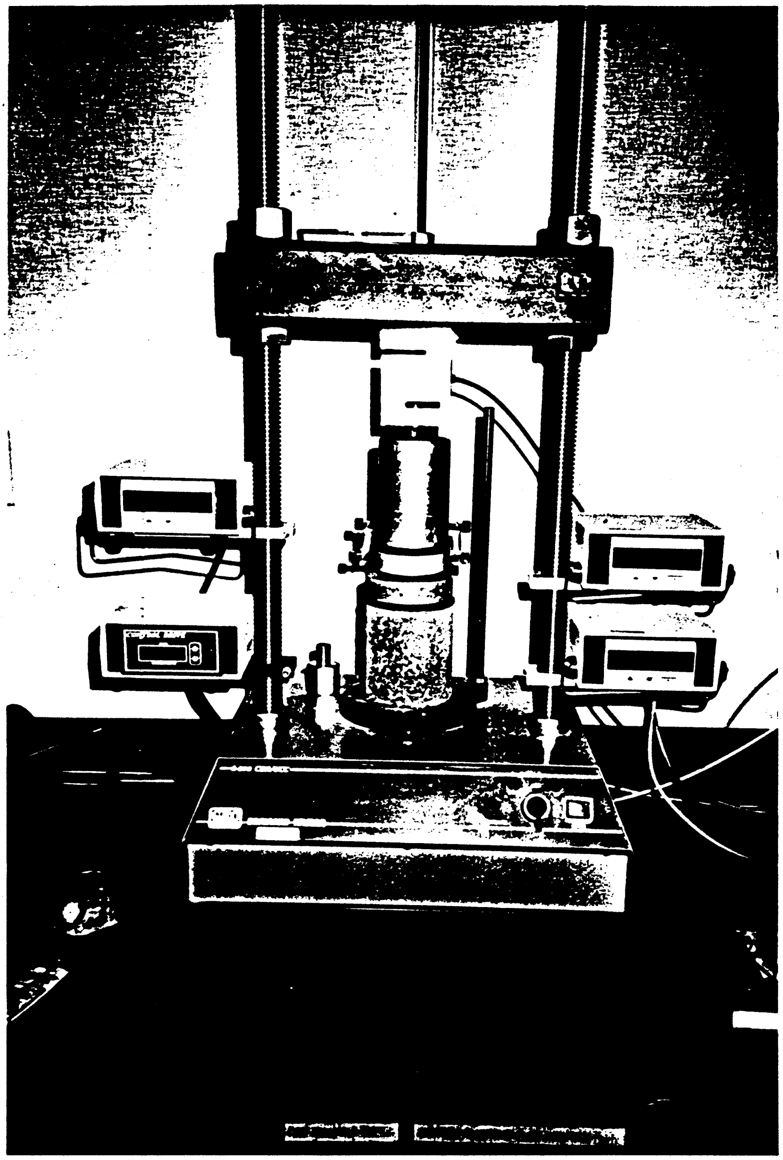

Photo 3.3. Unconfined compressive test on the WTE bottom ash specimen

4.0 PHYSICAL, GEOTECHNICAL AND ENVIRONMENTAL PROPERTIES

MWC bottom ash was collected from the facilities described in Section 3.2. Normally bottom ash is combined with fly ash at most WTE facilities. The MWC bottom ash from the MB facility was collected in two plastic 55 gallon drums and shipped to Florida Tech in Melbourne, on October 30, 1992 and January 22, 1993. The MWC bottom ash from the RDF facility was also collected in two plastic 55 gallon drums and shipped to Florida Tech in Melbourne, on January 21, 1993. The bottom ash was stored indoors in sealed 55 gallon plastic drums. The MB ash could be described as a coarse grained material that is dark gray to black in color while the RDF ash could be described as a medium grained material that is light gray to gray in color

4.1 Physical Composition

4.1.1 Visual Classification

The physical composition of the bottom ash evaluated at Florida Tech is shown in Figure 4.1. The MB bottom ash sample consisted of: 48% clinker and miscellaneous, 32% metals, 16% glass and 4% fines. The RDF bottom ash sample consisted of 60% clinker and miscellaneous, 16% metals, 20% glass and 4% fines. These analyses represent the composition of the ash sample that were used for this study and should not be considered as representative of the ash produced at the two facilities. The RDF bottom ash had a lower percentage of metals than the MB bottom ash. This lower percentage of metals in the RDF bottom ash can be attributed to the processing of the MSW prior to combustion. Thus, it could be inferred that the RDF facility was recovering twice as many of recyclable metals as the MB facility. The composition of bottom ash may be a significant factor in determining the suitability of different bottom ash sources for highway applications.

4.1.2 Specific Gravity

The average specific gravity for the MB bottom ash samples passing the #4 and #8 sieves were found to be 2.79 and 2.72, respectively. The average specific gravity for the RDF bottom ash samples passing the #4 and #8 sieves were found to be 2.55 and 2.45, respectively. These specific gravities fall within the range of values reported by: Chavez (1993) [2.72], Huang and Lovell (1990) [1.94 to 3.23] and Seals, Moulton and Ruth (1972) [2.28 to 2.78].

The specific gravity of bottom ash is a function its chemical constituents (Seals, *et al.*, 1972). Huang and Lovell (1990) found that bottom ash with high carbon content resulted in low specific gravity, whereas bottom ash with high iron content resulted in high specific gravity. The differences in specific gravity reported in this investigation can be attributed to the different compositions of the two bottom ashes. The MB bottom ash has a larger percentage of metals which tends to increase the specific gravity, while the RDF bottom ash has a higher percentage of glass which decreases the specific gravity. The specific gravity of the bottom ash decreased with a decrease in grain size which may be attributed to the mass being concentrated in the larger particles.

4.1.3 Moisture Content

The moisture content of the MB and RDF bottom ash when it was delivered ranged from 11% to 19%, and from 16% to 26%, respectively. These moisture contents were taken during the two year investigation period. Previous studies utilizing MB bottom ash have reported similar moisture contents at Florida Tech Wu (1990) 10.6% to 18%, Nevin (1992) 4.4% to 7.5% and Jain (1992) 12% to 18%. Chesner (1989) found that bottom ash samples from facilities which have ferrous metal removal systems tend to have a higher moisture content than ash samples from facilities without these systems. This was not found to be the case in this investigation where processing of ash for metals removal is conducted after combustion.

4.1.4 Absorption

The absorption of the MB and RDF bottom ash ranged from 9% to 12%, and 11%, respectively. The water absorption rates of the ash are higher than conventional fill materials.

4.1.5 Mineralogy

Results of mineral examination showed the presence of mineral fibers on the surface of ash particles (Figure 4.2). The fiber is embedded in the ash particle and is found to link ash particles together (Figure 4.3). Identification of the mineral fiber using an energy dispersive x-ray spectrophotometer has shown the predominance of aluminum(Al), silica (Si), and Calcium(Ca) on the fiber (Figure 4-4).

4.1.6 Pozzolanic Activity

The pozzolanic activity index of MB bottom ash was found to be 135– indicating that MB bottom ash possesses better pozzolanic properties than cement. The index value was very similar to that reported by Shieh and Kalajian (1994). The index of RDF bottom ash, however, was much less than 100,–*i.e.*, 65– indicating that RDF bottom ash possesses poor pozzolanic properties when compared to cement.

4.1.7 Loss on Ignition

The loss on ignition of MB and RDF bottom ash was found to range between 4.4% to 5% for both bottom ash sources. These values are at the low end of the range of coal fly ash (2% to 20%) used as a concrete admixture.

4.2 Engineering Classification

Grain size distribution curves for the bottom ash from both facilities are shown in Figure 4.5. Table 4.1 presents classification parameters and a brief summary of the physical properties of the bottom ash. Both ashes display physical characteristics similar to a well-graded, granular soil. Although the effective particle sizes, uniformity coefficients and coefficients of curvature differ between the two ashes, both materials would be classified under the Unified Soil Classification System as well graded sands with little or no fines (SW). Under the American Association of Transportation and Highway Officials, the ash is classified as a type A-1-a (0), which is characterized as granular material with a small amount of fines (Holtz and Kovacs, 1981). These classification systems are used only to classify the ash as a soil. The MB and RDF bottom ash would be classified as #89 using the ASTM aggregate classification.

4.3 Bulk Rodded Unit Weight

The bulk rodded unit weight of the MB and RDF bottom ash ranged from 77 pcf to 81 pcf, and 69 pcf, respectively. The bulk rodded unit weight of the ash are at the lower range associated with conventional fill materials.

4.4 Moisture Density Relationships

The moisture-density relationship results for the WTE bottom ash are summarized in Table 4.2 and are shown in Figures 4.6 to 4.9. The moisture-density relationships for the MB bottom ash samples have higher maximum dry densities and lower optimum moisture contents as compared to the RDF bottom ash samples. These results compare well with previous investigations summarized in Table 2.1. The shape of the compaction curves shown in Figures 4.6 to 4.9 resemble the parabolic Type A compaction curve found in typical laboratory investigations by Winterkorn and Fang (1975).

For a given ash source, the maximum dry density decreased with a decrease in grain size while the optimum moisture content increased. Increasing the compaction energy tends to increase the maximum dry density but also decreases the optimum moisture content. The moisture density relationships for ash behave very similar to conventional soils, as shown by Holtz and Kovacs (1981).

4.5 Permeability

The variation in permeability with respect to moisture content is shown in Figure 4.10. The RDF and MB bottom ash when compacted dry of optimum moisture content; displayed permeability with magnitudes less than 1 x 10^{-2} cm/sec. However, once optimum moisture content was reached, the permeability reduced by 3 orders of magnitude to 1 x 10^{-5} cm/sec in both bottom ashes. This behavior is similar to that of a sandy clay, where the coefficient of permeability decreases as the compaction moisture content increases (Holtz and Kovacs, 1981). Demars *et al.* (1994) report similar results for MB ash at optimum with a magnitude of 1 x 10^{-4} cm/sec. Huang and Lovell (1990) report permeability coefficients of 5.0×10^{-3} and 2.0×10^{-3} cm/sec for bottom ashes having 6 and 10 percent fines and compacted at 95 percent of the maximum dry density (109 pcf). They concluded that the percentage of fines has a predominant effect on the permeability of bottom ash. The percentage of fines for the MB bottom ash used in this investigation was 3 percent.

The effects that age after compaction has on permeability of bottom was determined by examining the results of tests conducted on compacted MB bottom ash at various compaction moisture contents (10% to 16%) and at time periods of 0, 7, 14, 21 and 120 days. Permeability tests conducted at 0, 7, 14 and 21 days were kept saturated while tests conducted at 120 days were allowed to air dry after compaction. The results are presented in Figure 4.11 and show very small variations of permeability with age for ash that is below or near optimum moisture content.

Permeability in bottom ash decreases significantly as the compaction moisture content increases past the optimum moisture content. Age has a minimal effect on the permeability of bottom ash compacted below optimum moisture content.

4.6 Shrink-Swell Potential

To evaluate the free shrink-swell characteristics of compacted WTE bottom ash, ten (10) specimens of MB bottom ash were compacted following ASTM D 698 at moisture contents ranging from 10 % to 16%. The moisture contents were selected so that the prepared specimens would bracket the optimum moisture content. Half of the specimens were allowed to air dry to determine volume change over a period of 120 days. These specimens will be referred as Dry Condition

Figure 4.12 represents the maximum and minimum of the percent axial change versus time of the compacted bottom ash specimens. The compacted bottom ash did not show any significant volume change over the initial ten to fourteen days. Approximately nine days after beginning the test, the bottom ash exhibited an increase in volume and white air bubbles where observed on the upper surface of the specimens. The rate of axial expansion in the compacted MWC bottom ash that was allowed to air dry decreased after fifty days, though axial expansion continued to the completion of the testing period. Figure 4.12 shows that after 120 days the axial expansion ranged from 2.3 % to 3.6 %.

The remaining specimens of compacted bottom ash were saturated in water. Figure 4.13 represents the percent axial expansion versus time of the five specimens that were submerged in water. During the initial 34 days of submersion, the compacted bottom ash had a negligible volume change. After day 34, it was decided that the specimens should be removed from the water. The bottom ash compacted wet of optimum shrunk about 0.5 percent, while the remaining specimens exhibited little volume change.

Fifteen days later (50 days after initial specimen fabrication) all the specimens began to increase in volume with axial expansion of 0.8 to 1.6 percent at 120 days. At the same time as the specimens increased in volume more air bubbles appeared on the upper surface of the specimens. These white air bubbles, observed in all the bottom ash specimens, may be an indication that a chemical reaction was inducing the change in volume.

When Figure 4.12 is compared with Figure 4.13, it is evident that bottom ash specimens that had been submerged for 34 days (Saturated Condition) had less of a tendency to swell than the specimens that had been allowed to air dry (Dry Condition). While the axial expansion of the bottom ash is less than that of expansive clay, it may be possible to reduce its magnitude by submerging in water immediately and allowing air drying for a period of time (aging). This aging procedure allows time for the swelling process to take place before the bottom ash is used in any construction application (Hjelmar, 1990).

4.7 Strength-Deformation

The strength-deformation properties of the bottom ash that were evaluated, were unconfined compressive strength, consolidated drained triaxial shear strength, the elastic and resilient moduli and the California and limerock bearing ratios.

4.7.1 Unconfined Compressive Strength

The unconfined compressive strength test results for the MB and RDF bottom ash passing the #4 and #8 sieves are shown in Figures 4.14 and 4.15, respectively. Both figures show significantly higher unconfined compressive strengths for bottom ash occurring at higher compaction energy levels and independent of ash source.

From Figures 4.14 and 4.15, both the MB and RDF bottom ash samples compacted utilizing ASTM D-1557 exhibited higher compressive strengths on the dry side of optimum and lower compressive strengths on the wet side of optimum. The MB and RDF ash samples passing the #8 sieve and compacted utilizing ASTM D-1557 or D-698 also displayed higher compressive strengths on the dry side of optimum. The only exception to this behavior was the bottom ash passing the #4 sieve and compacted utilizing D-698 which displayed maximum compressive strengths at or near the optimum moisture content.

Figure 4.14 also includes the results of the MB ash samples tested by Chavez (1993) for comparison to MB and RDF ash samples passing the #4. The bottom ash samples in this study were tested immediately after compaction while the MB ash samples tested by Chavez (1993) were compacted utilizing ASTM D-698 and then tested 120 days later. Chavez (1993) aged MB ash samples attained a compressive strength of nearly 100 psi while the MB ash samples that were tested immediately after compaction had a compressive strength of approximately 25 psi. From these results, it is evident that pozzolanic reactions which increase unconfined compressive strength have occurred as the compacted ash ages.

The unconfined compressive strength of compacted bottom ash is quite similar to compacted soils in that the unconfined compressive strength is higher either dry or near optimum moisture content and increases with compaction energy. Thus compaction moisture content and compaction energy are controlling factors for unconfined compressive strength. Allowing compacted bottom ash to age increases its strength due to pozzolanic activity of the bottom ash.

4.7.2 Consolidated Drained Triaxial Shear

The CD triaxial shear results are summarized in Table 4.3 for densities at relative compaction of 90%, 95%, and 100% of ASTM D-698 and D-1557. Every attempt was made to prepare the samples at moisture contents which were within 1% dry of optimum. The MB bottom ash samples passing the #4 sieve could not be compacted to the relative compaction of 95% and 100%. The number of layers and the number of blows were continually increased, however the required densities could not be achieved in the laboratory.

Typical stress-strain curves and the volumetric strain versus axial strain curves for MB and RDF ash passing the #4 and #8 sieves in lose and dense conditions are presented in Figures 4.16 and 4.17, respectively. The concepts regarding dilatancy and interlocking as presented by Lambe and Whitman (1979) were found to hold true during triaxial compression. The densely compacted ash samples displayed a well defined peak and the principal stress difference decreased following this peak. The loosely compacted ash samples did not display a well defined peak and the principal stress difference remained fairly constant once the compressive strength had been reached.

The densely compacted ash samples significantly expanded in volume as the strain increased while the loosely compacted ash samples first decreased in volume and then either expanded to almost the initial volume or continually decreased. Failure occurred between 2.3% and 6.6% axial strain for confining pressure ranging between 5 psi (35 kPa) and 15 psi (105 kPa), respectively.

The cohesion of both MB and RDF bottom ash ranges from 2 psi to 5 psi (14 kPa to 35 kPa). A cohesion of zero would have been expected since the bottom ash is a granular material. This relatively small amount of cohesion can be attributed to pozzolanic reactions occurring in the bottom ash. The friction angles of both MB and RDF bottom ash ranges from 24° to 50° and were found to be a function of relative compaction and grain size. When the compaction energy and relative compaction were kept constant, the bottom ash passing the #4 sieve tends to have slightly larger values of cohesion and larger friction angles than the bottom ash passing the #8 sieve. Both the MB and RDF bottom ash exhibited an increase in friction angle from 2° to 7° as the relative compaction increased. The MB bottom ash had slightly larger friction angles than the RDF bottom ash.

Figure 4.18 shows the relationship between the friction angle and the density of the bottom ash. This graph shows that the friction angle increases with an increase in density for both ash types. However, the MB bottom ash has a slightly greater increase in friction angle with respect to density than the RDF bottom ash. The RDF bottom ash exhibits higher friction angles with respect to density than the MB bottom ash.

4.7.3 Elastic Modulus

The elastic modulus results for the MB and RDF bottom ash are shown in Figures 4.19 and 4.20, respectively. The elastic moduli values were calculated over a strain difference of 0.2% in the elastic portion of the stress strain curve. Both figures show an increase in elastic modulus as the dry unit weight and confining pressures increase. Both ash types exhibit elastic modulus values in the range of 500 to 5,000 psi (3,500 kPa to 35,000 kPa). For a given density, the RDF bottom ash yields an elastic modulus approximately twice as large as the MB bottom ash, i.e. the RDF bottom ash is twice as stiff as the MB bottom ash.

Typical elastic moduli ranges for various granular materials are as follows: silty sand: 9,800 - 19,600 kN/m^2, loose sand: 9,800 - 30,000 kN/m^2, and dense sand: 39,000 - 78,500 kN/m^2 (Jumikis, 1984). The MB and RDF bottom ash samples exhibit elastic moduli within the range of loose sands.

4.7.4 Resilient Modulus

A strain increment of 0.1% was used to calculate the resilient moduli. The resilient modulus values for both the MB and RDF bottom ash are combined in these figures. The resilient modulus for the MB bottom ash resulted in the following equation: $Mr = 1.362q^{0.634}$ while the resilient modulus for the RDF bottom ash resulted in the following equation: $Mr = 1.336q^{0.645}$. Since there was little difference between these two equations, the MB and RDF resilient modulus values were combined to obtain the following correlation between the resilient modulus and the first stress invariant: $Mr = 1.349q^{0.640}$. The correlation between the resilient modulus and the deviator stress for the MB and RDF bottom ash is as follows: $Mr = 8.437 + 0.432\sigma_d$. These equations only give approximate relationships for the resilient modulus of bottom ash.

The resilient modulus equation was developed as follows: $Mr = K_1 q^{K_2}$ where $K_1 = 1.349$ and $K_2 = 0.640$. These values of K_1 and K_2 are much smaller than those reported by Sneddon (1988) for fine sands. Sneedon (1988) used a faster loading rate and a much smaller strain as compared to the loading rate and strain used in this study.

4.7.5 California Bearing Ratio (CBR)

The soaked and unsoaked CBR results for the MB and RDF bottom ash passing the #4 sieve are shown in Figures 4.21 and 4.22, respectively. The MB bottom ash exhibits CBR values approximately twice as large as the RDF bottom ash. The MB bottom ash also exhibits higher CBR values on the wet side of optimum with the peak occurring at a moisture content of 13.5% and a CBR of 194. The RDF bottom ash exhibits higher CBR values on the dry side of optimum with the peak occurring at a moisture content of 15.6% and a CBR of 80. The CBR values of both MB and RDF ash are very sensitive to the compaction moisture content of the sample.

The above results are based on the first trial run and were retested because the CBR values at 0.2" were greater than those at 0.1" (ASTM D-1883-87). However, only one sample was retested for each ash type. The retested CBR value for the MB bottom ash sample showed a decrease for the given moisture content while the retested CBR value for the RDF bottom ash sample showed an increase for the given moisture content. These results verify the inconsistency in the CBR test as discovered by Rodriquez *et al.*, (1988). Therefore, the remaining points along each curve were not retested and only one point for each ash type was tested soaked.

The CBR values obtained after soaking for both ash types were less than the unsoaked CBR values with respect to the compaction moisture content. Since both ash types are very sensitive to the compaction moisture content, a slight increase in the moisture content would have resulted in a very small difference between the soaked and unsoaked CBR values while a slight decrease in moisture content would have resulted in a large difference between the soaked and unsoaked CBR values. From the soaked samples, the recorded percent swell for both ash types over the four day period was found to be less than 0.02% and is considered negligible. Therefore, a loss in strength occurs when the samples are saturated.

From the above results, MB bottom ash can be utilized in road base since its CBR values exceed 100. However, RDF bottom ash exhibits CBR values below 100 and is not recommended for use in road base based on this criteria. Both ashes have CBR values greater than ten and can be classified as very good subgrade materials according to Baker (1982). Also, both ash types exhibit little to no swell and should not cause any field problems during saturated conditions.

4.7.6 Limerock Bearing Ratio (LBR)

The soaked and unsoaked LBR results for the MB and RDF bottom ash passing the #4 sieve are shown in Figures 4.21 and 4.22, respectively. According to these figures, the MB bottom ash exhibits LBR values approximately twice as large as the RDF bottom ash. The MB bottom ash also exhibits higher LBR values on the wet side of optimum with the peak occurring at a moisture content of

13.5% and an LBR of 183. The RDF bottom ash exhibits higher LBR values on the dry side of optimum with the peak occurring at a moisture content of 15.6% and an LBR of 92. The LBR values of both MB and RDF ash are very sensitive to the compaction moisture content of the sample.

The above results are based on the data obtained from the first CBR trial run and were retested since the CBR values at 0.2" were greater than those at 0.1" (ASTM D-1883-87). However, only one sample was retested for each ash type. The retested LBR value for the MB bottom ash sample showed a decrease for the given moisture content while the retested LBR value for the RDF bottom ash sample showed an increase for the given moisture content. These results also verify that there is an inconsistency in the LBR test, as well as in the CBR test. Therefore, the remaining points along each curve were not retested and only one point for each ash type was tested in the soaked condition.

The LBR values obtained after soaking for both ash types were less than the unsoaked LBR values with respect to the compaction moisture content. Since both ash types are very sensitive to the compaction moisture content, a slight increase in the moisture content would have resulted in a very small difference between soaked and unsoaked LBR values while a slight decrease in moisture content would have resulted in a large difference between soaked and unsoaked LBR values. From the soaked samples, the recorded percent swell for both ash types over the four day period was found to be less than 0.02% and is considered negligible. Therefore, a loss in strength occurs when the samples are saturated.

The above results suggest that MB bottom ash can be utilized in road base since its LBR values exceed 100. However, the RDF bottom ash exhibits LBR values below 100 and should not be recommended for use in road base. Also, both ash types exhibit little to no swell and should not be a problem in the field during saturated conditions.

4.8 Chemical and Environmental Analyses

The results of the column leaching study were presented both in leached concentration of selected metals and in accumulated leaching percentage (ALP) with respect to time. The ALP was expressed as the percentage of the selected metal that was leached from the column.

$$\mathrm{ALP} = \sum_{k=1}^{k=24} \frac{C_{L_k} \times V_{L_k}}{C_T \times W_T} \times 100$$

Where

k = sampling of leachate,

C_{L_k} = metal concentration of leachate collected at the k_{th} sampling (g/L),

V_{L_k} = volume of leachate collected in the k_{th} sampling (L),

C_T = metal concentration of MWC bottom ash (or g/kg), and

W_T = net weight of bottom ash compacted into the PVC cylinder (g).

4.8.1 Selected Elemental Concentrations of MWC Bottom Ash

Table 4.5 shows the results of the elemental analysis of Standard Reference Material 1633a coal fly ash from NIST. The technique of HF-H_3BO_3 digestion recovered 96 % of Ca, 88 % of As, 100 % of Cd, 94 % of Cr, and 99 % of Pb. The 88 % recovery of As was acceptable since the coefficient of variation of the certified value for As was about 11 %.

Table 4.6 shows the results of elemental analysis of this study and the reported values from another study (EPA, 1990) as well as the abundance of the selected metals in soil (Brooks, 1978). Metal concentrations in MWC bottom ash varied largely in the EPA's study. The MWC bottom ash provided by the Pinellas County Facility had Ag, Cd, and Ca concentrations at the low end of the EPA's reported values. Concentrations of As, Cr, and Pb in the study were found in the middle range of the EPA's reported values. When compared to the natural abundance in soil, As and Cd concentrations in MWC bottom ash were relative high, while Pb was much higher. Concentrations of Ag and Cr in MWC bottom ash were similar to those found in soil. Concentration of calcium, a major binding element in MWC bottom ash, was slightly lower in the MWC bottom ash than that in average soil.

4.8.2 Reproducibility of Column Leaching Test

All the compacted ash columns in the study had a density of 16.7 ± 0.5 $\mathrm{kN/cm^3}$ under the compaction energy of 605 $\mathrm{kJ/m^3}$. In each of columns 4, 5, and 6, two replicate tests were conducted to determine the reproducibility of the column leaching test. To estimate the degree of reproducibility of the two replicates, the p-value test was applied to the analytical data (Goldman and Weinberg, 1986). A hypothesis (H_0) assuming replicate tests 1 and 2 were the same and its alternative hypothesis (H_1) assuming replicate tests 1 and 2 were different were made. A " z " value was obtained according to the following equation, which expressed the difference between R_1 and R_2 in units of standard deviation of the replicate test 2.

$$z = \frac{R_2 - R_1}{s/\sqrt{n}}$$

where

R_1 = mean concentration of metals in the leachate from replicate test 1,

R_2 = mean concentration of metals in the leachate from replicate test 2,

n = number of leachate samples, and

s = standard deviation of metal concentrations in the leachate from R_2.

The p value for this test was the areas under the normal distribution curve to the right of z and to the left of -z. For convenience, a computer program of Microsoft Excel 4.0 was used to calculate the p-values. A significance level of 0.05 was used as an indicator to measure the extent to which the data do support H_0. If the p value < 0.05, the reproducibility of two replicate tests is not good at the 0.05 level of significance, and vice versa. The p-values of two replicate tests from columns 4, 5, and 6 are listed in Table 4.6. All the columns, except the leaching of Pb from column 4, had very good reproducibility, which was attributed to the invariant conditions under which the ash column was compacted. At pH 12.5, Pb in MWC bottom ash is highly leachable (Van Der Sloot *et al.*, 1989). The observed variations in the leaching of Pb from column 4 might be due to the presence of more leachable Pb in one of the column 4 tests. However, the leaching of Pb from columns 5 and 6 was reproducible when DDW at pH 4.5 was used as the leaching fluid.

4.8.3 Leaching of Calcium

4.8.3.a MB Ash Results

Effect of pH

Figures 4.23 and 4.24 show the leaching of Ca from columns 9 and 11 subjected to DDW and SAR, respectively. No significant difference in the leaching of Ca was found between columns 9 and 11 (Figure 4.23). Both columns exhibited the same release pattern of Ca over time; the leaching of Ca decreased at the beginning of test and increased afterwards. The percentage of the total Ca leached from both columns during the 8-hour test was about 0.16 % (Figure 4.24). The initial pH for SAR and DDW was 4.2 and 4.5, respectively. The major difference between SAR and DDW was that SAR contained various cations and anions. The results indicated that leaching of Ca from ash columns was not affected by other ionic species that were present in the SAR solution.

Effect of Flow Rate

Figures 4.25 and 4.26 show the leaching of Ca from columns 7, 8, and 9 subjected to DDW at a flow rate of 4, 7, and 10 ml/min., respectively. The measured pH of the leachate for the three columns declined steadily from 11.9 in the beginning to 10.7 at the end. Concentrations of Ca in the leachate from columns 7, 8, and 9 decreased within the first hour of the test and increased slowly in the rest of testing period (Figure 4.25). After an 8-hour test, approximately 0.04 %, 0.10 %, and 0.16 % of the total Ca were leached from columns 7, 8, and 9, respectively (Figure 4.26). The heights of columns 7, 8, and 9 were fixed at 15.2 cm. Under the same compaction technique, it could be assumed that same amount of ash was compacted into each of the three columns for testing. Therefore, the observed difference in the leaching of Ca (Figure 4.25) was from the difference in flow rate. That is, for ash columns with the same height, a higher flow rate of leaching fluid results in a higher leaching of Ca.

Figures 4.27 and 4.28 show the leaching of Ca from columns 10 and 11 subjected to SAR at a flow rate of 4 and 10 ml/min., respectively. Similarly, the higher flow rate of leaching fluid resulted in higher leaching of Ca from ash column (Figure 4.27). The percentages of the total Ca leached from columns 10 and 11 were 0.03 % and 0.17 %, respectively (Figure 4.28).

Effect of Column Height

Figures 4.29 and 4.30 show the leaching of Ca from columns 1, 2, 5, and 6 at different heights subjected to DDW at a flow rate of 7 ml/min. Concentrations of Ca in the leachate from columns 1 and 5 (15.2 cm) decreased in the beginning of the test to a minimum, and subsequently increased steadily as a function of time (Figure 4.29). Concentrations of Ca in the leachate from columns 2 and 6 (45.7 cm) leveled off within 3 hours. As shown in Figure 4.30, the total percentages of Ca leached over time from columns 1, 2, 5, and 6 were 0.11 %, 0.01 %, 0.09 %, and 0.02 %, respectively, during the 8-hour test. Over the 8-hour test, the release of Ca from 15.2-cm ash columns increased steadily.

Summary

It was found that SAR and DDW had similar effects on the leaching of Ca from ash columns. For ash columns with the same height, a higher flow rate resulted in higher leaching of Ca. For ash columns with different heights at the same flow rate of leaching fluid, 15.2-cm columns resulted in higher leaching of Ca than 45.7-cm columns.

4.8.3.b RDF Ash Results

Figures (4.31), (4.32) and (4.33) show the leaching of Ca from 6- and 18-inch RDF and MB ash columns when they were subjected to DDW or SAR. The trend in Ca leaching for both MB and RDF ashes was very similar, however, RDF ash had more leachable Ca than MB ash. No significant difference in the leaching of Ca was found between RDF and MB ash when SAR was used in the leaching test.

4.8.4 Leaching of Arsenic

4.8.4.a MB Ash Results

Effect of pH

Figures 4.34 and 4.35 show the leaching of As from columns 9 and 11 subjected to DDW and SAR, respectively. Concentrations of As in the leachate from columns 9 and 11 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time—leveled off within 2 hours (Figure 4.34). The release pattern of As from columns 9 and 11 was very similar, suggesting that an

SAR solution had no significant effect on the leaching of As, when compared with DDW. Approximately the same amount of the total As (i.e., 0.12 %) was leached from columns 9 and 11 (Figure 4.35).

Effect of Flow Rate

Figures 4.36 and 4.37 show the leaching of As from columns 7, 8, and 9 at a flow rate of 4, 7, and 10 ml/min., respectively. Concentrations of As in the leachate from columns 7, 8, and 9 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.36). Most of the leachate had As concentrations below the drinking water standard of 50 g/L. Concentrations of As in the leachate from columns 8 and 9 leveled off within 2 hours. Column 7 had higher concentrations of As in the leachate than columns 8 and 9 at the same sampling period. However, approximately the same amount of the total As (i.e., 0.12 %) was leached from columns 7, 8, and 9 regardless of the flow rate of the leaching fluids (Figure 4.37).

Figures 4.38 and 4.39 show the leaching of As from columns 10 and 11 after they were subjected to SAR at a flow rate of 4 and 10 ml/min., respectively. The results observed in columns 10 and 11 were similar to those observed in columns 7 and 9 (Figures 4.36 and 4.37). Approximately 0.12 % of the total As was leached from each of columns 10 and 11 (Figure 4.39). This suggested that the increase of flow rate using SAR resulted in no significant difference in the leaching of Cr.

Effect of Column Height

Figures 4.40 and 4.41 show the leaching of As from columns 1, 2, 5, and 6 at different heights when they were subjected to DDW at a flow rate of 7 ml/min. Concentrations of As in the leachate from columns 1, 2, 5, and 6 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.40). With the exception of some initial samples collected within 30 minutes, most of the leachate had As concentrations below the drinking water standard of 50 g/L. The leaching of As from 15.2-cm columns and 45.7-cm columns leveled off within 2 and 4 hours, respectively. The 45.7-cm columns had higher concentrations of As in the leachate than the 15.2-cm columns. Approximately 0.06 %, 0.04 %, 0.08 %, and 0.06 % of the total As were leached from columns 1, 2, 5, and 6, respectively (Figure 4.41).

Figures 4.42 and 4.43 show the leaching of As from columns 10 and 12 at different heights when subjected to SAR at a flow rate of 4 ml/min. Concentrations of As in the leachate from columns 10 and 12 were below the

EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.42). The percentages of the total As leached from columns 10 and 12 were 0.12 % and 0.08 %, respectively (Figure 4.43).

Summary

Concentrations of As in the leachate from ash columns were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time. Other than some samples collected within the initial 30 minutes of testing, most of the leachate had As concentrations below the drinking water standard of 50 g/L. The SAR solution had no significant effect on the leaching of As when compared with DDW. Approximately the same percentage of As was leached from the columns regardless of the flow rate of leaching fluids and the column height.

4.8.4.b RDF Ash Results

Figures (4.44), (4.45) and (4.46) show the leaching of As from 6- and 18-inch RDF and MB ash columns when they were subjected to DDW or SAR. The trend in As leaching for both MB and RDF ashes was very similar; however, unlike Ca, RDF ash had less leachable As than MB ash. No significant difference in the leaching of As was found between RDF and MB ash when SAR was used in the leaching test.

4.8.5 Leaching of Chromium

4.8.5.a MB Ash Results

Effect of pH

Figures 4.47 and 4.48 show the leaching of Cr from columns 9 and 11 when they were subjected to DDW and SAR, respectively. Concentrations of Cr in the leachate from columns 9 and 11 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time. They both leveled off to minimum values within 3 hours (Figure 4.47). The release patterns of Cr from columns 9 and 11 were very similar, suggesting that an SAR solution has little more significant effect on the leaching of Cr than DDW. The total percentages of Cr leached from columns 9 and 11 during the 8-hour test were 0.05 % and 0.07 %, respectively (Figure 4.48).

Effect of Flow Rate

Figures 4.49 and 4.50 show the leaching of Cr from columns 7, 8, and 9 when they were subjected to DDW at a flow rate of 4, 7, and 10 ml/min., respectively. Concentrations of Cr in the leachate from columns 7, 8, and 9 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time. All three leveled off to minimum values after 2 hours (Figure 4.49). Approximately the same amount of the total Cr (i.e., 0.04 %) was leached from each of the three columns regardless of the flow rate of leaching fluids (Figures 4.50).

Figures 4.51 and 4.52 show the leaching of Cr from columns 10 and 11 when subjected to SAR at a flow rate of 4 and 10 ml/min., respectively. The results observed in columns 10 and 11 were similar to those observed in columns 7, 8, and 9 (Figures 4.49 and 4.50). This once again evidenced that SAR and DDW resulted in no significant difference in the leaching of Cr. The percentages of the total Cr leached from columns 10 and 11 were 0.06 % and 0.07 %, respectively (Figure 4.52).

Effect of Column Height

Figures 4.53 and 4.54 show the leaching of Cr from different heights. Columns 1, 2, 5, and 6 were subjected to DDW at a flow rate of 7 ml/min. Concentrations of Cr in the leachate were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time. The leaching of Cr from columns 1 and 2 leveled off within 2 and 5 hours, respectively (Figures 4.53). Concentrations of Cr in the leachate from columns 5 and 6 remained at a lower level than those from columns 1 and 2, respectively. Approximately 0.03 %, 0.03 %, 0.02 %, and 0.02 % of the total Cr were leached from columns 1, 2, 5, and 6, respectively, after the 8-hour tests (Figure 4.54). This suggested that a change of column height resulted in no significant difference in the leaching of Cr.

Figures 4.55 and 4.56 show the leaching of Cr from columns 10 and 12 at different heights subjected to SAR at a flow rate of 4 ml/min. Concentrations of Cr in the leachate from columns 10 and 12 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.55). The percentages of the total Cr leached from columns 10 and 12 were 0.06 % and 0.05 %, respectively (Figure 4.56).

The observed difference in the leaching of Cr between columns 1 and 5 and between columns 2 and 6 might be the result of sampling from different batches of ash with different initial water content. No attempt was made to compare a difference, if there was one, in the batches or water content in the study. The water content of the ash for columns 1 and 2 was 10 %, and 16 % for columns 5 and 6. MWC bottom ash aged under different water content for a period of time could result in the formation of different minerals (Shieh, 1994), and thus might affect the leaching characteristics of the ash.

Summary

Concentrations of Cr in the leachate from ash columns were below the EPA toxicity standard of 5,000 g/L. The SAR and DDW solution had no different effects on the leaching of Cr. Regardless of the flow rate of the leaching fluid and the height of the ash column, approximately the same amount of the total Cr would leach from each ash column during the testing period.

4.8.5.b RDF Ash Results

Figures (4.57), (4.58) and (4.59) show the leaching of Cr from 6- and 18-inch RDF and MB ash columns when they were subjected to DDW or SAR. The trend of Cr leaching was very similar for both MB and RDF ashes. When SAR was used, more leachable Cr was released though the amount of leaching decreased with time.

4.8.6 Leaching of Lead

4.8.6.a MB Ash Results

Effect of pH

Figures 4.60 and 4.61 show the leaching of Pb from columns 9 and 11 when subjected to DDW and SAR, respectively. Concentrations of Pb in the leachate from columns 9 and 11 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.60). Columns 9 and 11 had a similar release pattern of Pb with respect to time, suggesting that an SAR solution had no significant effect on the leaching of Pb, when compared with DDW. Approximately 0.006 % and 0.004 % were leached from columns 9 and 11, respectively, during the 8-hour testing period (Figure 4.61).

Effect of Flow Rate

Figures 4.62 and 4.63 show the leaching of Pb from columns 7, 8, and 9 at a flow rate of 4, 7, and 10 ml/min., respectively. Concentrations of Pb in the leachate from columns 7, 8, and 9 were all below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.62). Regardless of the flow rate of the three columns, approximately the same percentage of the total Pb (i.e., 0.005 %) was leached from each of the three columns (Figure 4.63). This suggested that the leaching of Pb was not affected by the flow rate of DDW.

Figures 4.64 and 4.65 show the leaching of Pb from columns 10 and 11 when they were subjected to SAR at a flow rate of 4 and 10 ml/min., respectively. The results observed in columns 10 and 11 were similar to those observed in columns 7 and 9 (Figures 4.62 and 4.63). Concentrations of Pb in the leachate from columns 10 and 11 were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time (Figure 4.64). Approximately 0.003 %, and 0.004 % of the total Pb were leached from columns 10 and 11, respectively (Figure 4.65). This suggested that the leaching of Pb was not affected by the flow rate of SAR.

Effect of Column Height

Figures 4.66 and 4.67 show the leaching of Pb from different heights. Columns 1, 2, 5, and 6 were subjected to DDW at a flow rate of 7 ml/min. Concentrations of Pb in the leachate from columns 1, 2, 5, and 6 were all below the EPA toxicity standard of 5,000 g/L. Leachate concentrations from columns 1, 5, and 6 decreased as a function of time, and those from column 2 tended to increase at the beginning of leaching to a maximum and then decreased as a function of time (Figure 4.66). The leaching of Pb from columns 1 and 2 leveled off to minimum values within 2 and 6 hours, respectively. Concentrations of Pb in the leachate in columns 5 and 6 remained at lower levels than those in columns 1 and 2. Approximately 0.016 %, 0.014 %, 0.008 %, and 0.005 % of the total Pb were leached from columns 1, 2, 5, and 6 respectively after the 8-hour test (Figure 4.67).

Figures 4.68 and 4.69 show the leaching of Pb from different heights. Columns 10 and 12 were subjected to SAR at a flow rate of 4 ml/min. Concentrations of Pb in the leachate in columns 10 and 12 were below the EPA toxicity standard (Figure 4.68). Approximately 0.003 % and 0.002 % of the total Pb were leached from columns 10 and 12, respectively (Figure 4.69).

The observed difference in the leaching of Pb between columns 1 and 5 and between columns 2 and 6 might be the result of sampling from different batches of ash with different initial water content. No attempt was made to compare a difference, if there was one, in the batches or water content in the study. The water content of the ash for columns 1 and 2 was 10 %, and 16 % for columns 5 and 6. MWC bottom ash, if aged under different water content for a period of time, could result in the formation of different minerals (Shieh, 1994), and thus affect the leaching characteristics of the ash.

Summary

Concentrations of Pb in the leachate from ash columns subjected to DDW and SAR were below the EPA toxicity standard of 5,000 g/L and decreased as a function of time. The SAR solution and DDW had no different effects on the leaching of Pb. Approximately the same amount of Pb was leached from the ash columns regardless of the flow rate of the leaching fluid and the height of ash column.

4.8.6.b RDF Ash Results

Figures (4.70), (4.71) and (4.72) show the leaching of Pb from 6- and 18-inch RDF and MB ash columns when they were subjected to DDW or SAR. The results showed that MB ash had more leachable Pb than RDF ash. The leaching of Pb from both ashes was found to decrease with time. DDW and SAR caused no significant difference in Pb leaching.

4.8.7 Leaching of Cadmium and Silver

Most of the leachate had Cd concentrations that were below the detection limit (1 g/L) of the analytical methods. All the leachate had Ag concentrations below the detection limit (1 g/L) of the analytical methods, and hence comparisons of the results are not presented (i.e., the effect of various controlling factors, pH, flow rate, and column height, on the leaching of Cd and Ag remained unidentified since most of the leachate had concentrations below the detection limit). Since very little Ag and Cd were detectable in the leachate, it is suggested that the Ag and Cd in the ash column did not pose a toxicity threat to the environment.

4.9 Data Base

A data base of MB and RDF bottom ash properties is presented in Table 4.7.

4.10 Availability, Costs and Regulatory Aspects

This investigation was predicated on the availability of ash and regulatory issues in place at the time of the study. At the onset of the study, bottom ash was provided and available as a fill at no charge. The only costs of using ash as a source of fill would be the trommel costs to insure correct sizing and the hauling costs to the specific site. MWC facilities would also realize a potential savings of at least $20/ ton by not landfilling the ash.

Changes to ash management practices used by MWC facility operators have occurred as a result of US Supreme Court ruling 92-1639 of May 1994. This ruling does not categorize MWC ash as hazardous waste, however it instructs municipalities to test MWC ash following TCLP for compliance with Federal EPA standards. As a result of this ruling, MWC facility operators have been formulating operational practices and are reluctant to separate ash into bottom and fly ash components. They have taken the viewpoint that combined ash currently meets the specified EPA standards. If the ash is separated, then the fly ash may not meet EPA standards and would require treatment as a hazardous waste. As a result of the various changes in ash management practice, it is currently impossible to make a reliable estimate of the availability and costs of bottom ash.

The State of Florida has enacted legislation limiting the amount of metals in consumer goods and is conducting trial household battery recycling programs. These policy changes will reduce the amounts of metals avaiable to the MSW ash stream and it may be speculated that MWC ash will become "cleaner". This statement suggests that ash produced by MWC facilities could be considered for use as a highway fill material in the future.

Table 4.1 Summary of WTE surveys completed by July 15, 1993

FACILITY NAME	LOCATION	PLANT OPERATOR	TYPE [1]	BURN RATE (T/day)	PRODUCTION RATE of ASH (T/day)			Additional Treatment	Current use of Bottom ash
					Fly ash	Bottom ash	Scrubber ash		
Bay Co. RRF	Bay Co.	Westinghouse En. Sys.	MB	510	SNR	SNR	SNR	SNR	SNR
N. Broward Co. RRF	Broward Co.	Wheelabrator	MB	2250	SNR	SNR	SNR	SNR	SNR
S. Broward Co. RRF	Broward Co.	Wheelabrator	MB	2250	SNR	SNR	SNR	SNR	SNR
Hillsborough Co. ERF	Hillsborough Co.	Ogden Martin Systems	MB	1200	SNR	SNR	SNR	SNR	SNR
Metro Key West Co. RRF	Monroe Co.	Montenay	MB	150	SNR	SNR	SNR	SNR	SNR
Lake Co. RRF	Lake Co.	Ogden Martin Systems	MB	528	SNR	SNR	SNR	SNR	SNR
Mcintosh Power Plant RRF	Polk Co.	City of Lakeland	RDF	300	SNR	SNR	SNR	SNR	SNR
McKay Bay REP	Hillsborough Co.	Wheelabrator	MB	1000	SNR	SNR	SNR	SNR	SNR
Miami International Airp. I.	Dade Co.	Dade Co.	MB	60	SNR	SNR	SNR	SNR	SNR
Pasco Co. RRF	Pasco Co.	Ogden Martin Systems	MB	750	177.6	combined	N/A	A	Landfill
Ogden Martin of Lake	Lake Co.	Ogden Martin Systems	MB	528	6.5	97.5	26	none	N/A
Dade Co. RRF	Dade Co.	Montenay Power Corp.	RDF	2100	60	318	0	none	Landfill
North Co. RRF	Palm Beach Co.	Babcock & Wilcox	RDF	2000	100	200	0	none	none
Mayport Naval St.	Duval Co.	Global Associates	RDF	36	0.125	5	0	A	Landfill
Pinellas Co. RRF	Pinellas Co.	Wheelabrator	MB	3000	75	675	0	***	
			TOTAL	16662					

Waste-to-energy facilities under construction

FACILITY NAME	LOCATION	PLANT OPERATOR	TYPE [1]	BURN RATE (T/day)	PRODUCTION RATE of ASH (T/day)			Additional Treatment	Current use of Bottom ash
					Fly ash	Bottom ash	Scrubber ash		
Lee County Solid Waste RRF	Lee Co.	Ogden Martin Systems	MB	1200	SNR	SNR	SNR	SNR	SNR
Ridge Generating Station	Polk Co.	Wheelabrator	TDF	1000	SNR	SNR	SNR	SNR	SNR
			TOTAL	2200					

N/A = Not Available

SNR = Survey not Returned

[1] MB = Mass Burn RDF = Resource Derived Fuel

A = Removal of Metals

Table 4.2 Summary of physical properties for MWC bottom ash

Property	Mass Burn	Refuse-Derived-Fuel
Moisture Content Range as Delivered %	11-19	16-26
Grain Diameter at 10% passing (mm)	0.33	0.17
Grain Diameter at 60% passing (mm)	4.1	1.8
Grain Diameter at 30% passing (mm)	1.5	0.55
Uniformity Coefficient, Cu	12.4	10.6
Coefficient of Curvature, Cc	1.66	0.99
Specific Gravity (Passing #4 sieve)	2.79	2.55
Specific Gravity (Passing #8 sieve)	2.72	2.45
AASHTO Classification	A-1-a	A-1-a
USCS Classification	SW	SW
ASTM Aggregate Classification	# 89	# 89

Table 4.3 Moisture-density results for MWC bottom ash

Bottom Ash Source	Compactive Energy ASTM	Passing #4 sieve		
		OMC	Maximum Dry Density	
		(%)	(pcf)	(kN/m^3)
MB	D-698	15.5	114.8	18.1
	D-1557	12.6	121.7	19.1
RDF	D-698	18.3	98.0	15.4
	D-1557	17.6	103.8	16.3
Bottom Ash Source	**Compactive Energy ASTM**	**Passing #8 sieve**		
		OMC	Maximum Dry Density	
		(%)	(pcf)	(kN/m^3)
MB	D-698	17.8	104.9	16.5
	D-1557	16.4	112.9	17.8
RDF	D-698	20.8	82.0	12.9
	D-1557	19.3	98.0	15.4

OMC = Optimum Moisture Content

Table 4.4 CD triaxial shear results for MWC bottom ash

Ash Type	Relative Compaction	Dry Unit Weight as Tested		Compactive Energy	Friction Angle	Cohesion	
	(%)	(pcf)	(kN/m^3)	ASTM	(°)	(psi)	(kPa)
MB < #4	100	115.0	18.1	D-698	50	4	27.6
	95	108.4	17.0	D-698	48	4	27.6
	90	105.2	16.5	D-698	44	4	27.6
MB < #4	100	NA	NA	D-1557	NA	NA	NA
	95	NA	NA	D-1557	NA	NA	NA
	90	108.7	17.1	D-1557	47	2	13.8
RDF < #4	100	97.8	15.4	D-698	45	4	27.6
	95	94.0	14.8	D-698	42	4	27.6
	90	87.7	13.8	D-698	38	2	13.8
RDF < #4	100	102.7	16.1	D-1557	47	5	34.5
	95	97.3	15.3	D-1557	45	3	20.7
	90	93.3	14.6	D-1557	41	3	20.7
MB < #8	100	106.3	16.7	D-698	42	2	13.8
	95	101.5	15.9	D-698	39	2	13.8
	90	93.3	14.6	D-698	30	2	13.8
MB < #8	100	112.5	17.7	D-1557	47	3	20.7
	95	107.9	16.9	D-1557	43	3	20.7
	90	102.3	16.1	D-1557	40	2	13.8
RDF < #8	100	82.6	13.0	D-698	41	2	13.8
	95	78.1	12.3	D-698	35	2	13.8
	90	74.3	11.7	D-698	24	2	13.8
RDF < #8	100	99.5	15.6	D-1557	46	3	20.7
	95	93.4	14.7	D-1557	42	3	20.7
	90	89.2	14.0	D-1557	39	2	13.8

NA - Not Attainable

Table 4.5 Selected elemental concentrations of standard reference material 1633a coal fly ash from NIST and percent recovery using the technique of HF-H_3BO_3 digestion

Element	Certified Value	Measured Value	Recovery (%)[a]
Ca (%)	1.11 ± 0.01	1.07 ± 0.02	96
Ag (g/g)	NA[b]	NA	NA
As (g/g)	145 ± 15	128 ± 19	88
Cd (g/g)	1.00 ± 0.15	1.03 ± 0.10	100
Cr (g/g)	196 ± 6	184 ± 4	94
Pb (g/g)	72.4 ± 0.4	71.4 ± 1.1	99

[a] Percent recovery was considered as 100 % if the measured mean value was within the range of the certified mean ± standard deviation. Where measured mean value was beyond the range of certified value, percent recovery was calculated by dividing the measured mean value by the certified mean value.

[b] No certified value available.

Table 4.6 Comparison of selected elemental concentrations (mg/kg) of bottom ash

Element	This Study	EPA (1990)	Soil (Brooks, 1978)
Ag	1.3 ± 0.2	ND[a] - 38	1
As	18.8 ± 1.9	1.3 - 24.6	5
Ca	53,000 ± 3,000	5,900 - 69,500	63,000
Cd	7.2 ± 1.2	1.1 - 46	0.5
Cr	254 ± 56	13 - 520	200
Pb	2590 ± 950	110 - 5,000	10

[a] Not detectable.

Table 4.7 Data base of MB and RDF bottom ash properties

Property	Mass Burn	Comments	Refuse Derived Fuel	Comments
Moisture Content (mc)	11%-19 %	as delivered	16%-26%	as delivered
Physical Composition		higher % of metals		lower % of metals
Specific Gravity	2.72-2.79		2.45-2.55	
Classification	A-1-a (0) SW # 89	well-graded granular material	A-1-a (0) SW # 89	same as MB
Absorption	9%-12%	greater than conventional fill	11%	greater than conventional fill
Mineralogy		predominance of Al, Si & Ca		same as MB
Pozzolanic Activity Index	135	more active than coal fly ash	65	less active than coal fly ash
Loss on Ignition	4.4%-5%	similiar to coal fly ash	5%	similiar to coal fly ash
Bulk Rodded Unit Weight	77 pcf -81 pcf	lower than conventional fill	69 pcf	lower than conventional fill
Moisture-Density	(pcf) @ (mc %)	higher unit weight	(pcf) @ (mc %)	lower unit weight
ASTM D-698 < #4 sieve	114.8 @ 15.5	lower OMC	98.0 @ 18.3	higher OMC
ASTM D-698 < #8 sieve	104.9 @ 17.8	increase of compaction energy and	82.0 @ 20.8	
ASTM D-1557 < #4 sieve	121.7 @ 12.6	grain size will increase dry density	103.8 @ 17.6	
ASTM D-1557 < #8 sieve	112.9 @ 16.4	(.0157 kN/m3 = 1 pcf)	98 @ 19.3	

Table 4.7 Data base of MB and RDF bottom ash properties,continued

Property	Mass Burn	Comments	Refuse Derived Fuel	Comments
Permeability	cm/sec		cm/sec	
wet of optimum	1.00E-02	very sensitve to	1.00E-02	same as MB
dry of optimum	1.00E-05	compaction moisture content	1.00E-05	
Free Shrink Swell				
soaked	<.1%	neglible volume change		not evaluated
dry	2.3%-3.6%	axial expansion		
soaked then dry	.50%-1.50%	axial expansion reduced		
Unconf. Compressive Strength	10-70 psi 70-490 kPa	decrease with increase in moisture content increase with compaction energy increase with age	10-50 psi 70-350 kPa	decrease with increase in moisture content increase with compaction energy
Friction Angle	degrees 30-50	increase with density increase with grain size	degrees 24 -46	increase with density increase with grain size
Elastic Modulus	500-5000 psi 3,500-35,000 kPa		500-5000 psi 3,500-35,000 kPa	
CBR	100-200	very sensitve to	25-85	same as MB
LBR	100-185	compaction moisture content	25-100	same as MB

Table 4.7 Data base of MB and RDF bottom ash properties, continued

Property	Mass Burn	Comments	Refuse Derived Fuel	Comments
Leaching: Ag, Cd	BDL	below detection limits	BDL	same as MB
Leaching: Cr, Pb	< EPA TS	EPA Toxicity Std (5000µg/l)	< EPA TS	same as MB
Leaching: Ca		No available standard		
Leaching: As	< EPA TS < DWS	EPA Toxicity Std (5000µg/l) Drinking Water Std (50 µg/l)	< EPA TS < DWS	same as MB same as MB

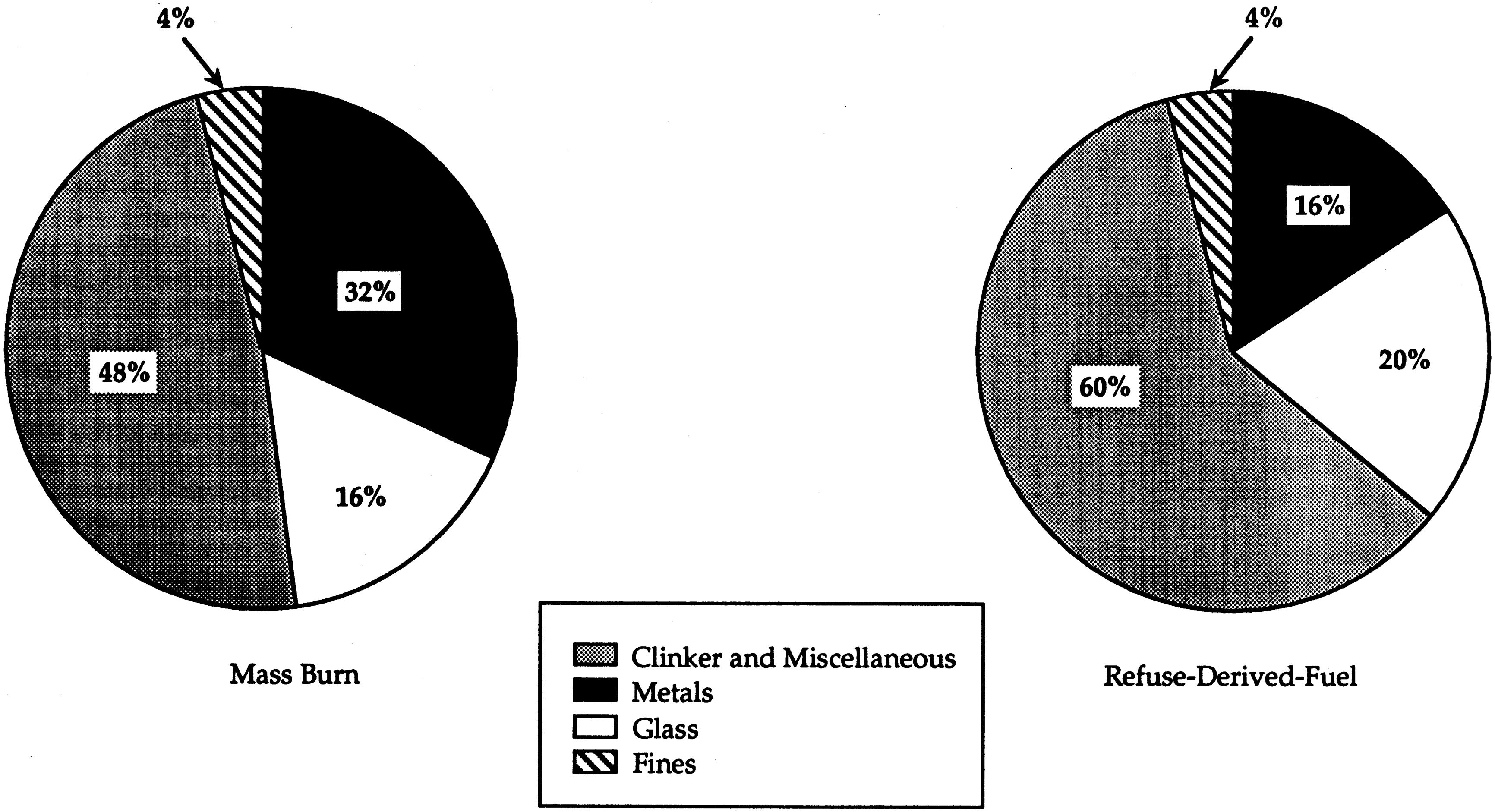

Figure 4.1 Physical compostion for mass-burn and refuse-derived-fuel MWC bottom ash

Figure 4.2 Scanning electron micrograph of MWC bottom ash prior to aging

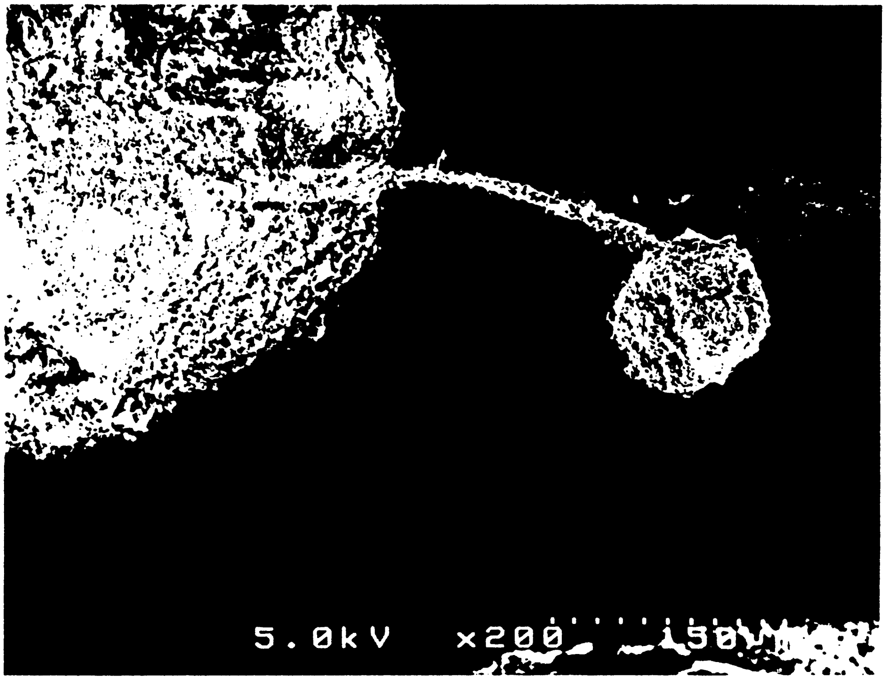

Figure 4.3 Scanning electron micrograph of mineral fibers linking ash particles together

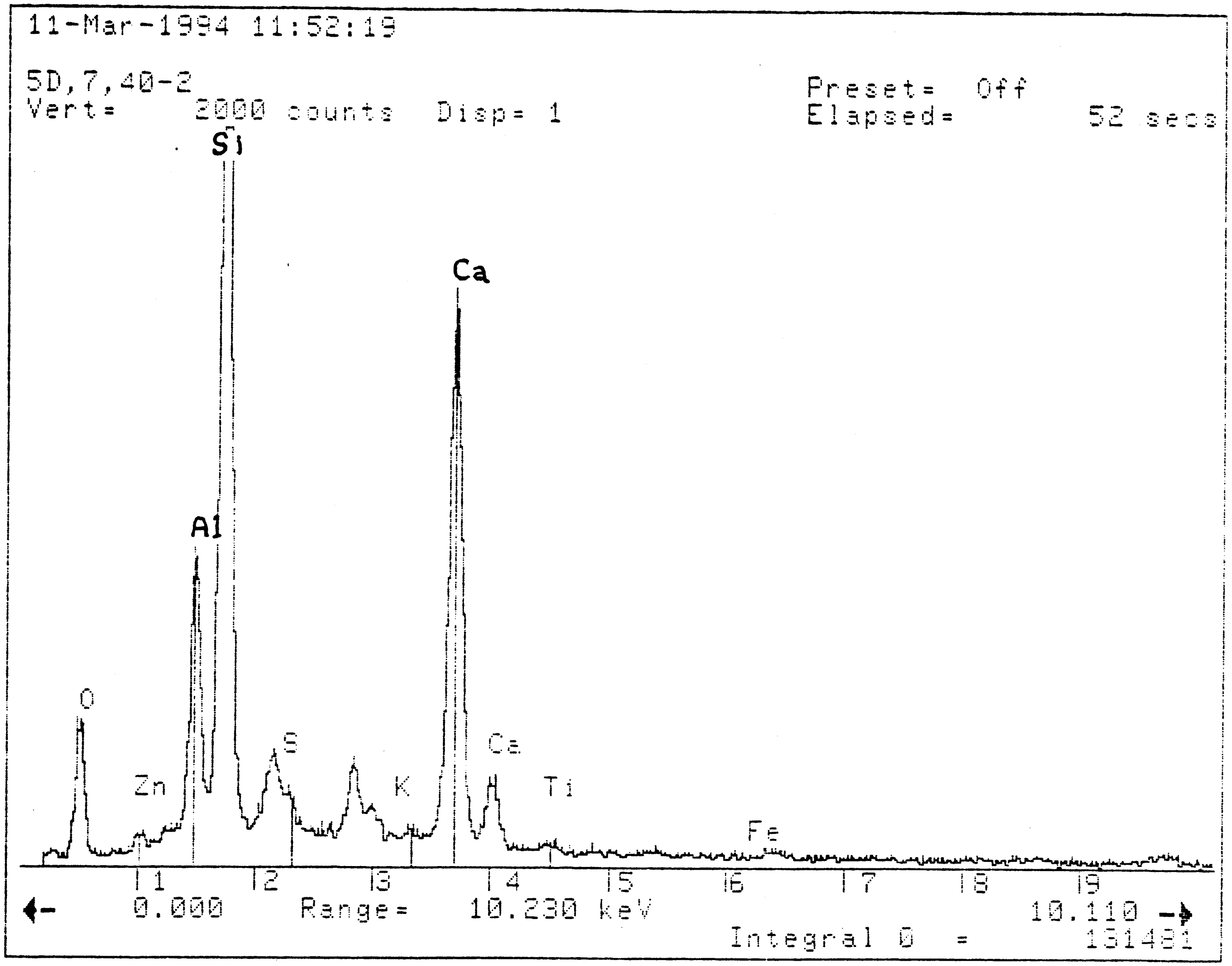

Figure 4.4 Enrichment of Al, Ca, and Si on the material fiber found in the MWC bottom ash at 40°C with 33% saturation (7% water content) for 5-day

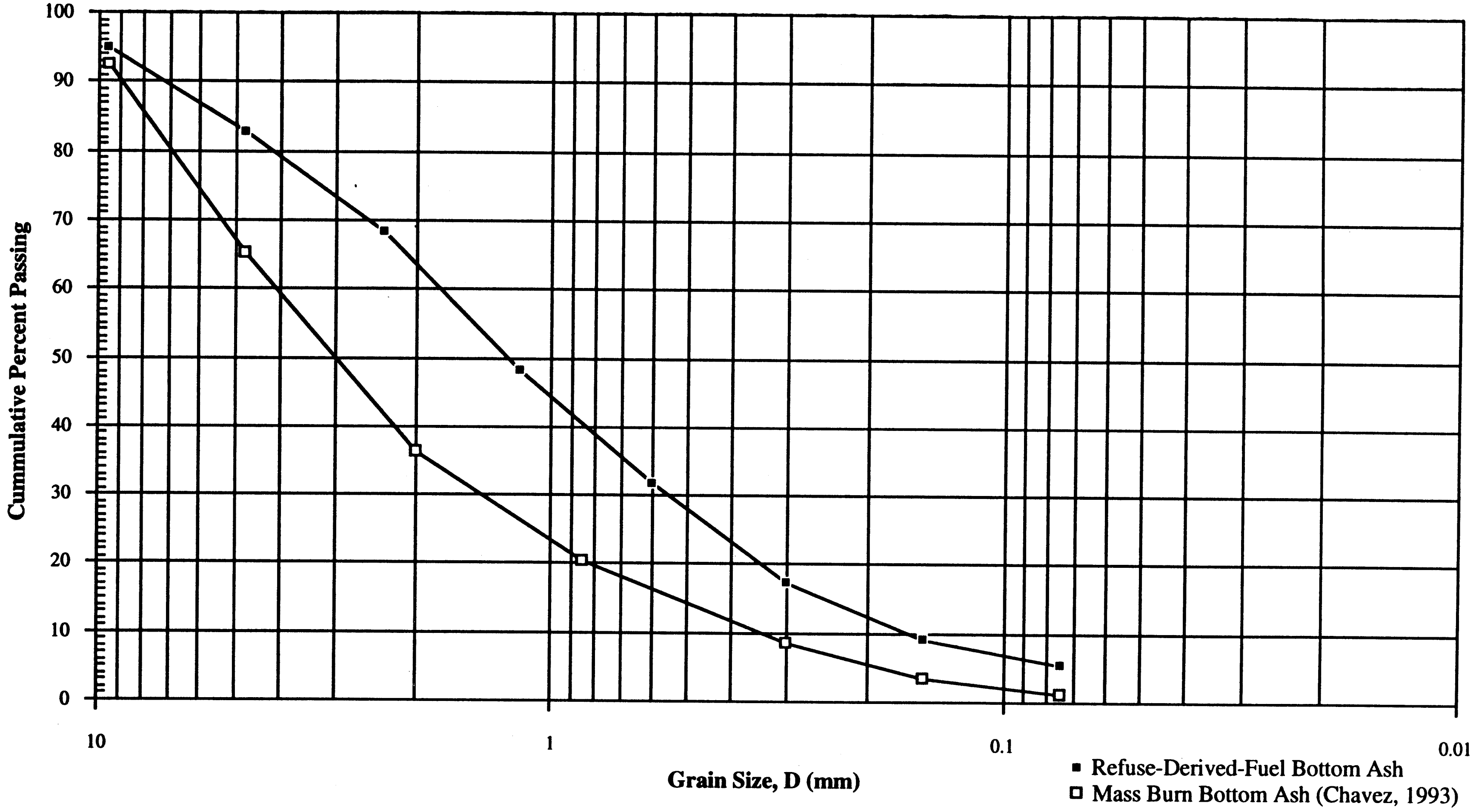

Figure 4.5 Grain size distribution for MB and RDF bottom ash

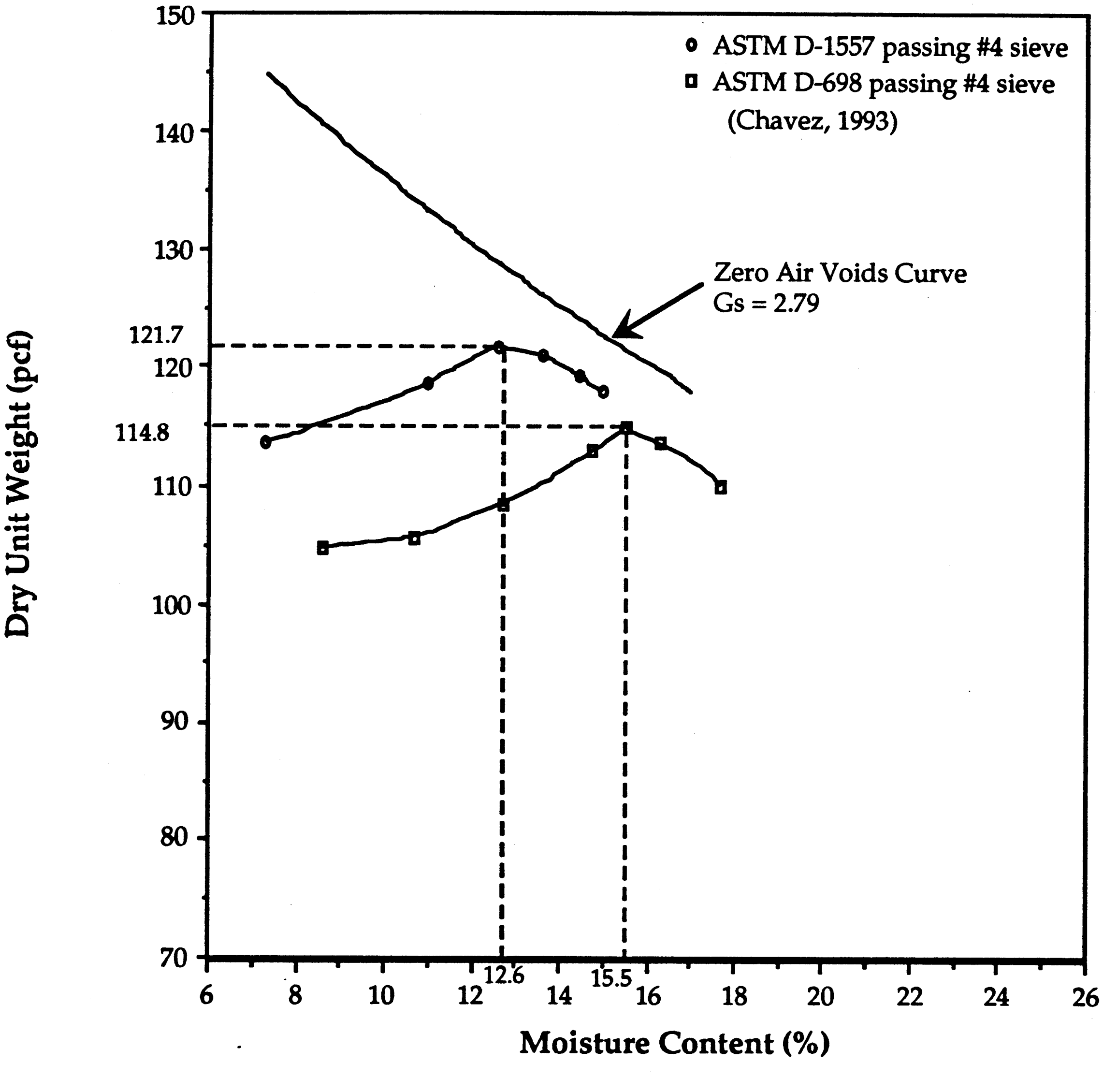

Figure 4.6 Moisture density relationship for MB bottom ash passing the #4 sieve (1 pcf = 0.157 kN/m^3)

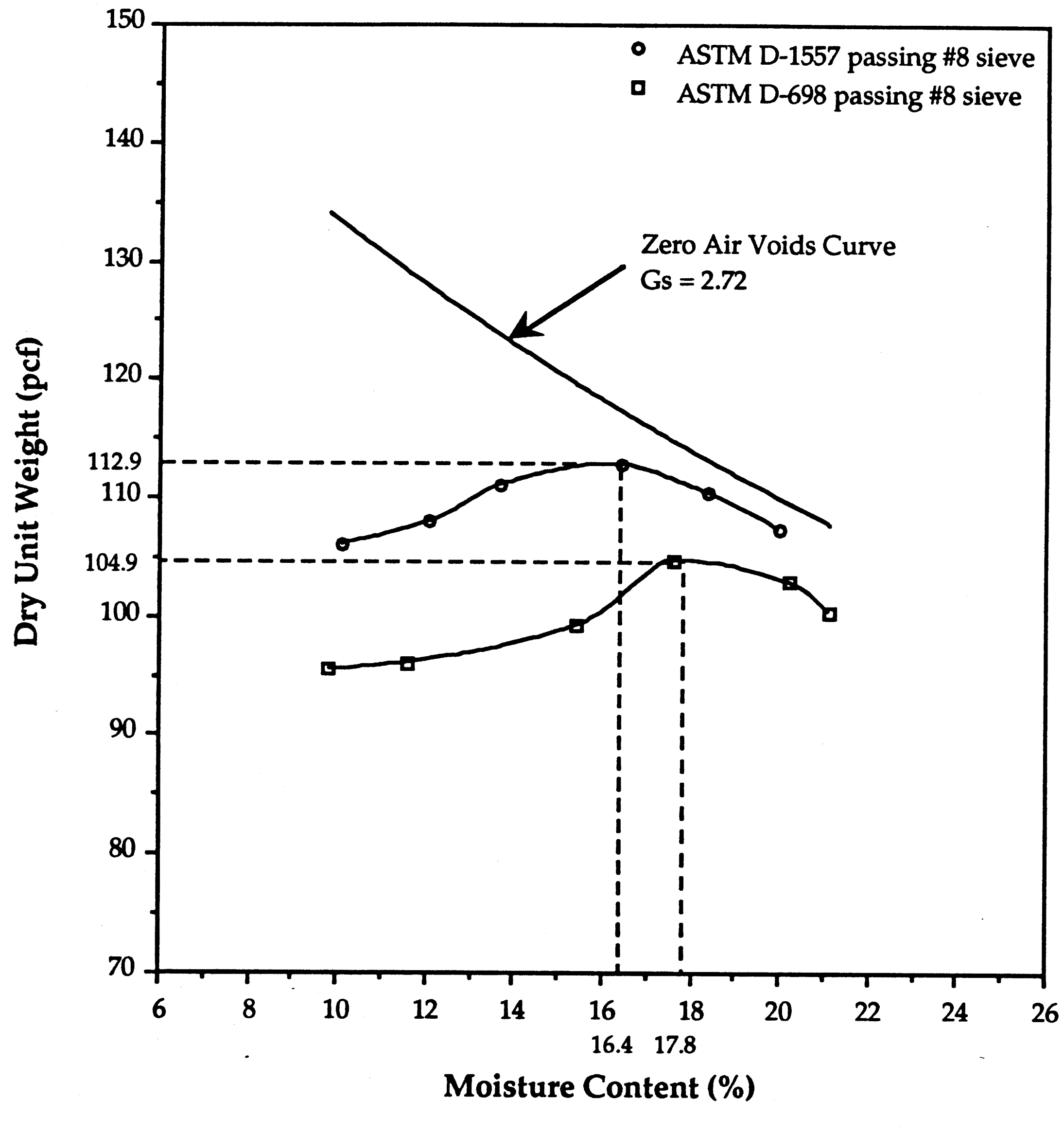

Figure 4.7 Moisture density relationship for MB bottom ash passing the #8 sieve (1 pcf = 0.157 kN/m^3)

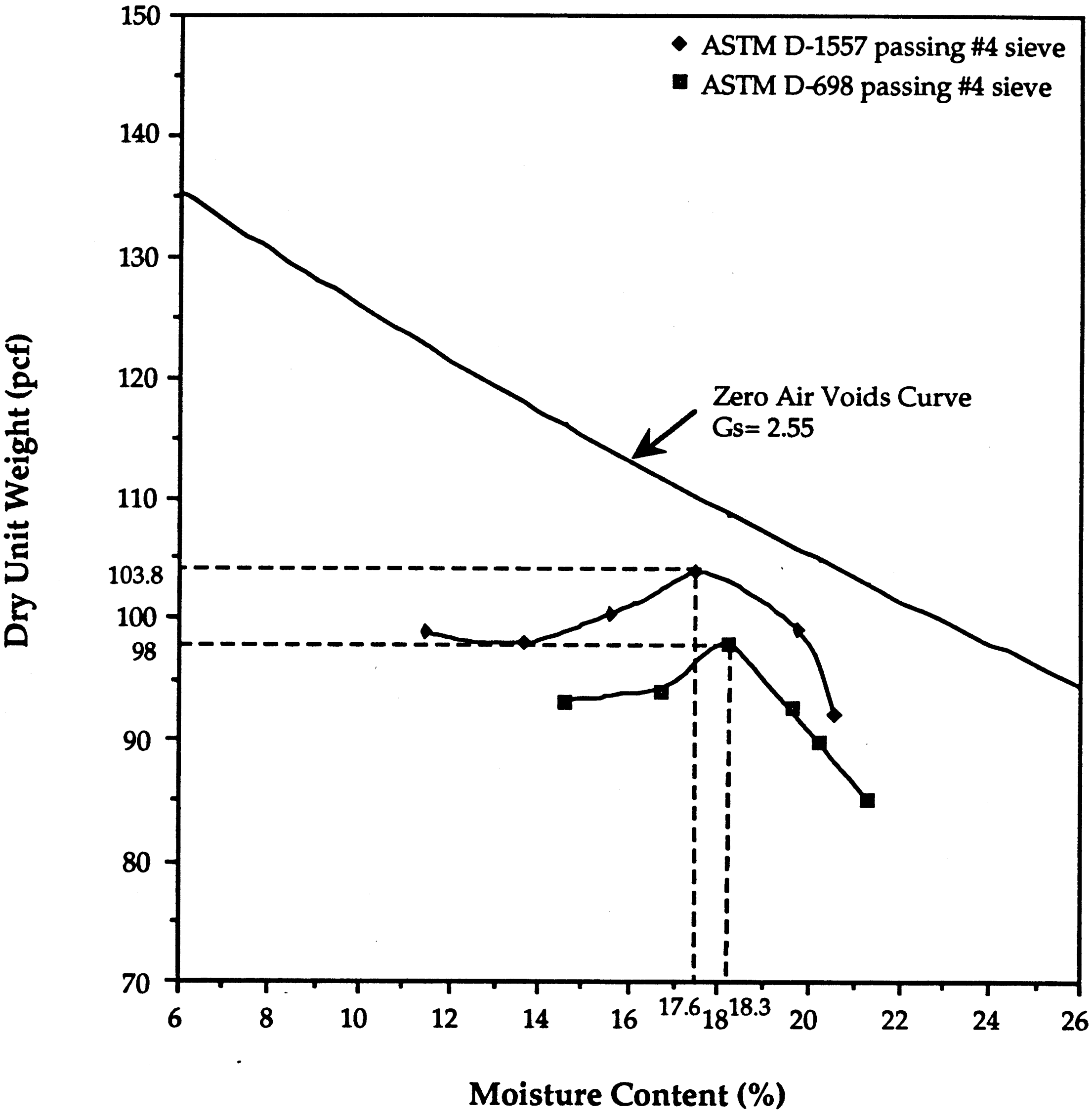

Figure 4.8 Moisture density relationship for RDF bottom ash passing the #4 sieve (1 pcf = 0.157 kN/m^3)

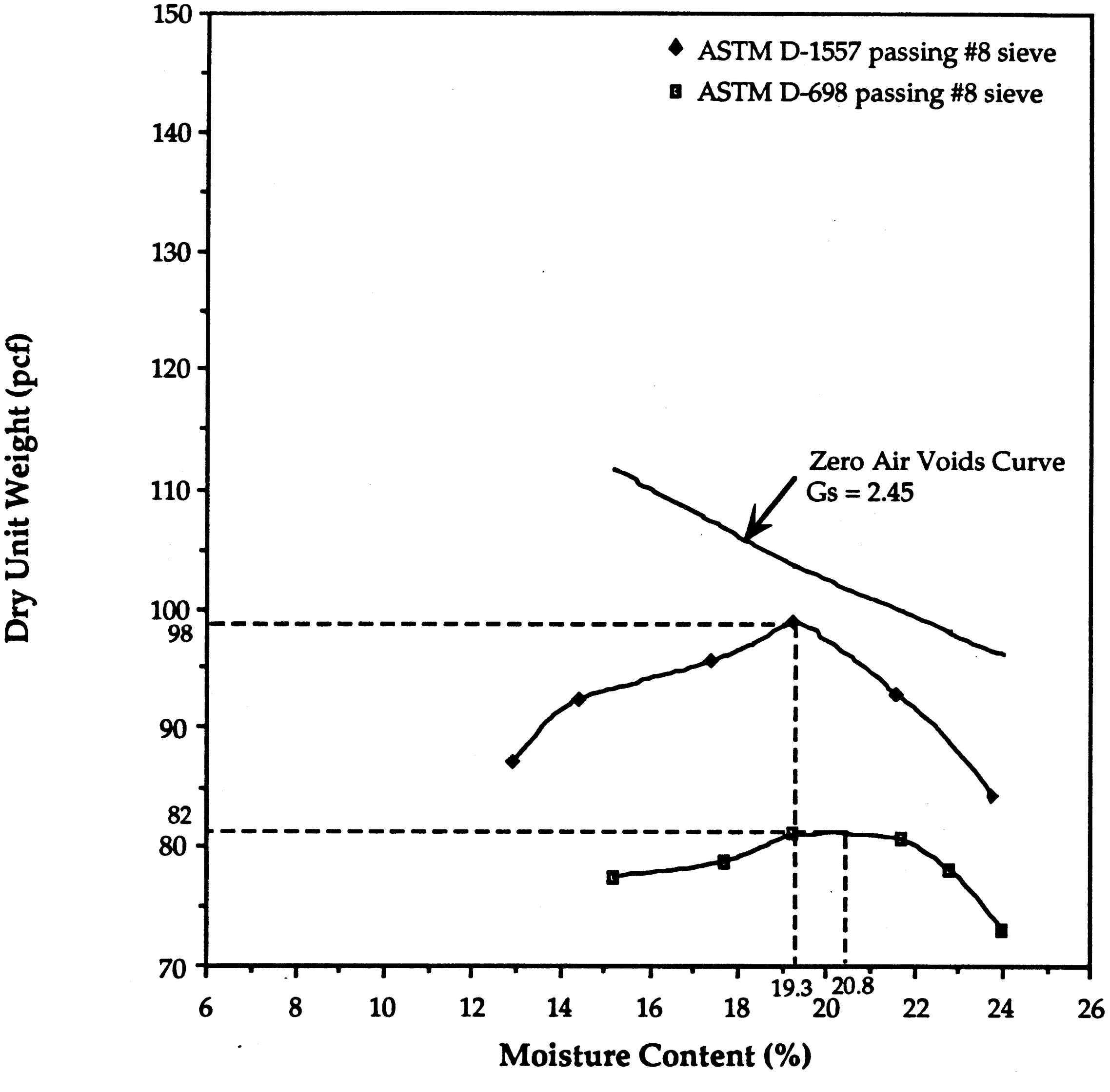

Figure 4.9 Moisture density relationship for RDF bottom ash passing #8 sieve (1 pcf = 0.157 kN/m^3)

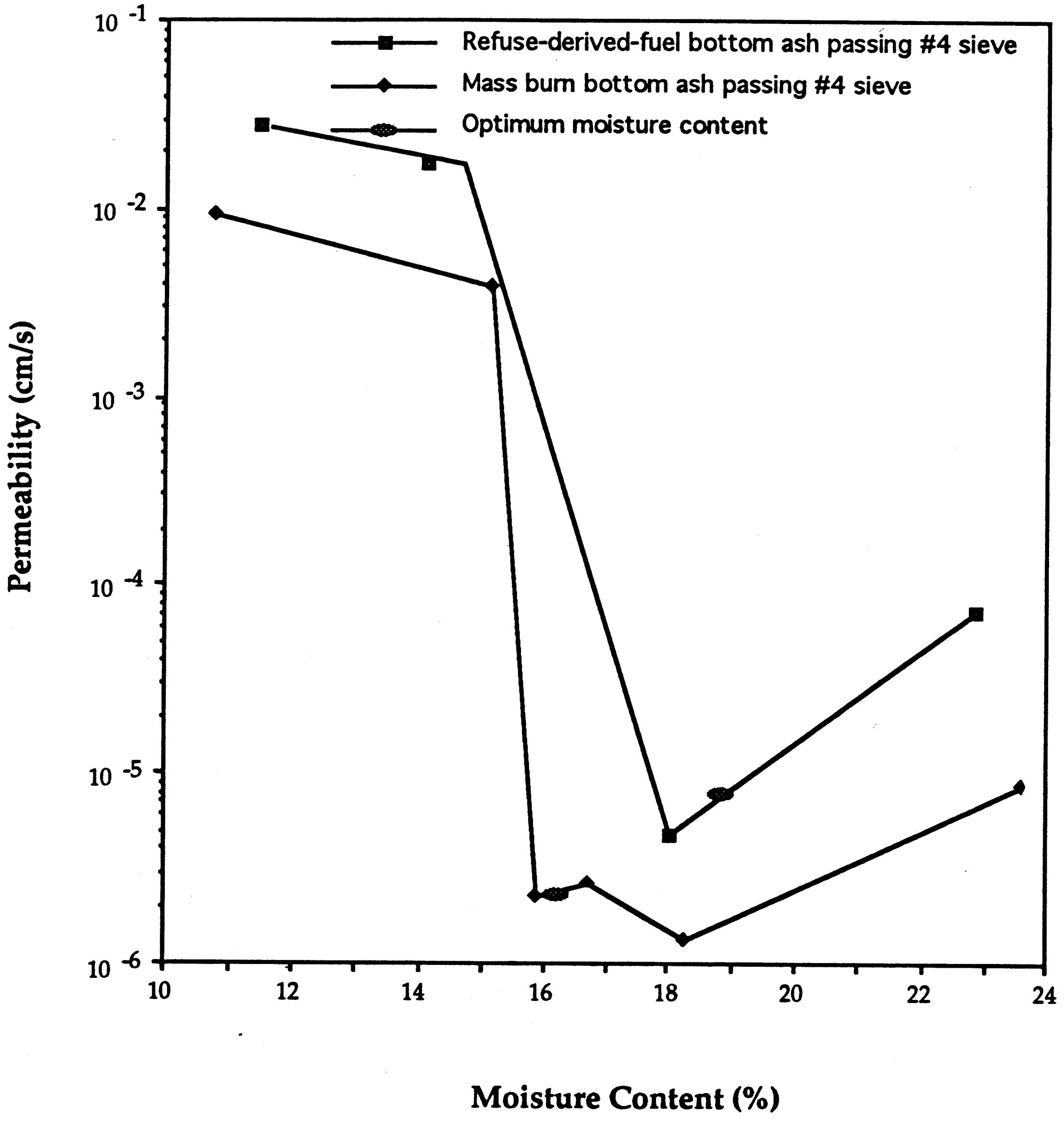

Figure 4.10 Permeability versus moisture content for MB bottom ash passing #4 sieve compacted following ASTM D-698

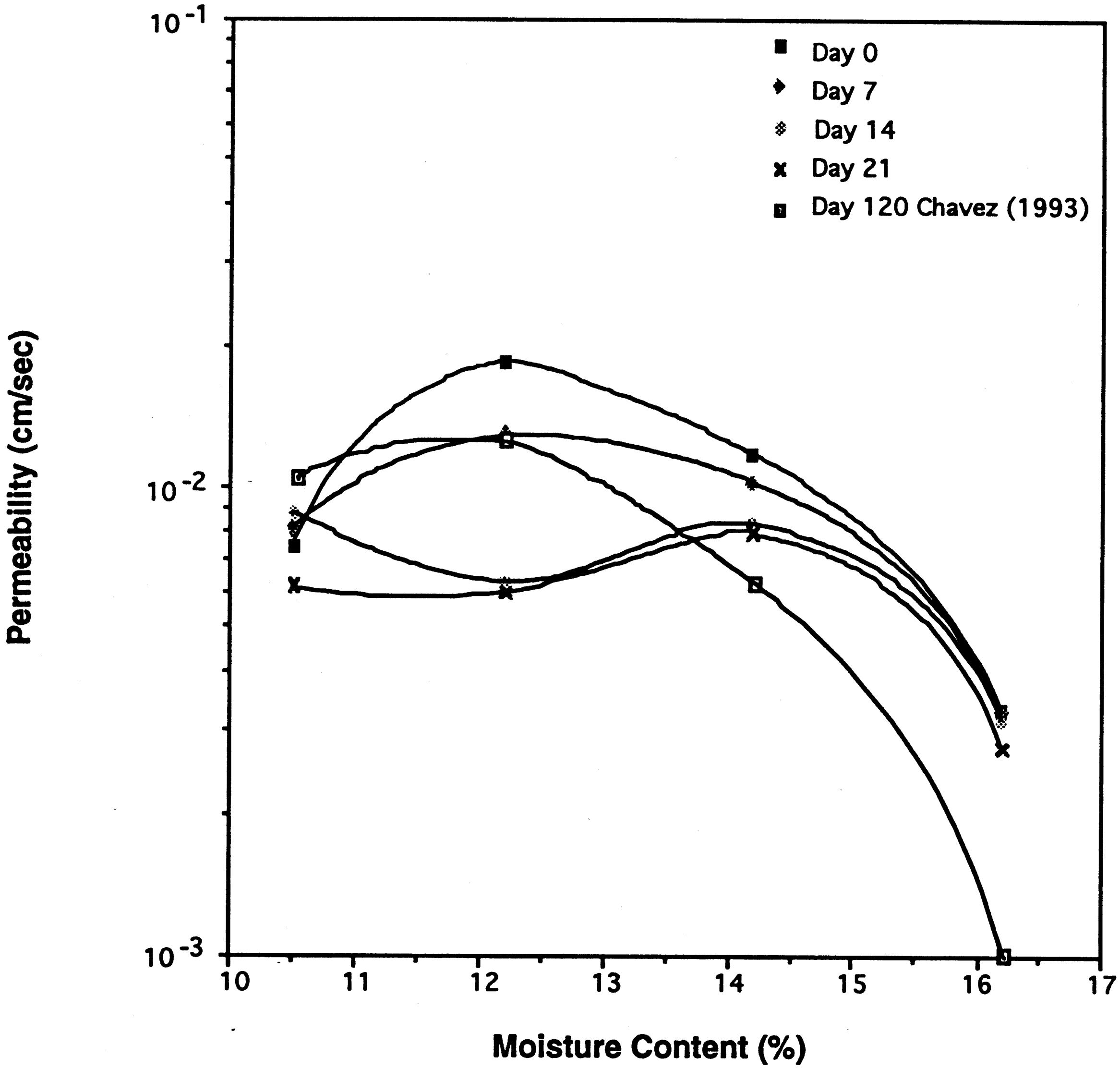

Figure 4.11 Permeability versus moisture content for the MB bottom ash passing #4 sieve compacted following ASTM D-698

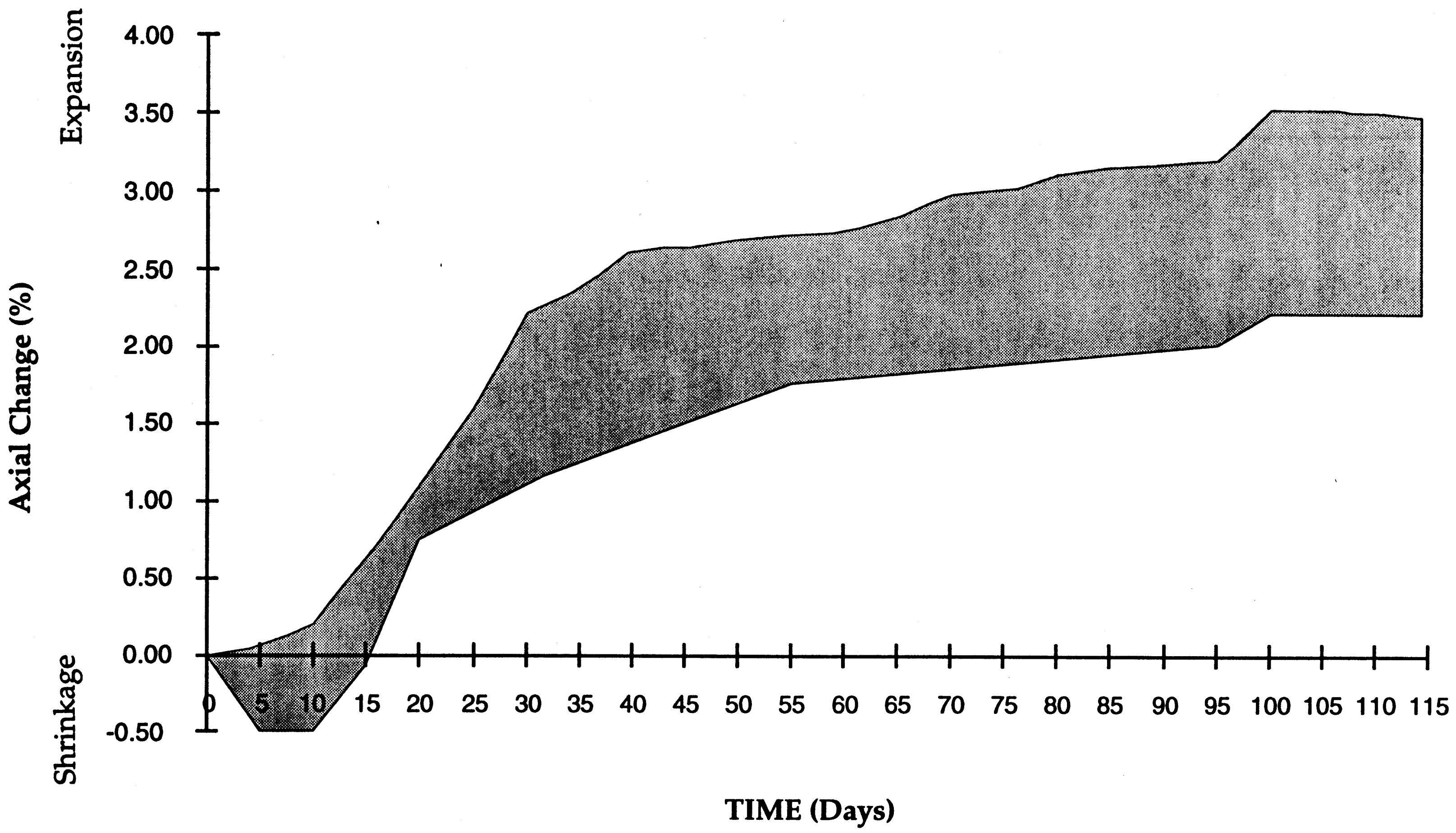

Figure 4.12 Axial change versus time of compacted WTE botttom ash, dry

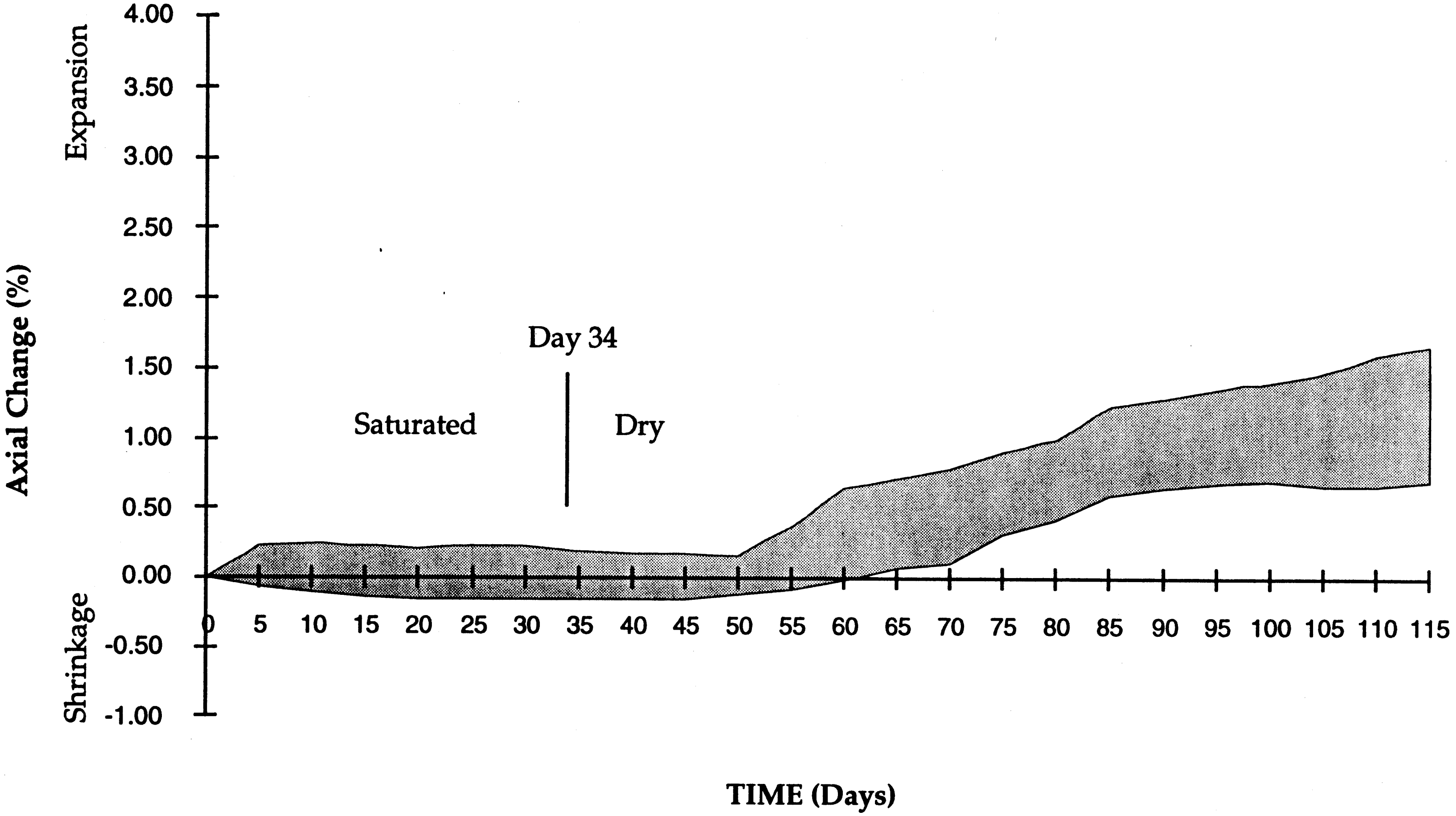

Figure 4.13 Axial change versus time of compacted MB bottom ash, passing #4 sieve compacted following ASTM D-698 saturated for 34 days and allowed to air dry

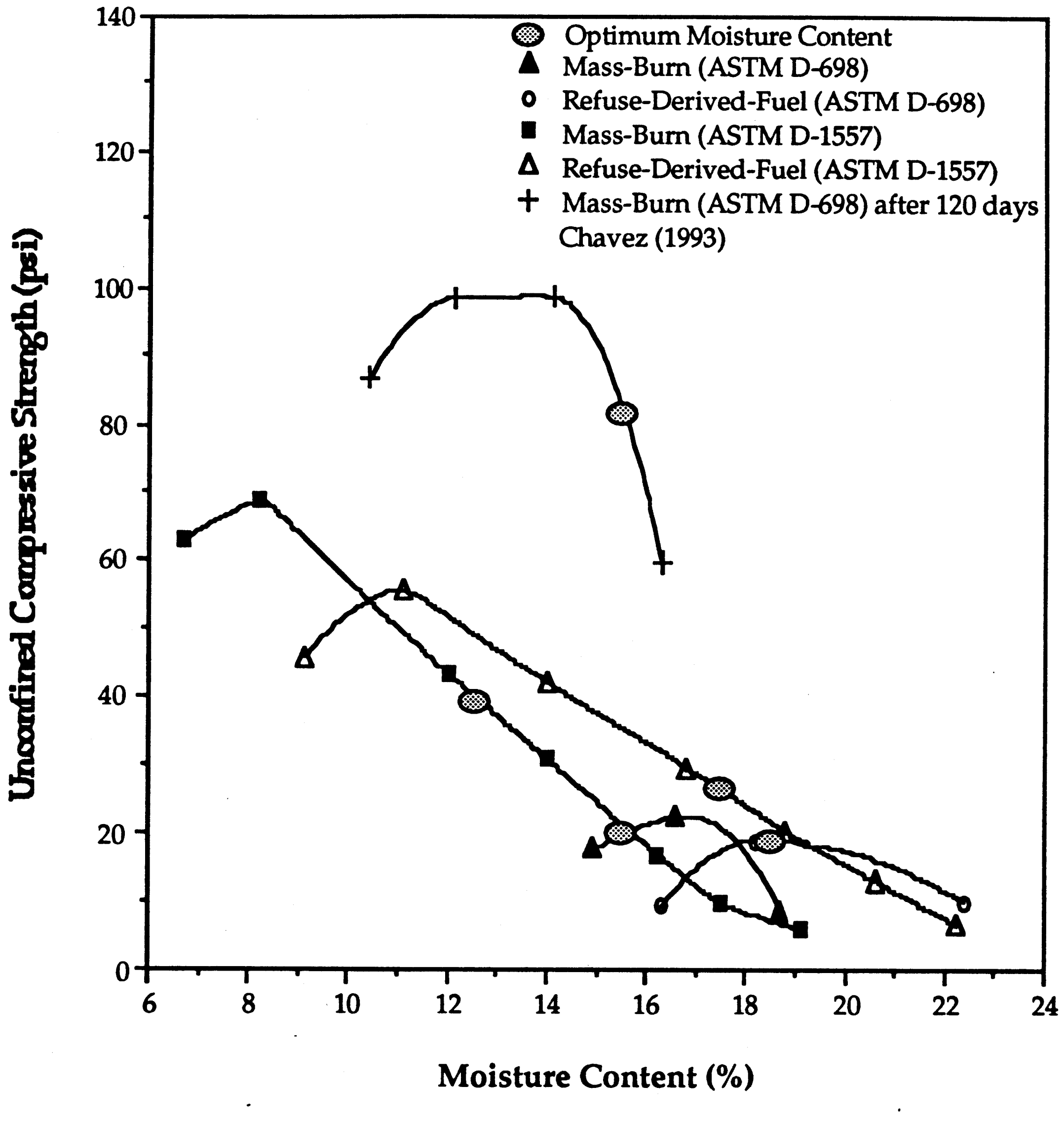

Figure 4.14 Unconfined compressive strength versus moisture content for standard and modified compaction of mass-burn and refuse-derived-fuel WTE bottom ash passing the #4 sieve
(1 psi = 6.895 kpa)

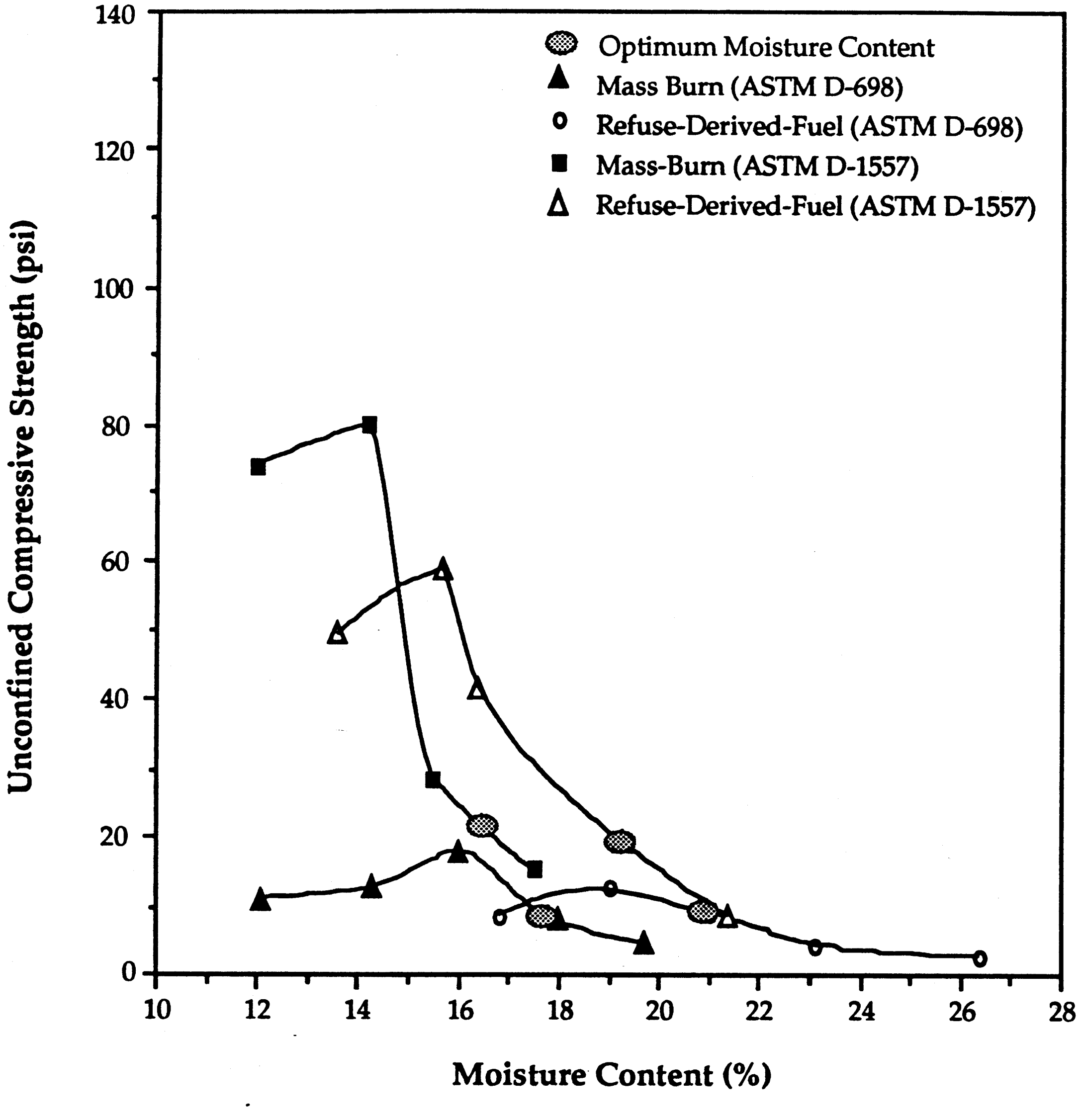

Figure 4.15 Unconfined compressive strength versus moisture content for standard and modified compaction of mass-burn and refuse-derived-fuel WTE bottom ash passing the #8 sieve (1 psi = 6.895 kpa)

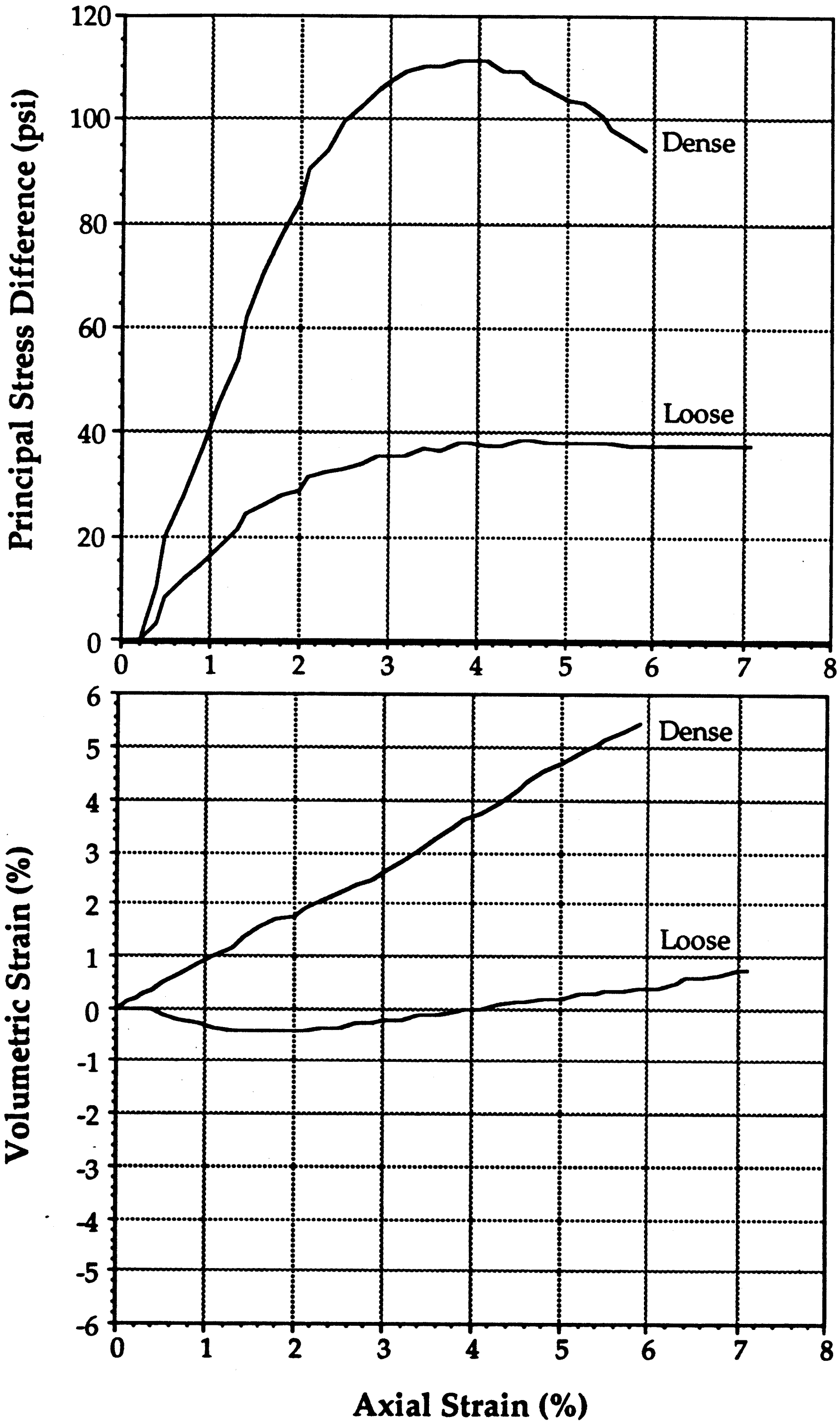

Figure 4.16 Typical stress strain curves for loose and dense MB bottom ash specimens (1 psi = 6.895 kPa) Dense (#4, 100%, 15 psi), Loose (#8, 95%, 10 psi)

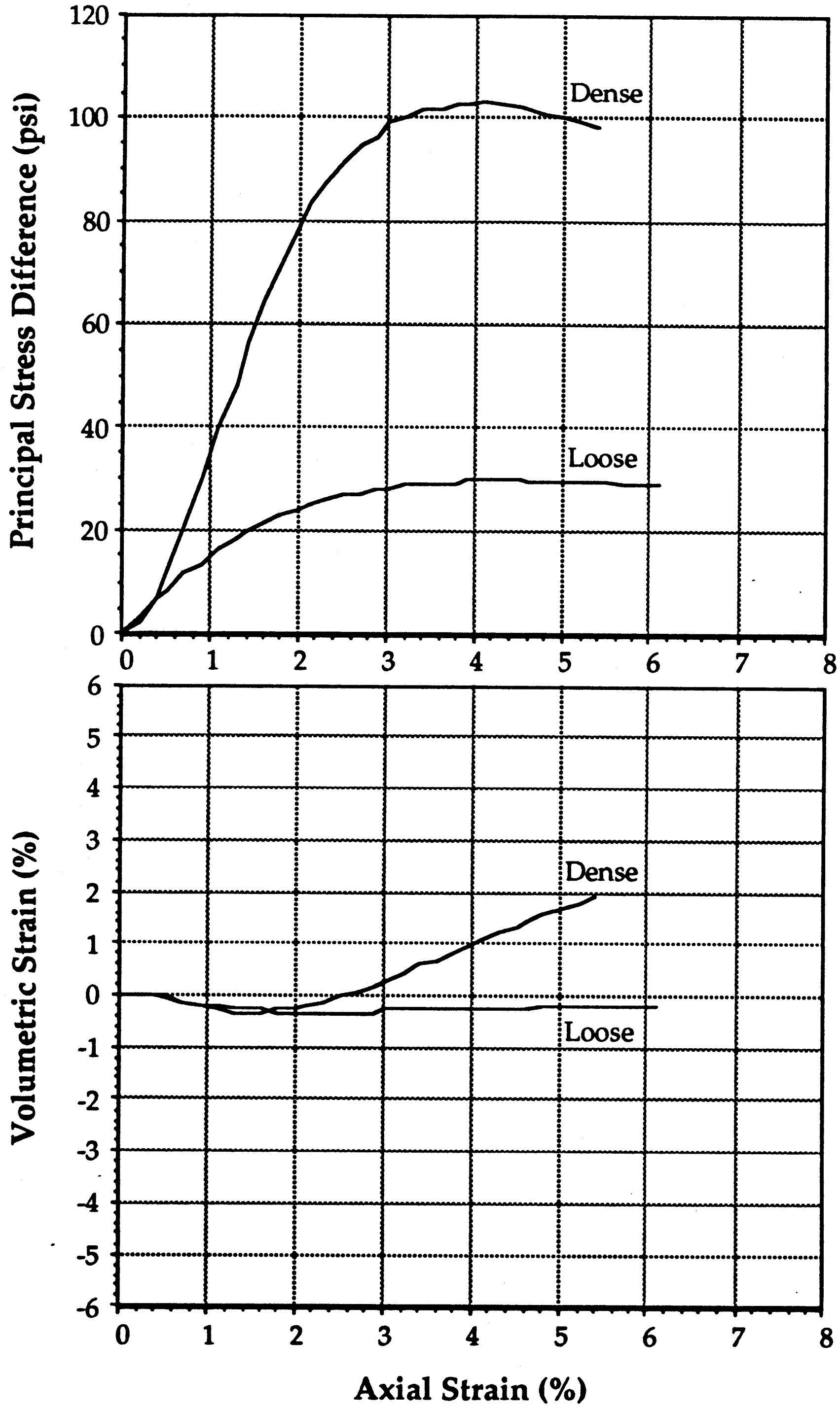

Figure 4.17 Typical stress strain curves for loose and dense RDF bottom ash specimens (1 psi = 6.895 kPa) Dense (#4, 100%, 15 psi), Loose (#8, 95%, 10 psi)

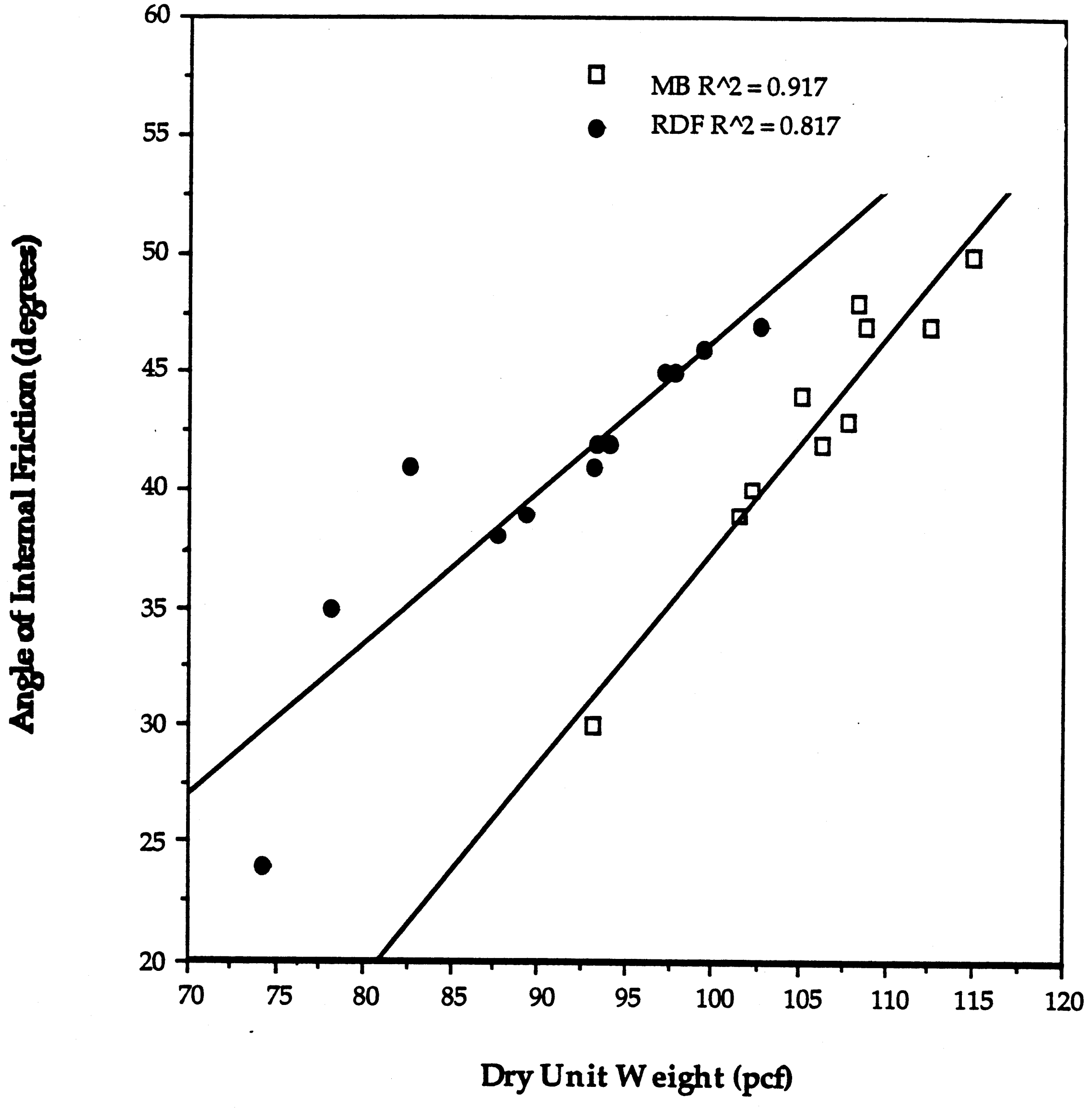

Figure 4.18 Angle of internal friction versus dry unit weight for MB and RDF MWC bottom ash (1 pcf = 0.157 kN/m^3)

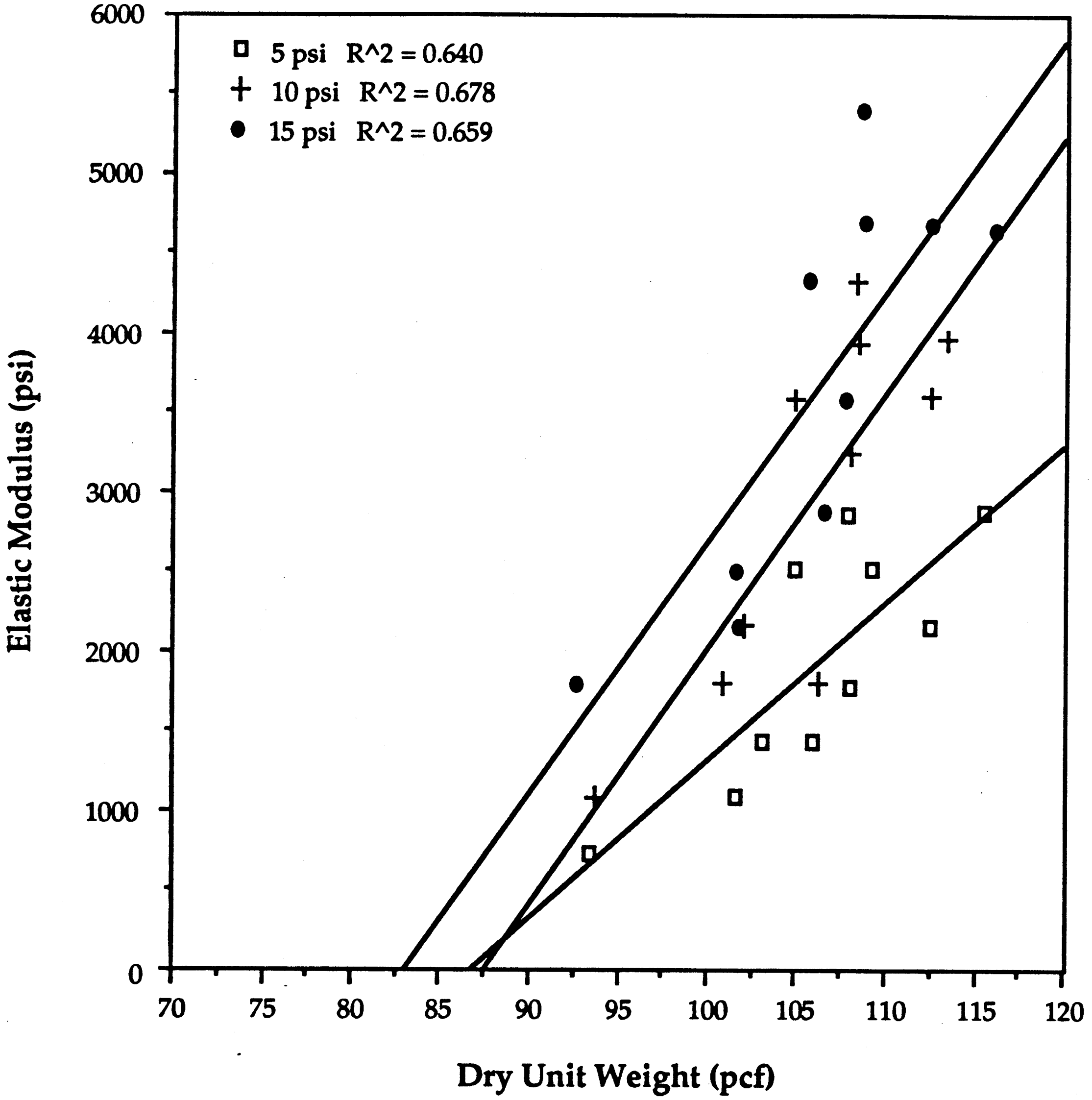

Figure 4.19 Elastic modulus versus dry unit weight for MB bottom ash over a strain difference of 0.2% (1 psi = 6.895 kPa, 1 pcf = 0.157 kN/m^3)

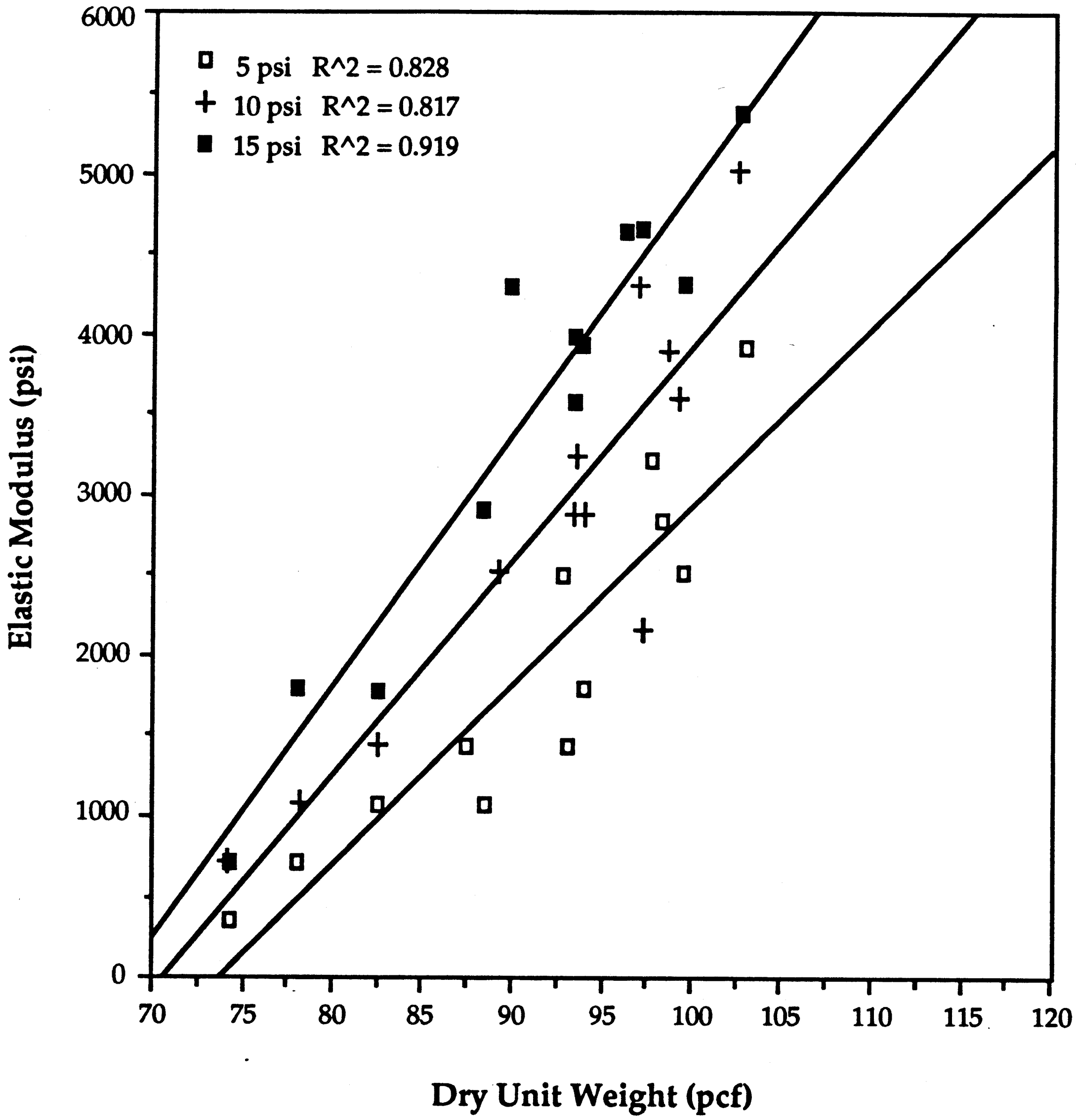

Figure 4.20 Elastic modulus versus dry unit weight for RDF bottom ash over a strain difference of 0.2% (1 psi = 6.895 kPa, 1 pcf = 0.157 kN/m^3)

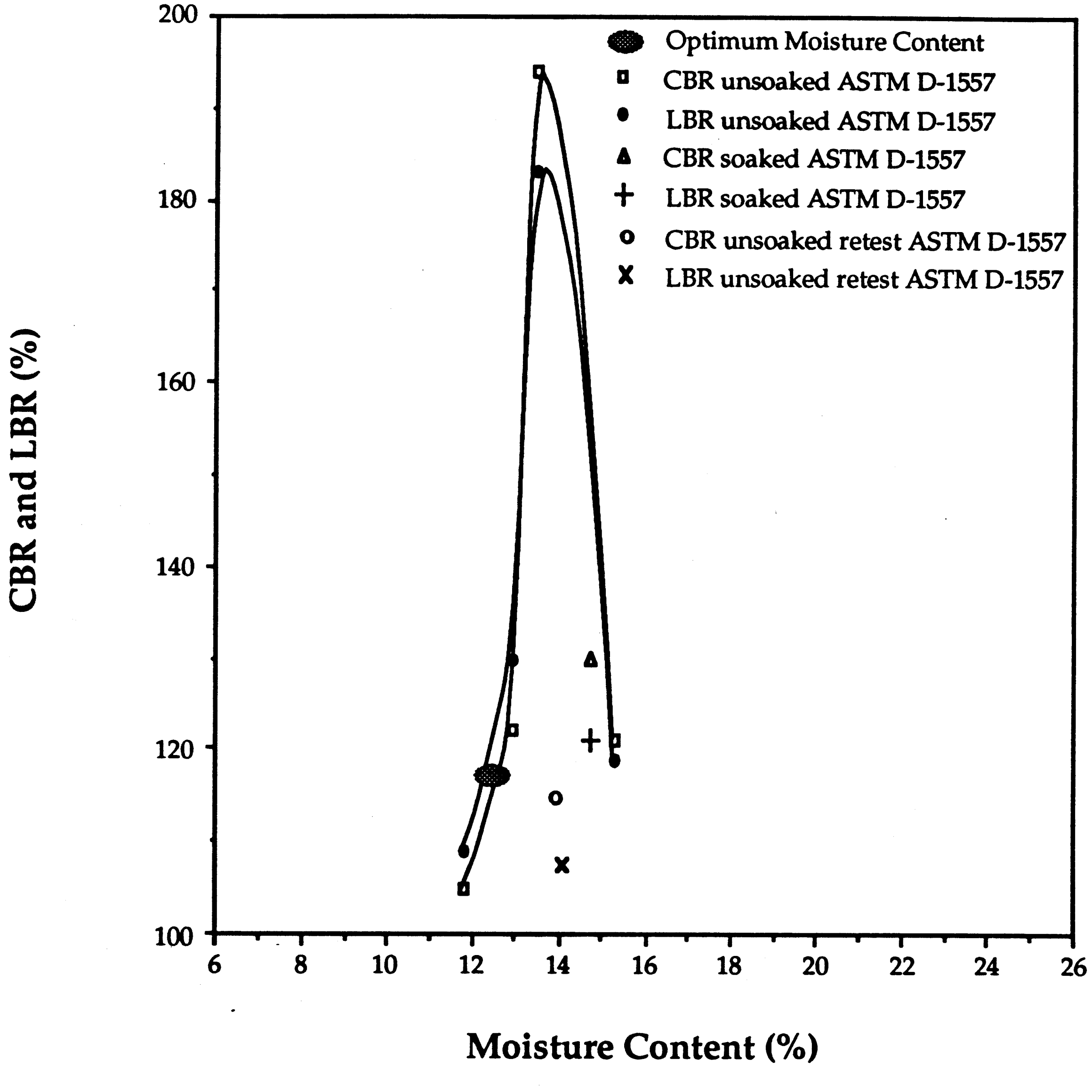

Figure 4.21 Unsoaked and soaked CBR and LBR values versus moisture content for MB bottom ash passing the #4 sieve compacted following ASTM D-1557

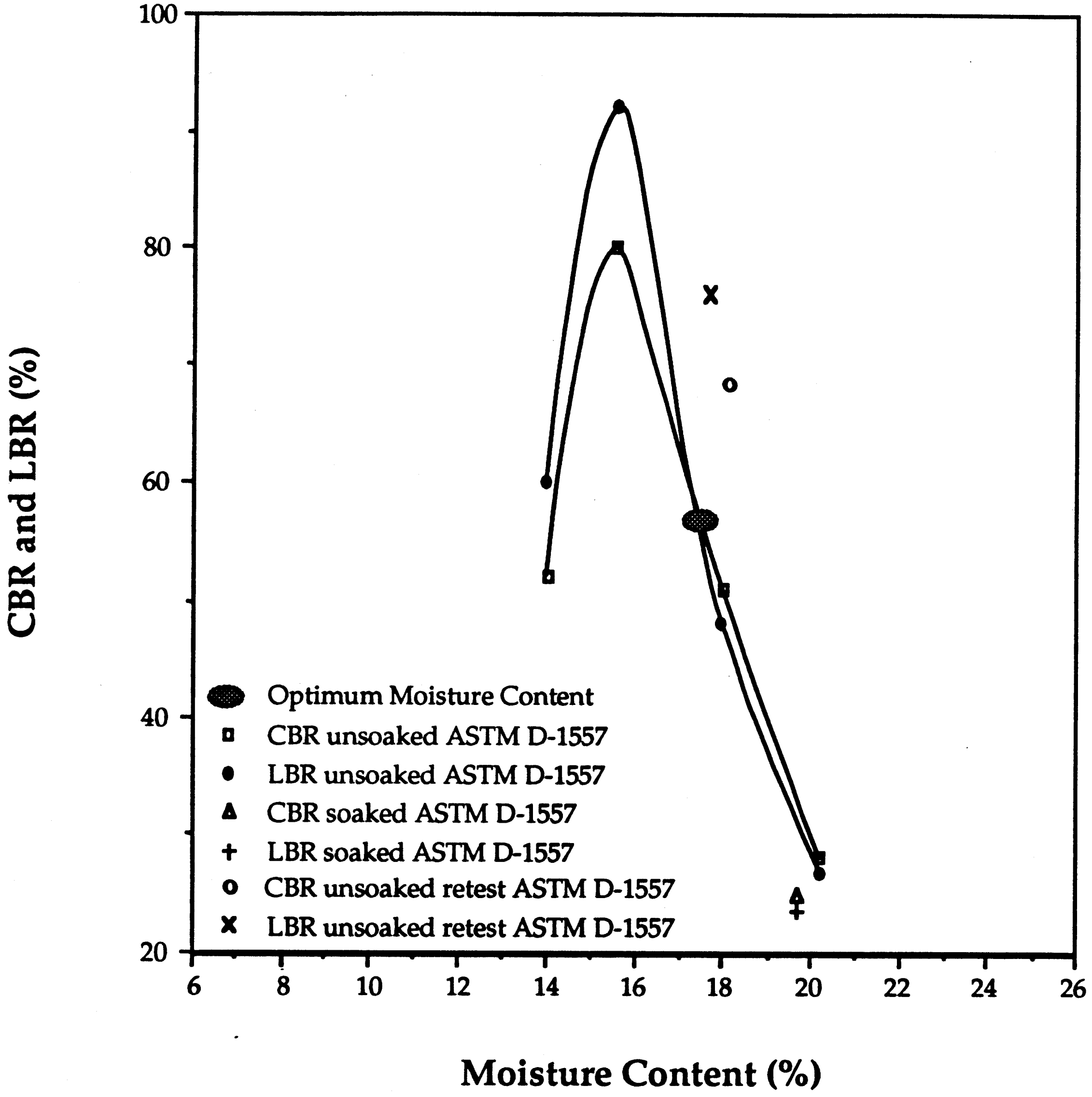

Figure 4.22 Unsoaked and soaked CBR and LBR values versus moisture content for RDF bottom ash passing the #4 sieve compacted following ASTM D-1557

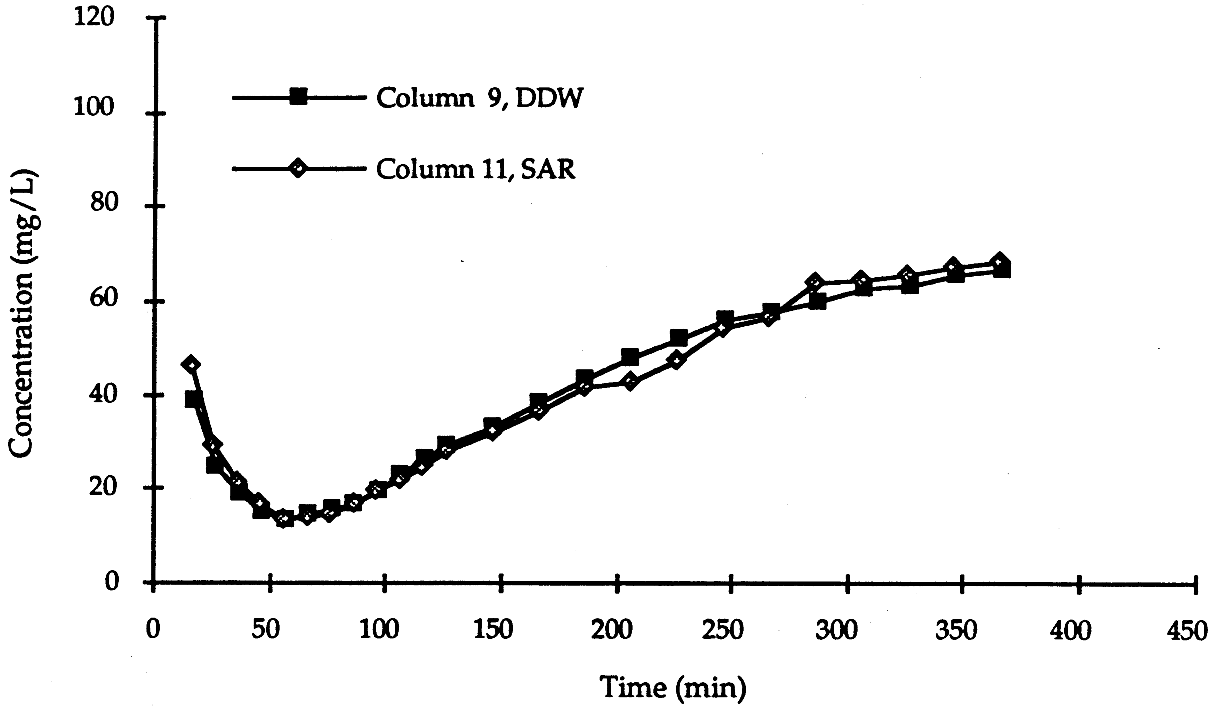

Figure 4.23 Leaching of calcium using DDW and SAR as leaching fluids.

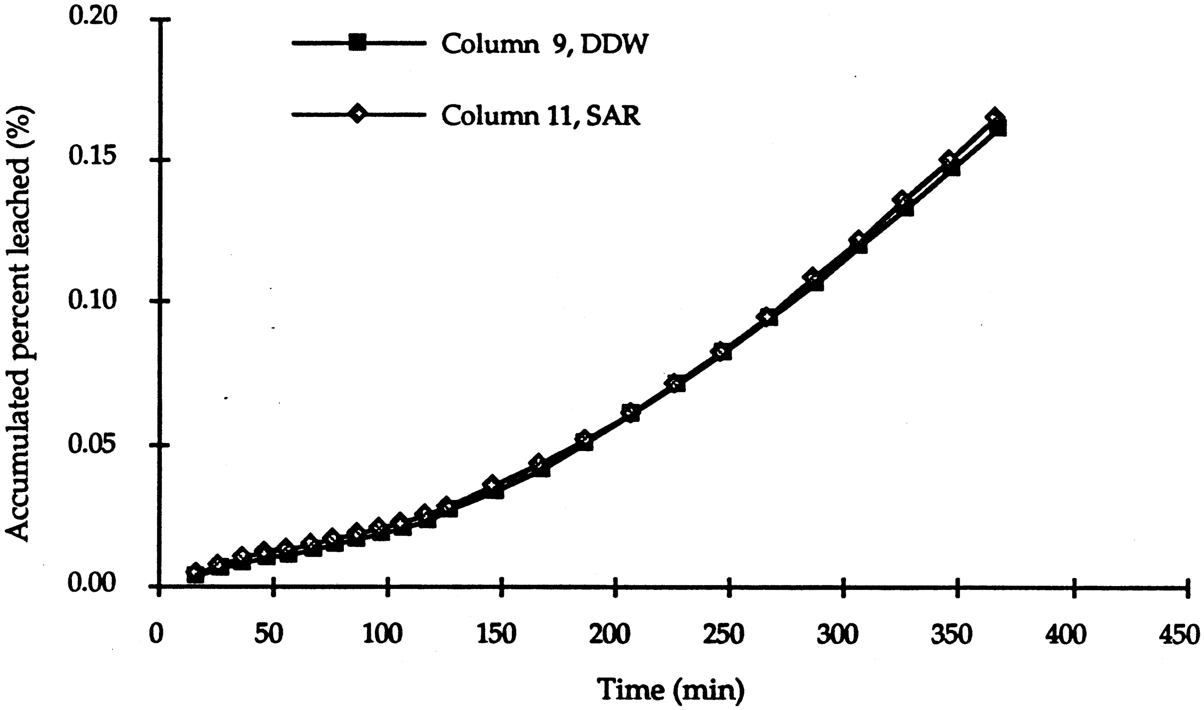

Figure 4.24 Accumulated percent leaching of calcium using DDW and SAR as leaching fluids

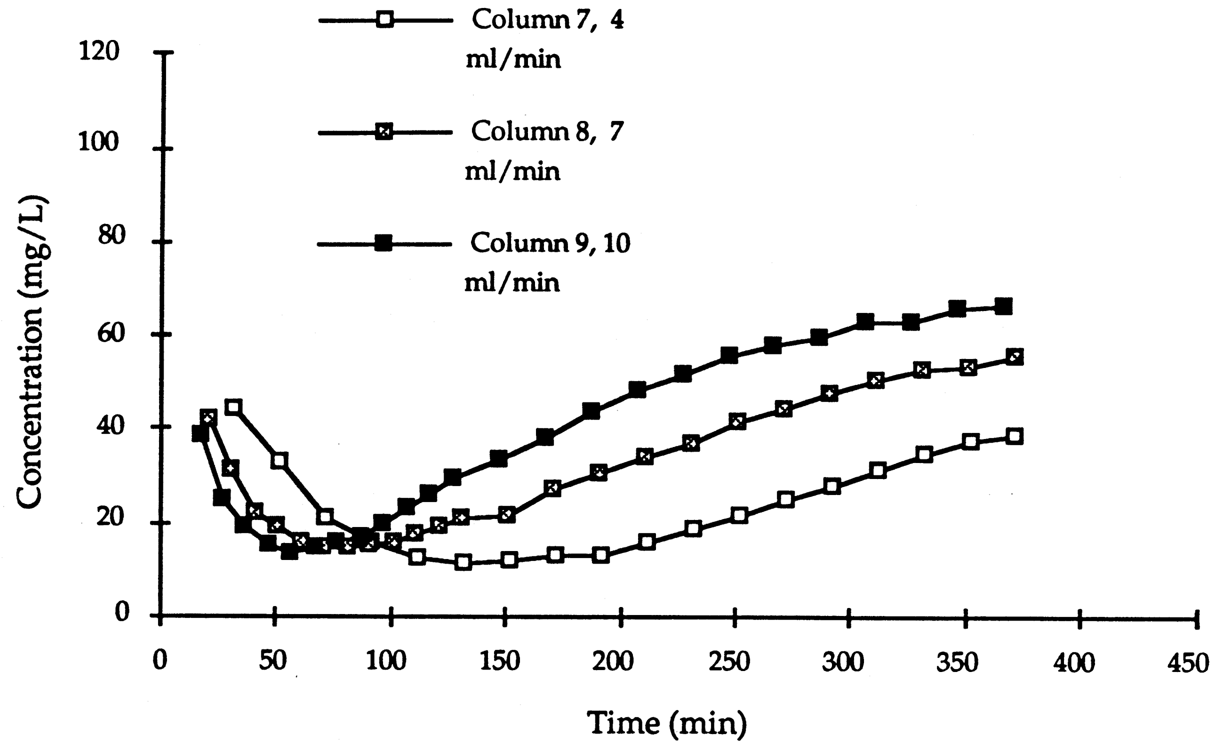

Figure 4.25 Leaching of calcium using DDW at different flow rate

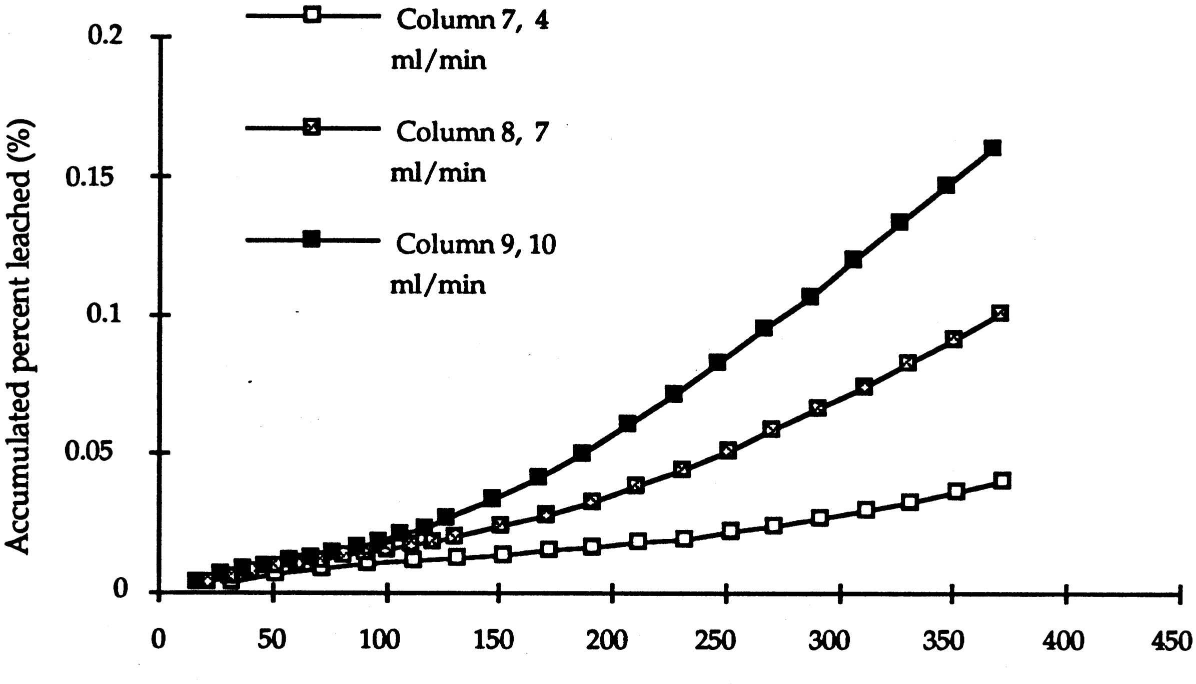

Figure 4.26 Accumulated percent leaching of calcium using DDW at different flow rate

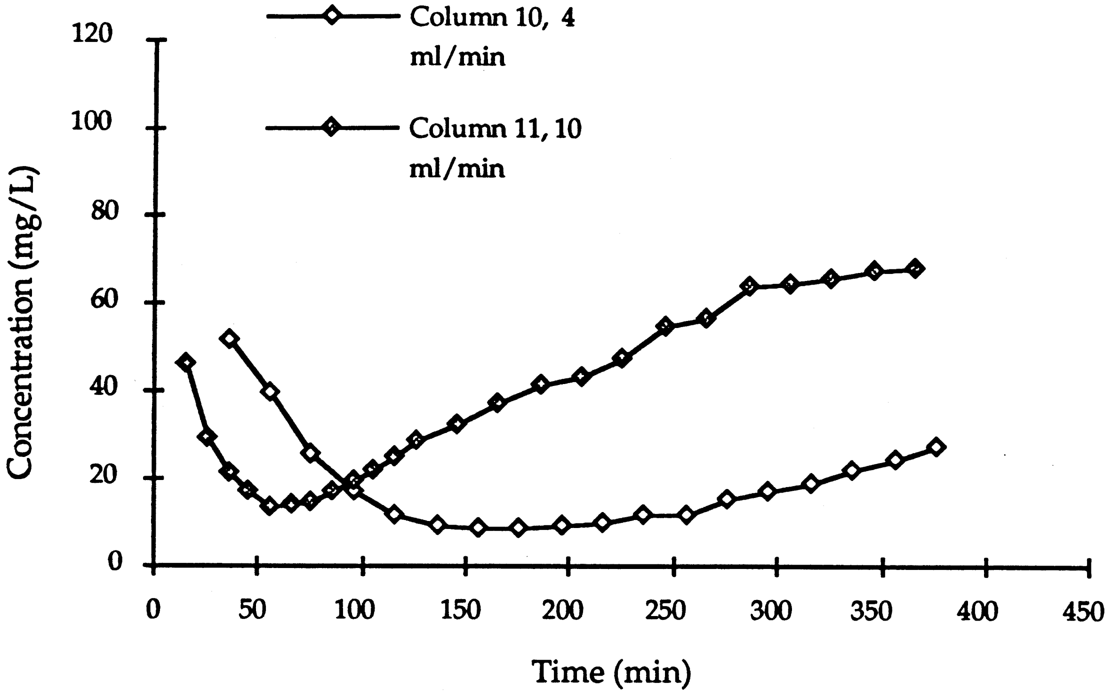

Figure 4.27 Leaching of calcium using SAR at different flow rate

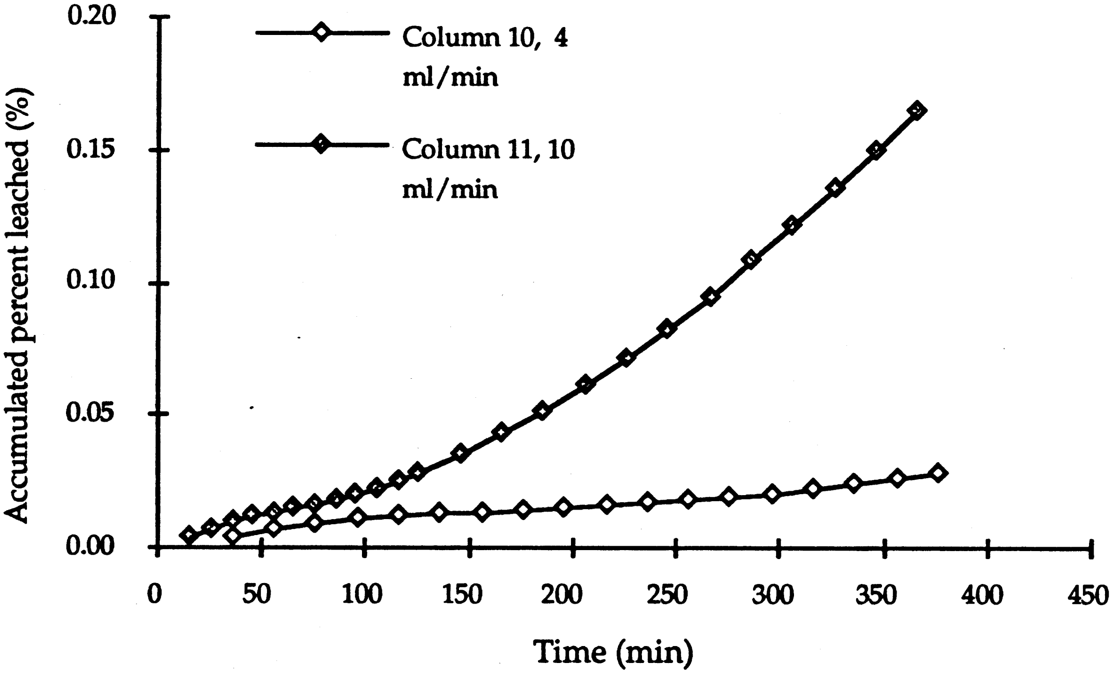

Figure 4.28 Accumulated percent leaching of calcium using SAR at different flow rate

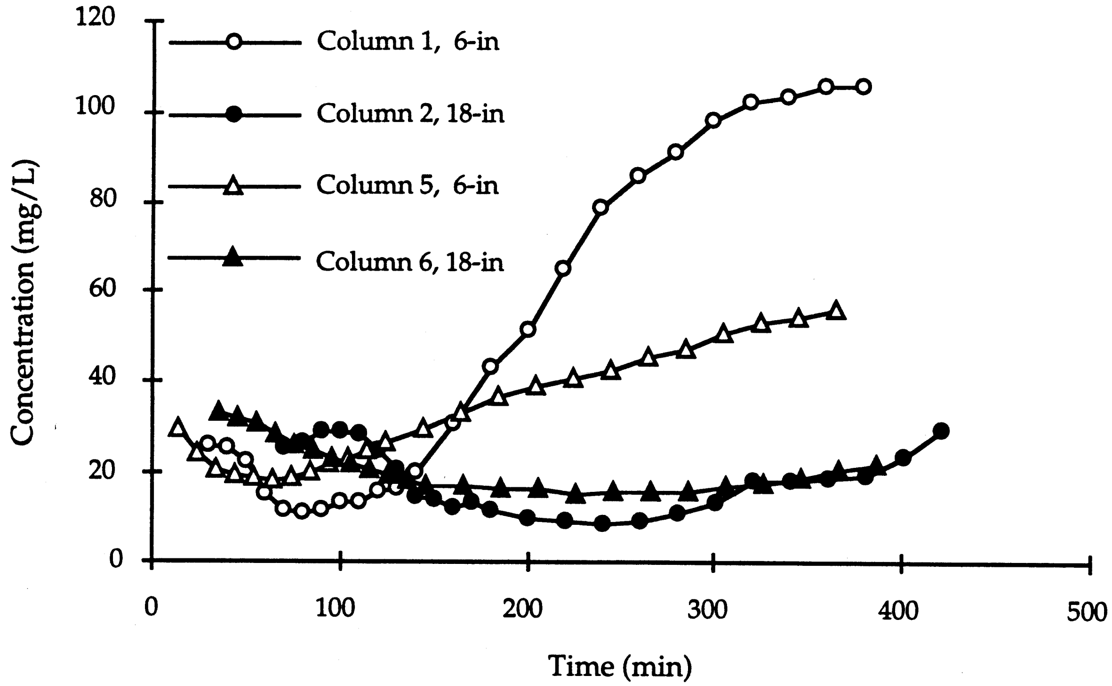

Figure 4.29 Variation in calcium leaching from 15.2-cm and 45.7-cm columns subjected to DDW

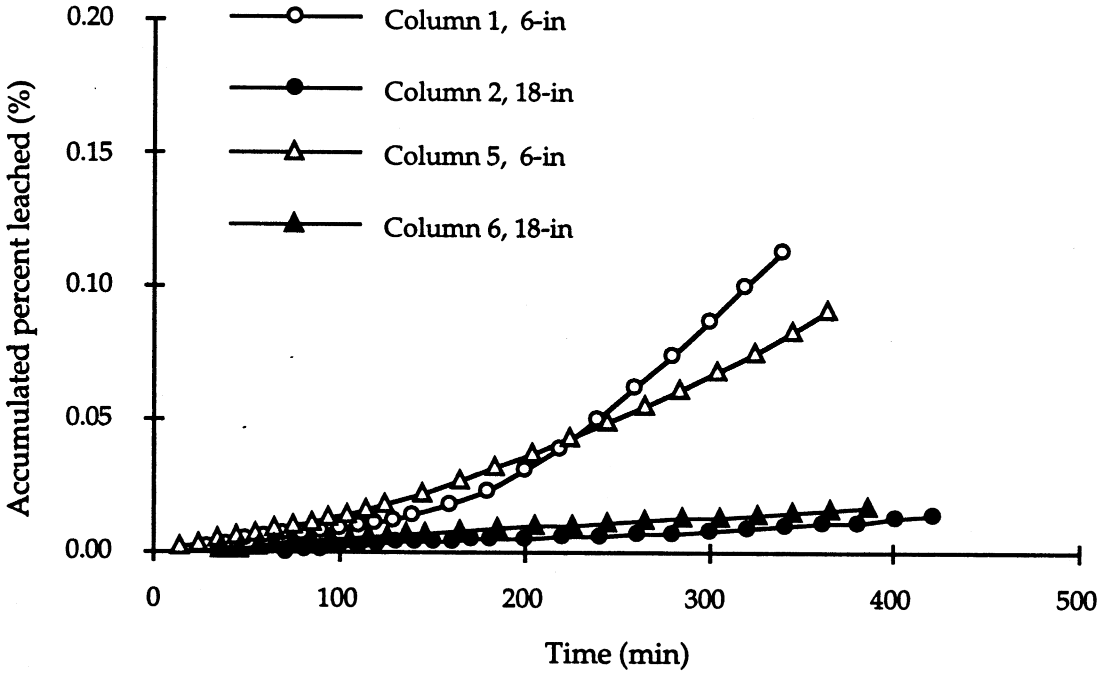

Figure 4.30 Accumulated percent of calcium leached from 15.2-cm and 45.7-cm columns subjected to DDW

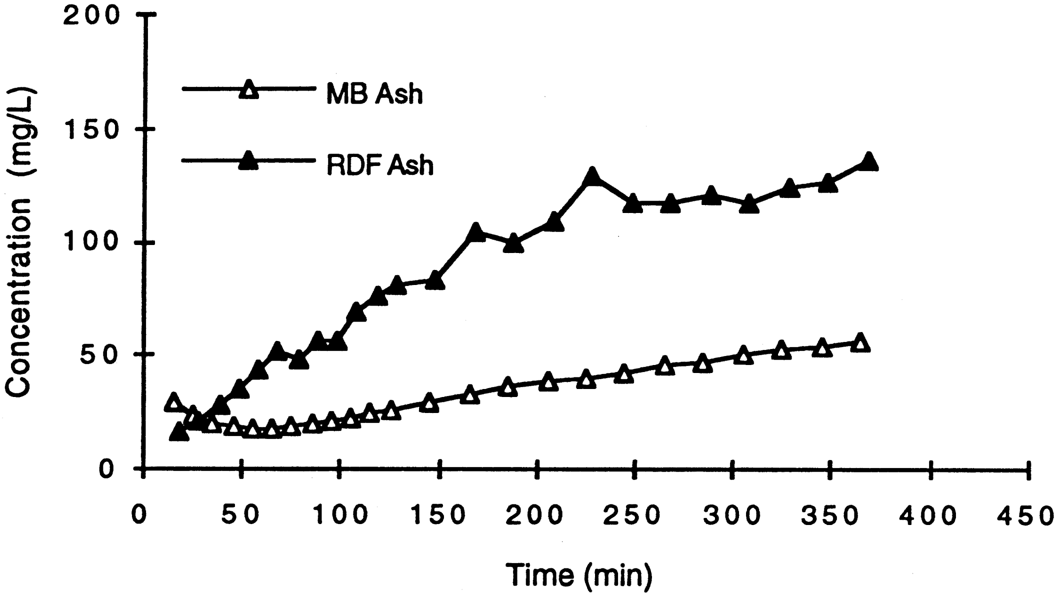

Figure 4.31 Variation in calcium leaching from 6-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

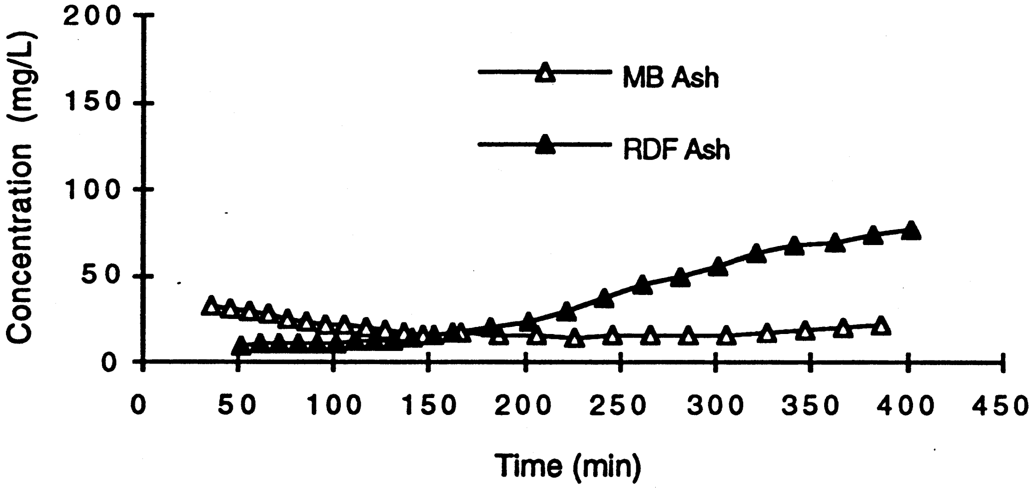

Figure 4.32 Variation in calcium leaching from 18-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

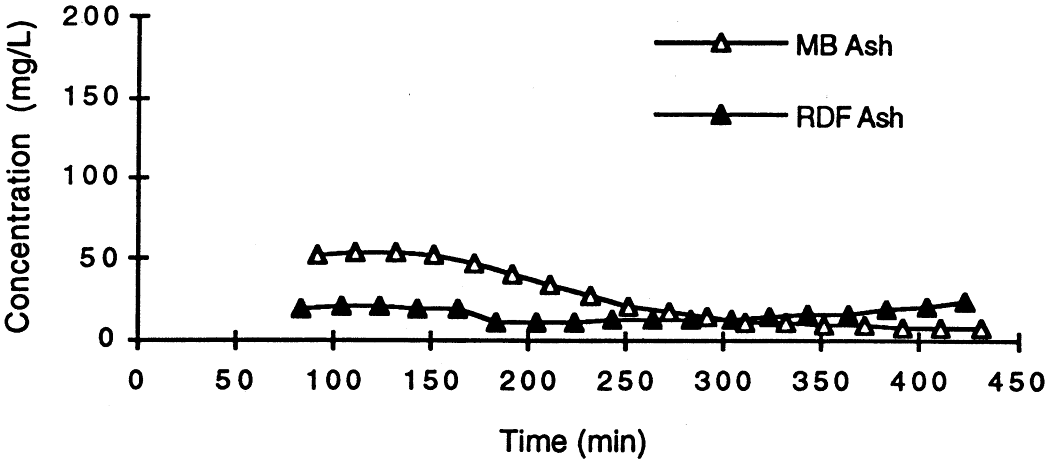

Figure 4.33 Variation in calcium leaching from 18-in columns subjected to SAR using Pinellas County MB ash and Palm Beach County RDF ash

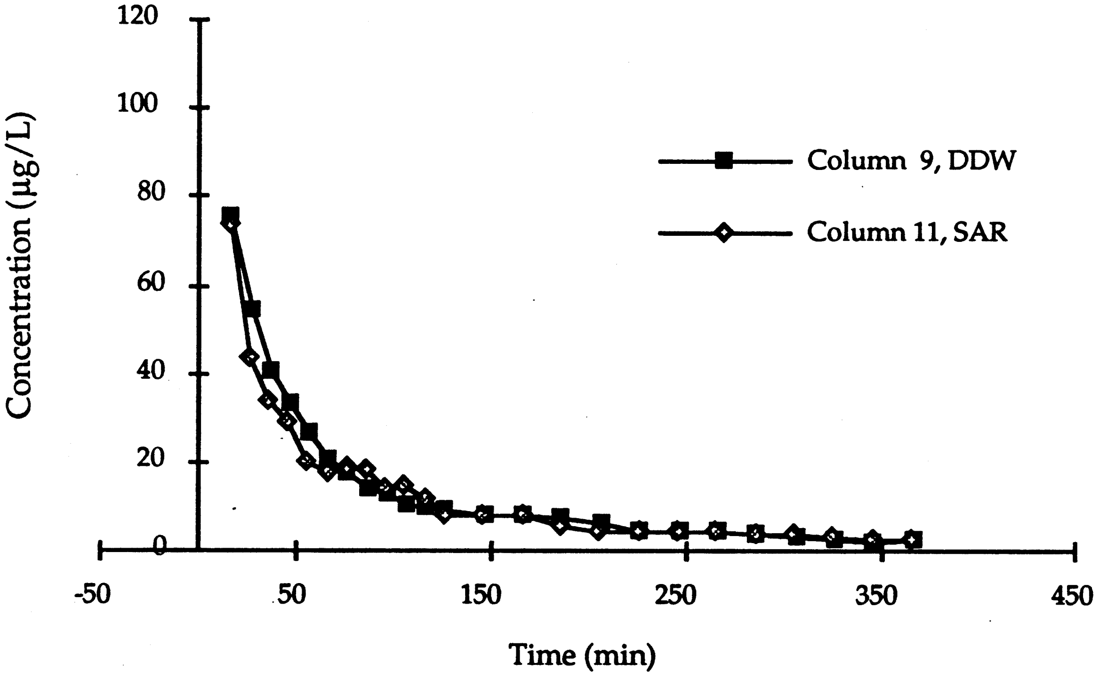

Figure 4.34 Leaching of arsenic using DDW and SAR as leaching fluids.

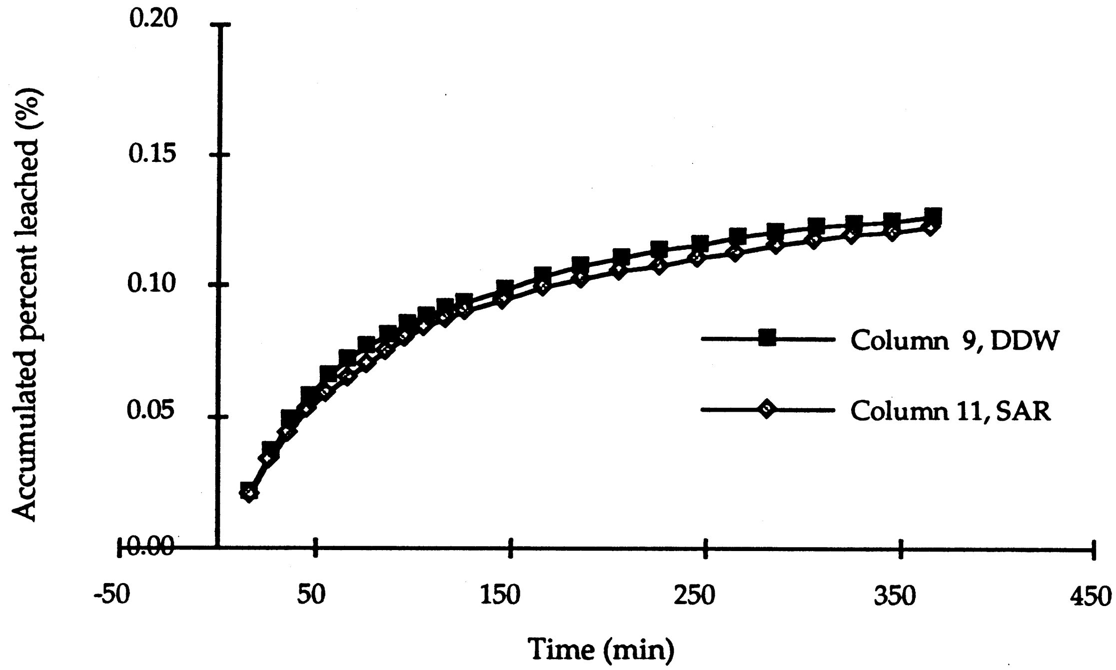

Figure 4.35 Accumulated percent leaching of arsenic using DDW and SAR as leaching fluids

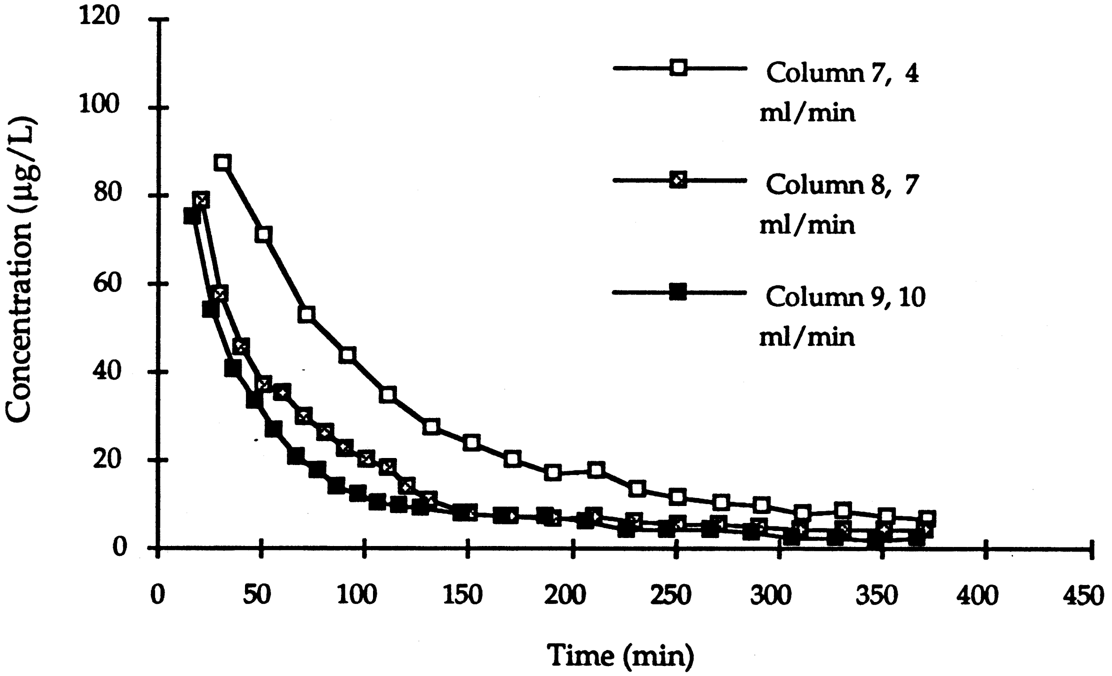

Figure 4.36 Leaching of arsenic using DDW at different flow rate

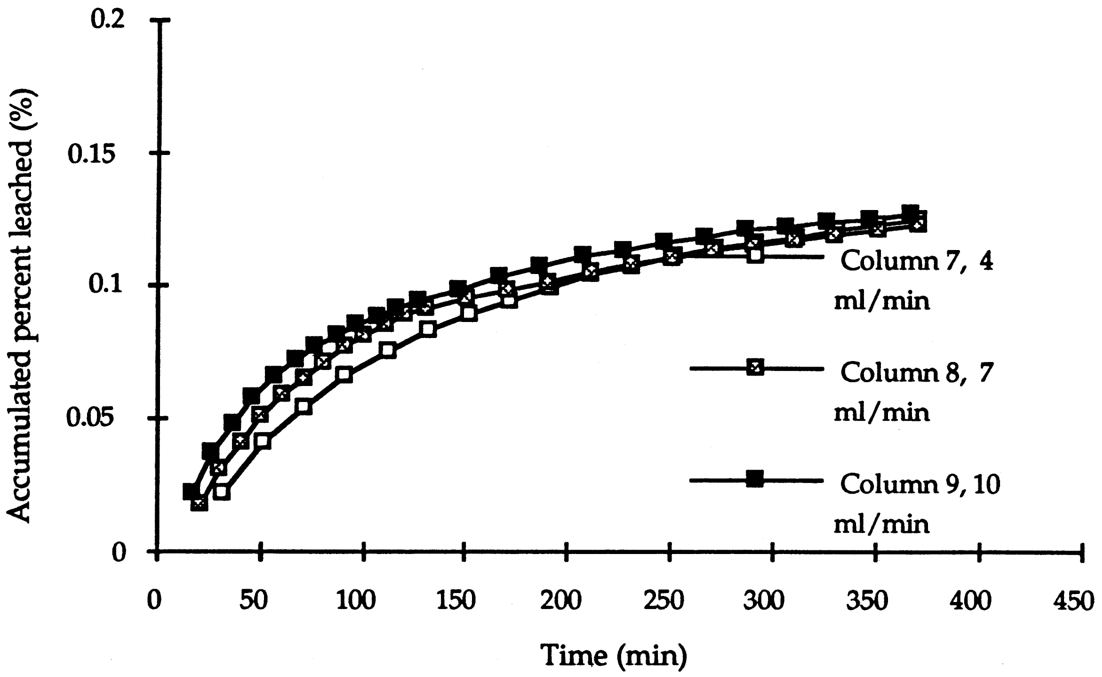

Figure 4.37 Accumulated percent leaching of arsenic using DDW at different flow rate

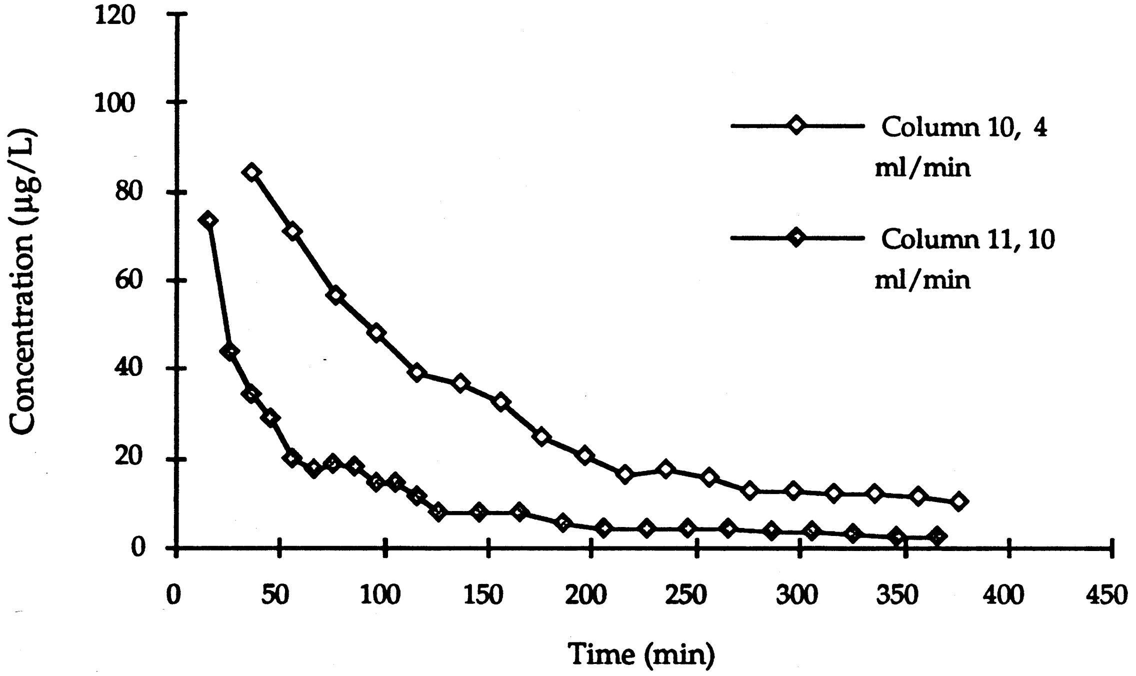

Figure 4.38 Leaching of arsenic using SAR at different flow rate.

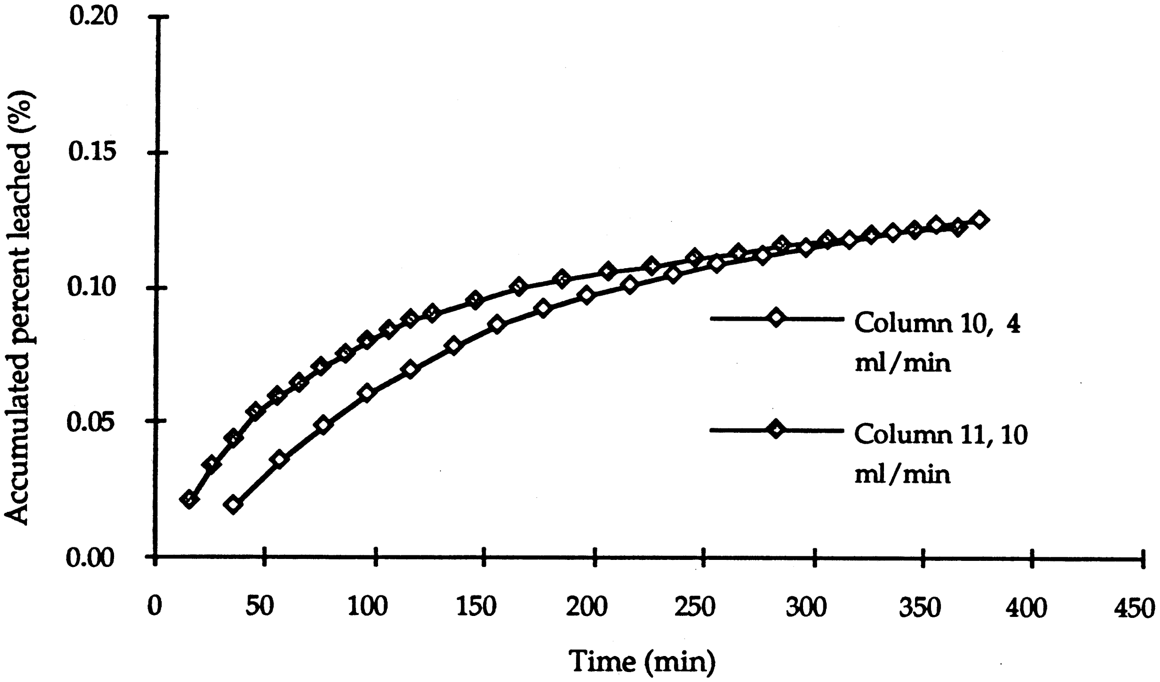

Figure 4.39 Accumulated percent leaching of arsenic using SAR at different flow rate

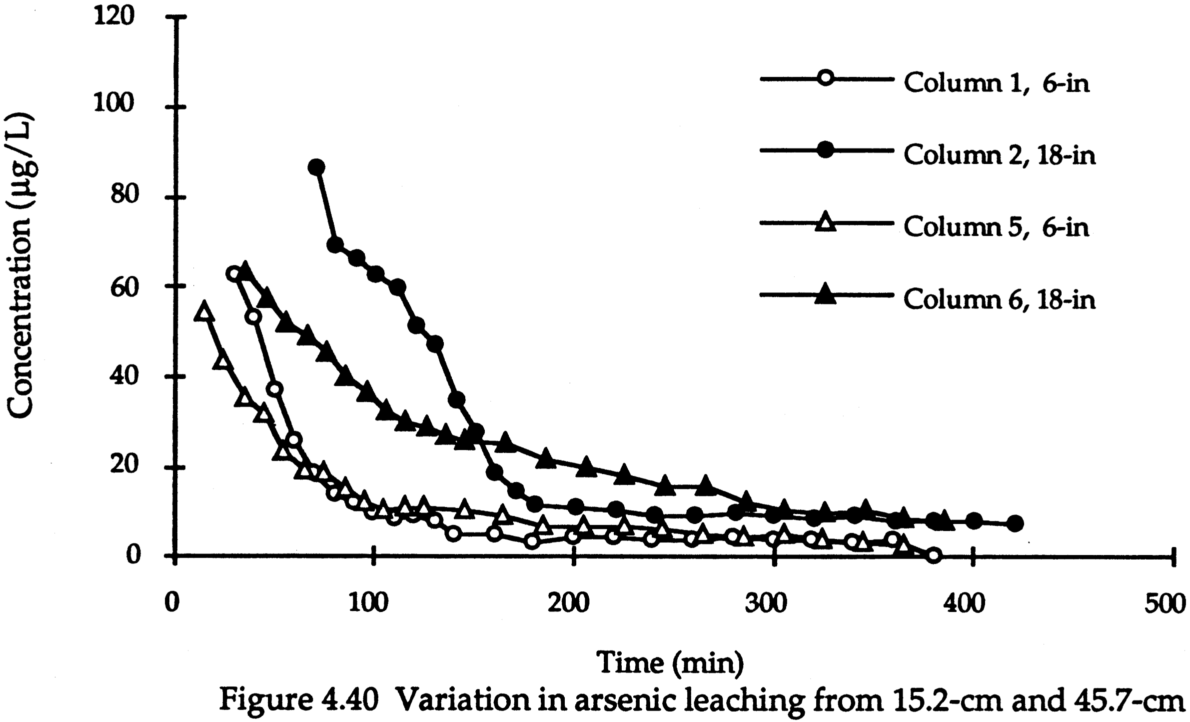

Figure 4.40 Variation in arsenic leaching from 15.2-cm and 45.7-cm columns subjected to DDW

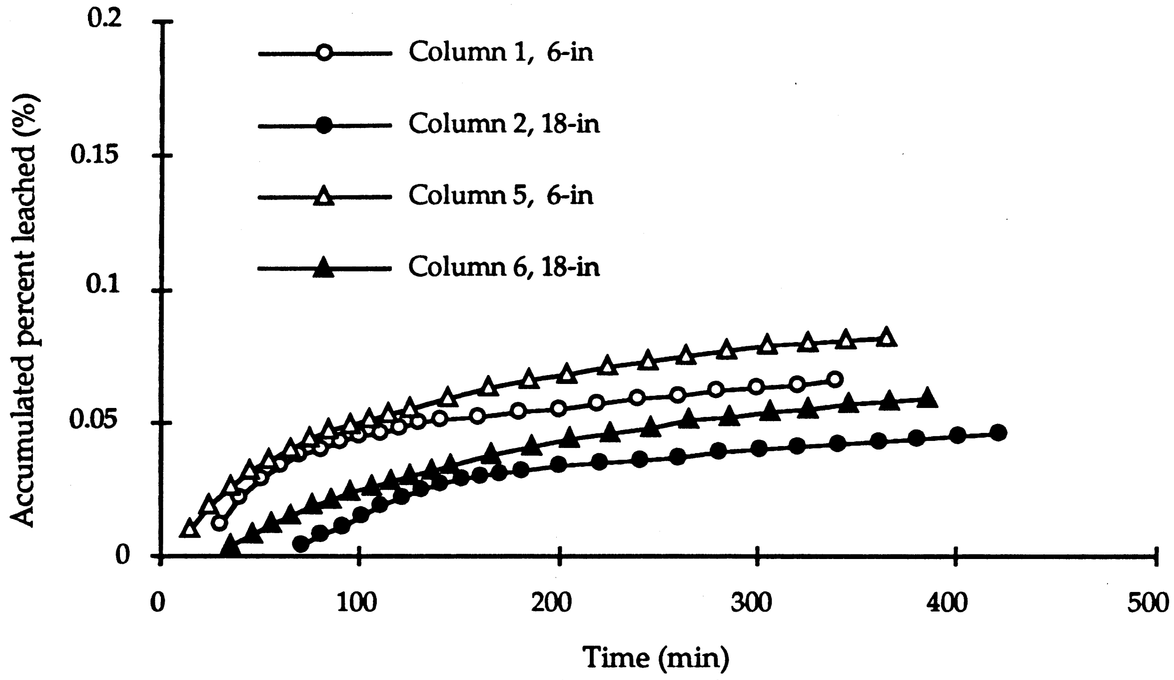

Figure 4.41 Accumulated percent of arsenic leached from 15.2-cm and 45.7-cm columns subjected to DDW

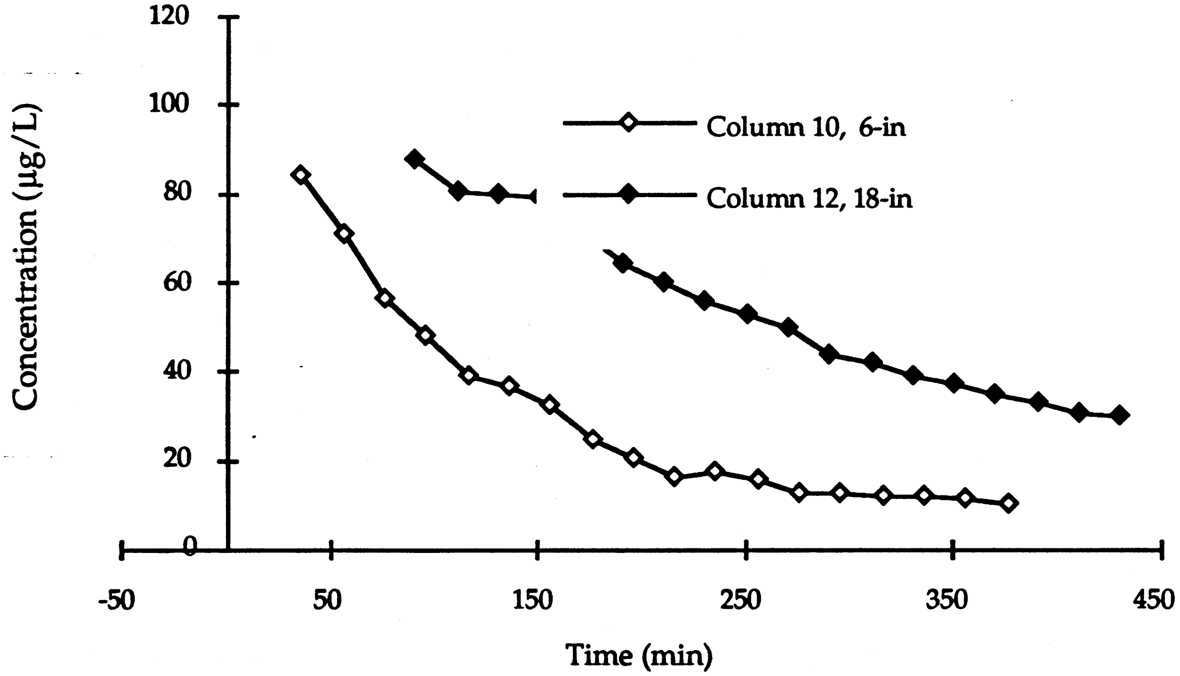

Figure 4.42 Variation in arsenic leaching from 15.2-cm and 45.7-cm columns subjected to SAR

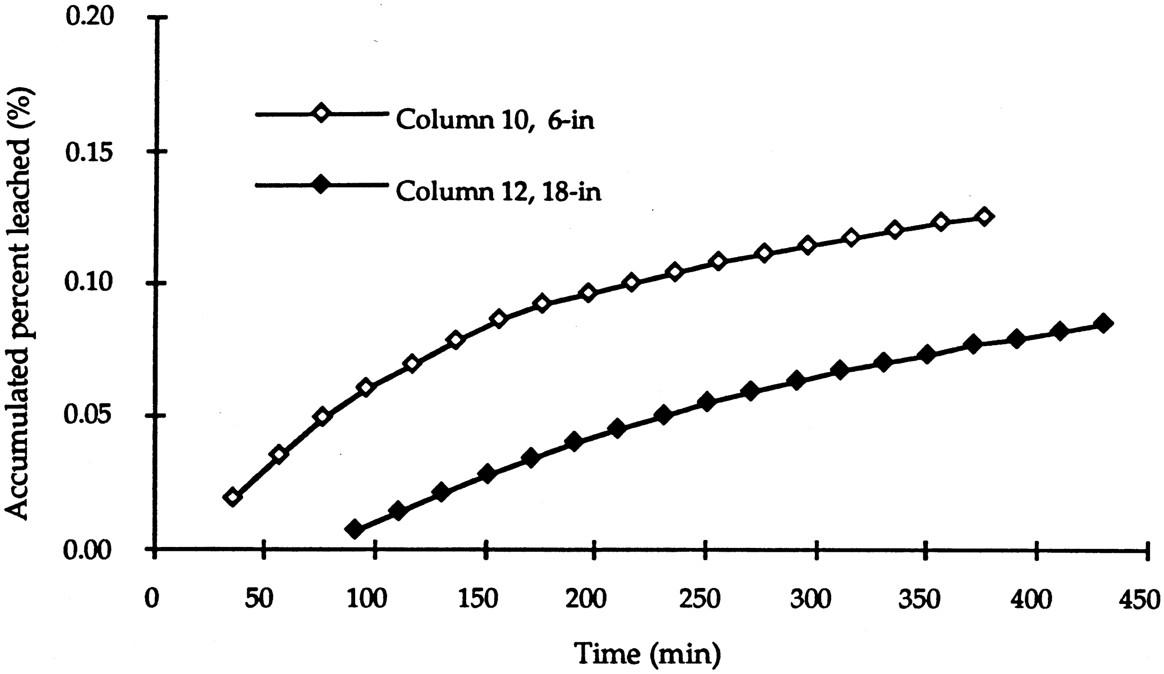

Figure 4.43 Accumulated percent of arsenic leached from 15.2-cm and 45.7-cm columns subjected to SAR

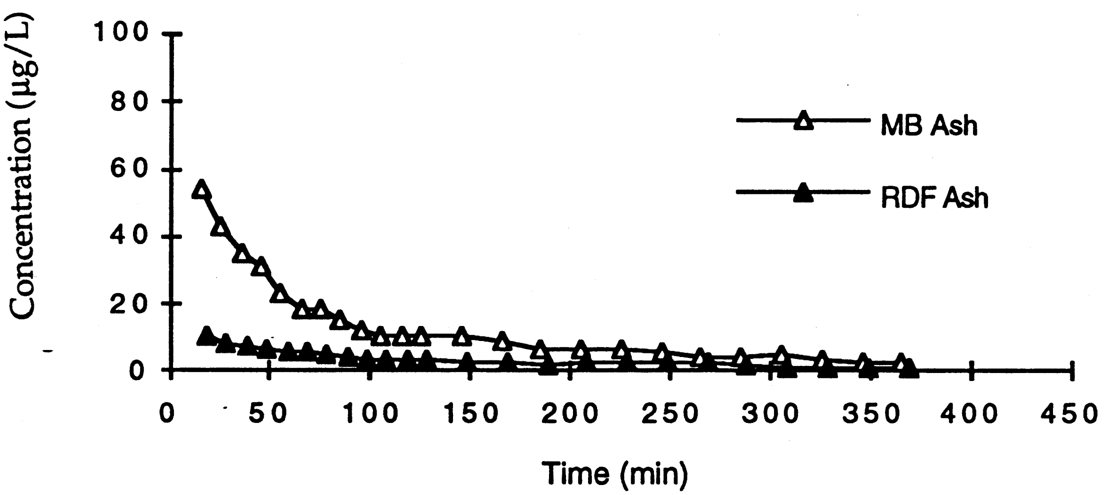

Figure 4.44 Variation in arsenic leaching from 6-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

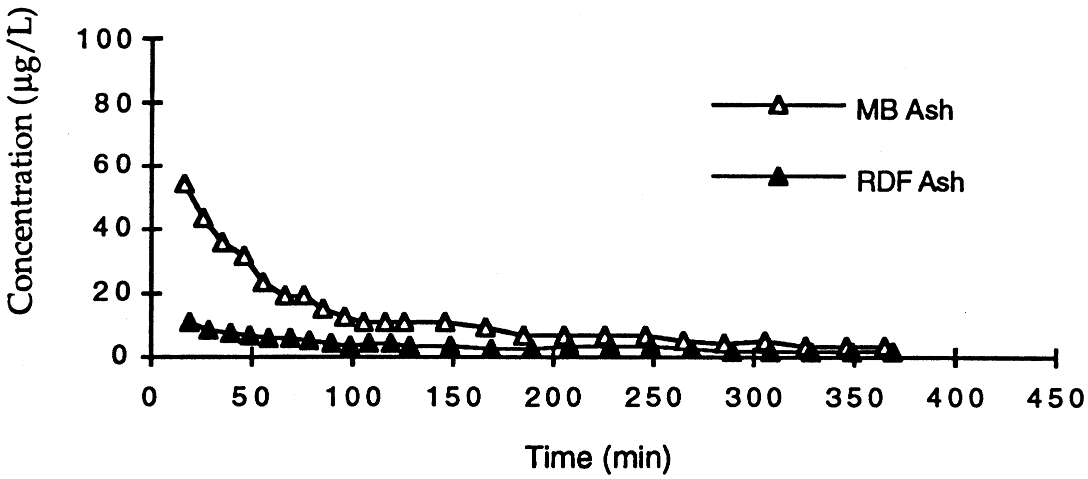

Figure 4.45 Variation in arsenic leaching from 18-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

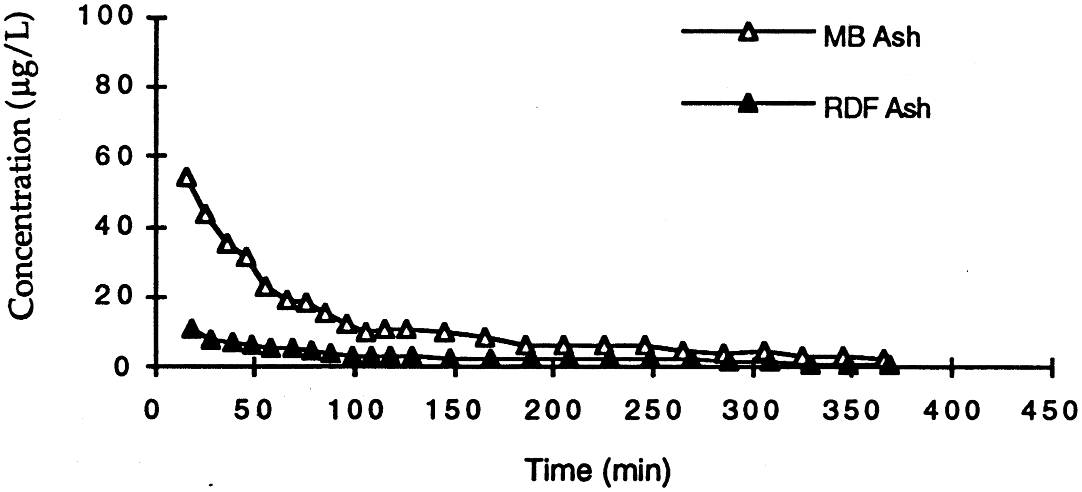

Figure 4.46 Variation in arsenic leaching from 18-in columns subjected to SAR using Pinellas County MB ash and Palm Beach County RDF ash

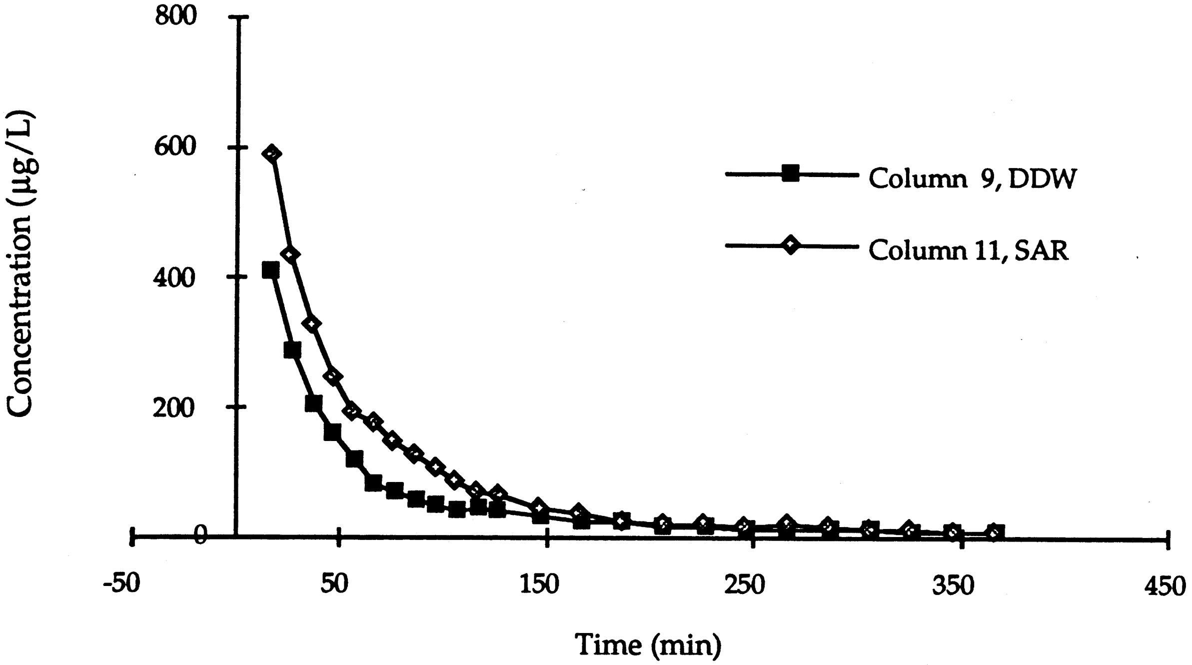

Figure 4.47 Leaching of chromium using DDW and SAR as leaching fluids

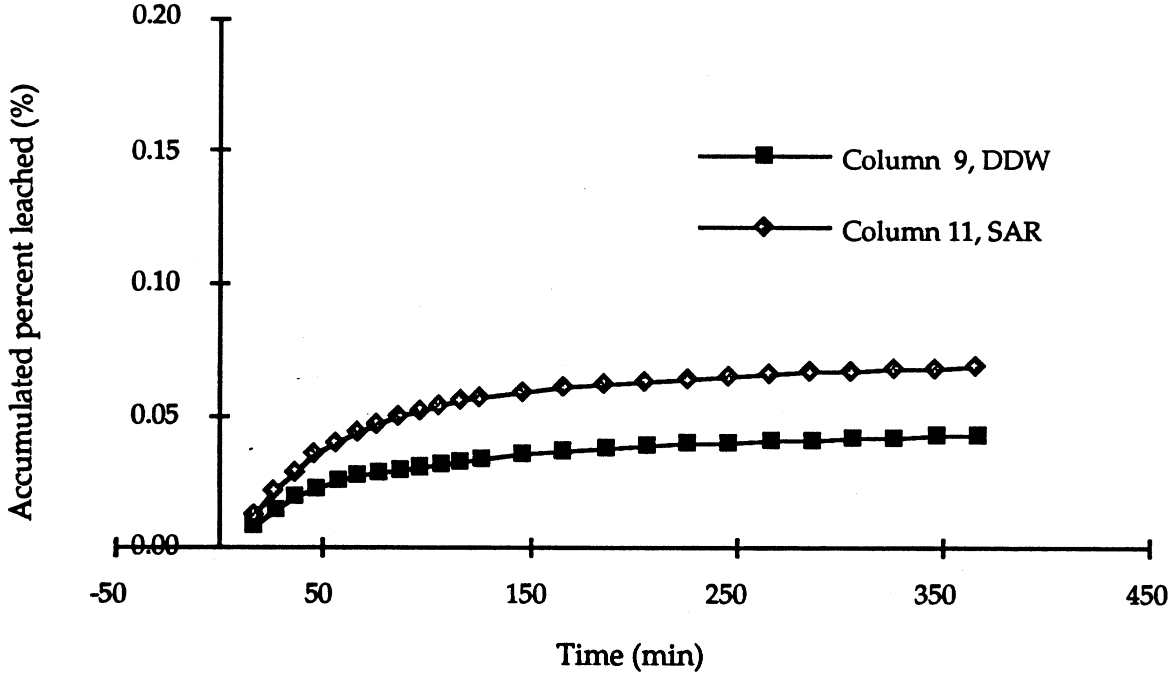

Figure 4.48 Accumulated percent leaching of chromium using DDW and SAR as leaching fluids

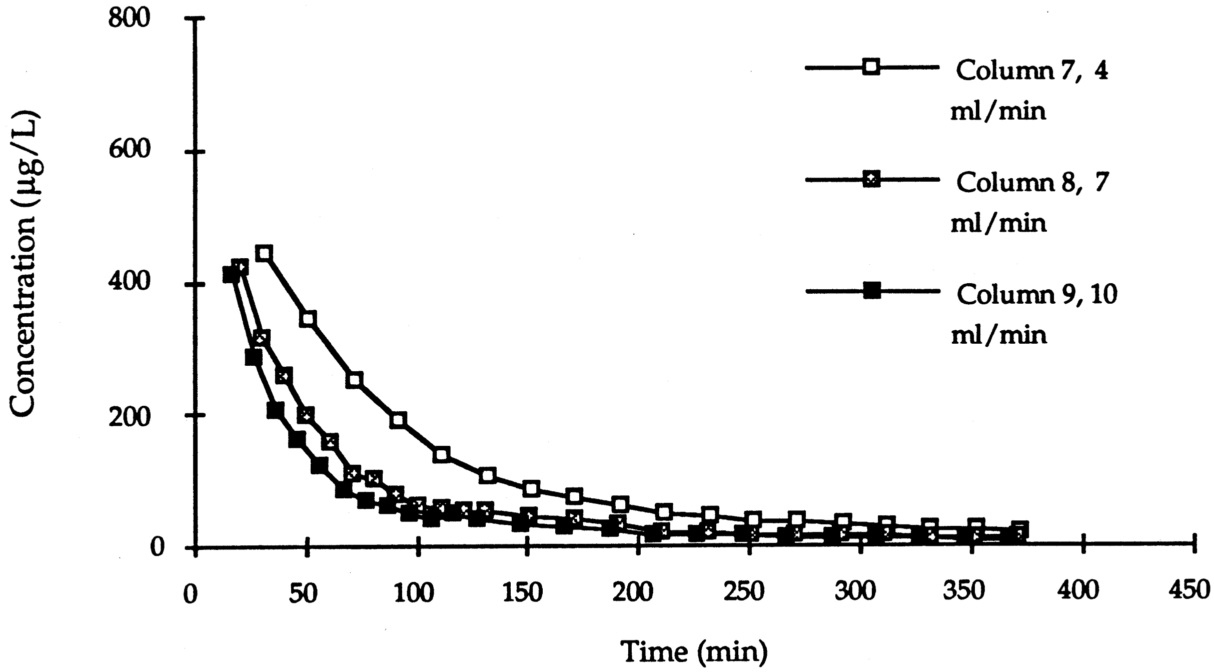

Figure 4.49 Leaching of chromium using DDW at different flow rate

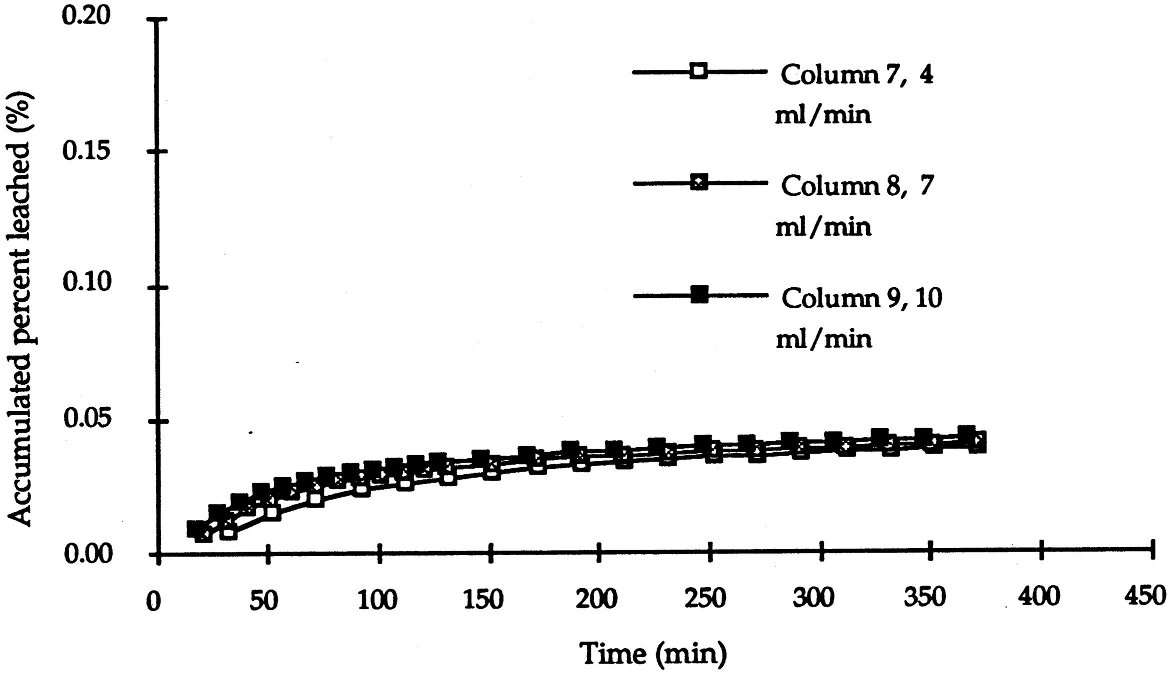

Figure 4.50 Accumulated percent leaching of chromium using DDW at different flow rate

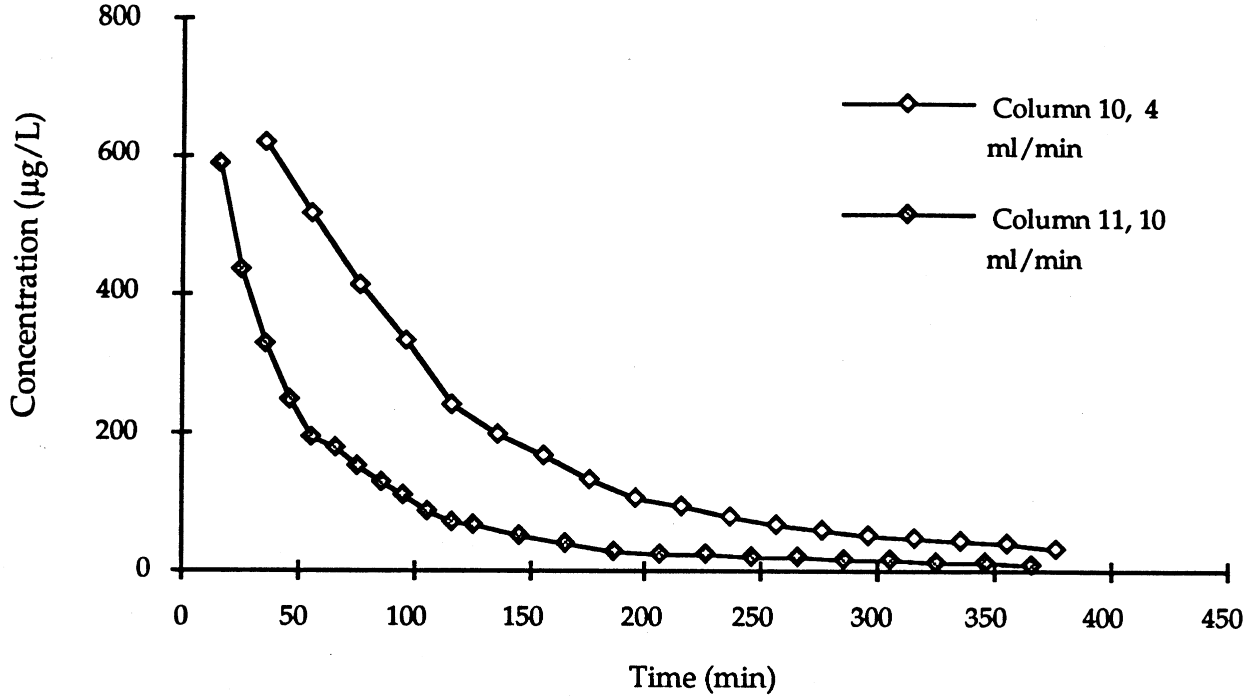

Figure 4.51 Leaching of chromium using SAR at different flow rate

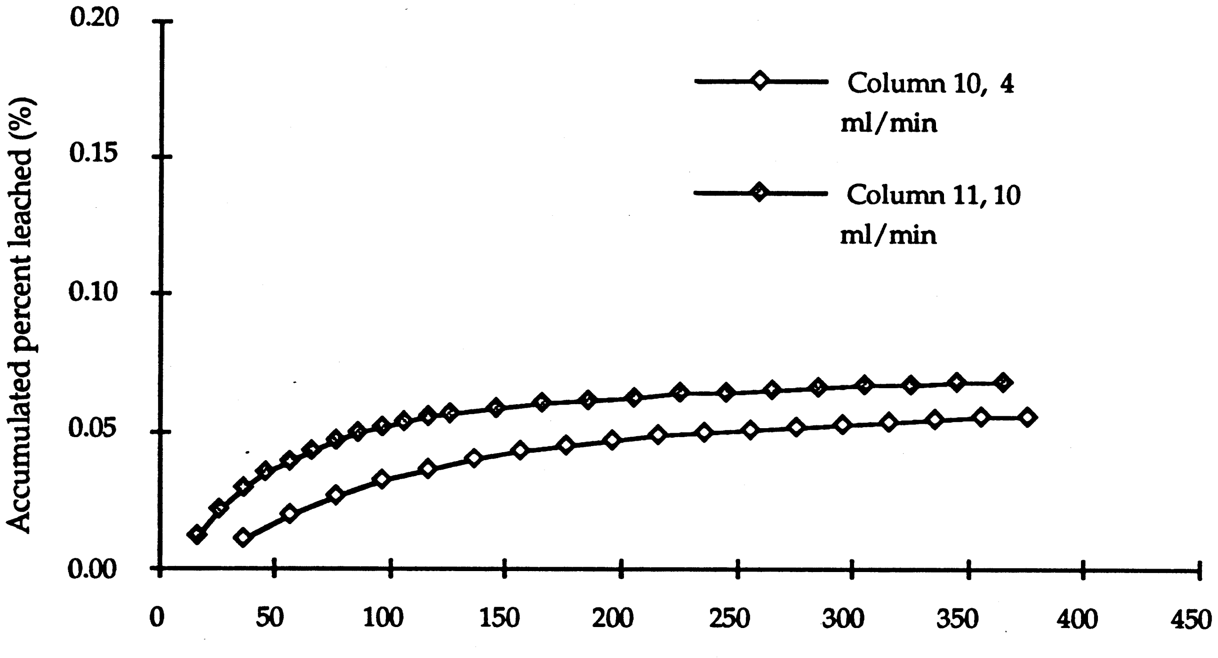

Figure 4.52 Accumulated percent leaching of chromium using SAR at different flow rate

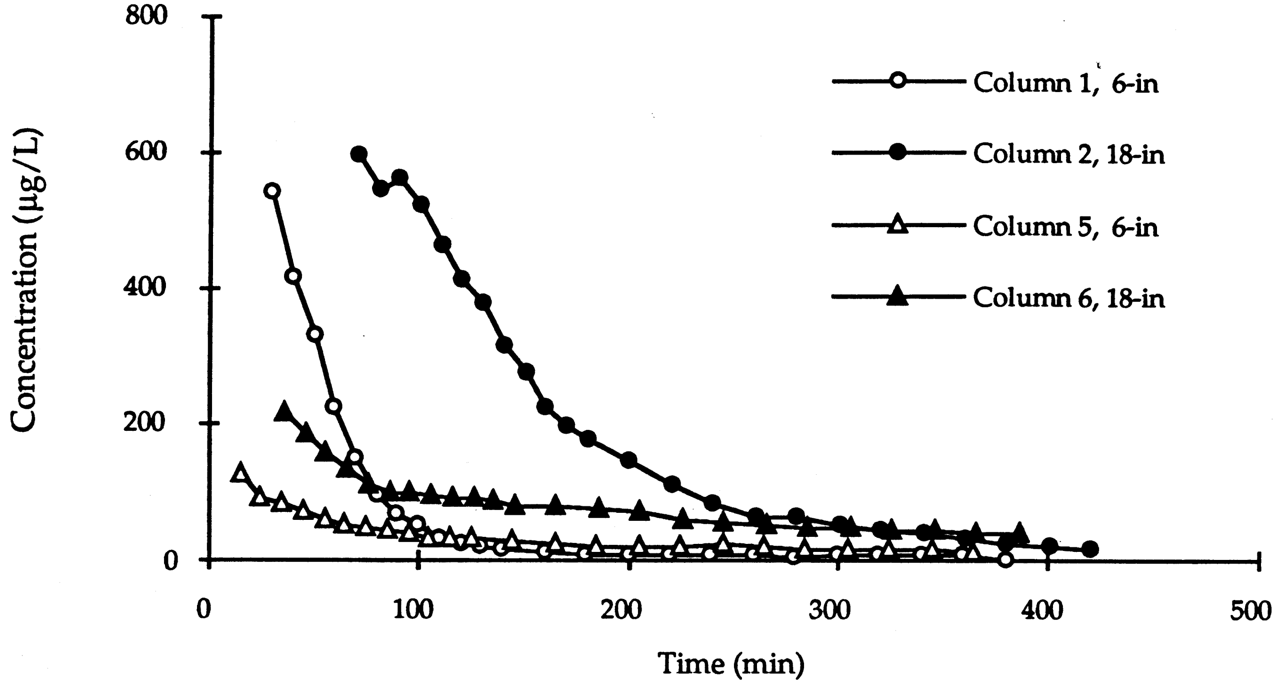

Figure 4.53 Variation in chromium leaching from 15.2-cm and 45.7-cm columns subjected to DDW

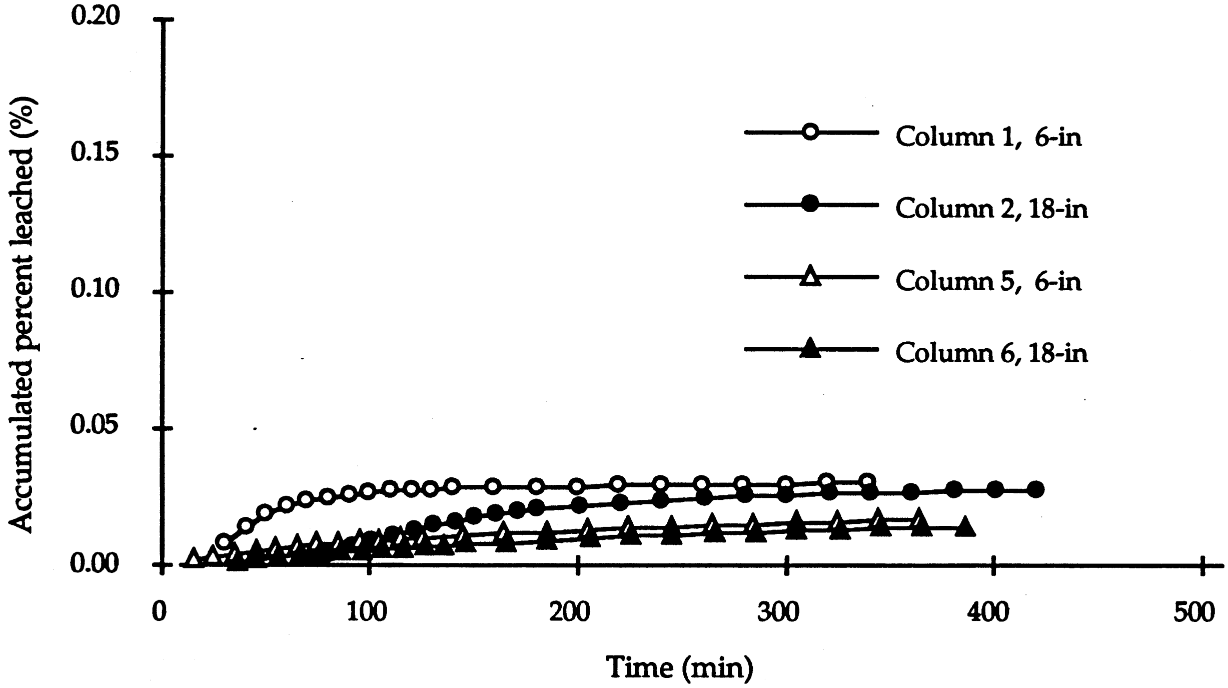

Figure 4.54 Accumulated percent of chromium leached from 15.2-cm and 45.7-cm columns subjected to DDW

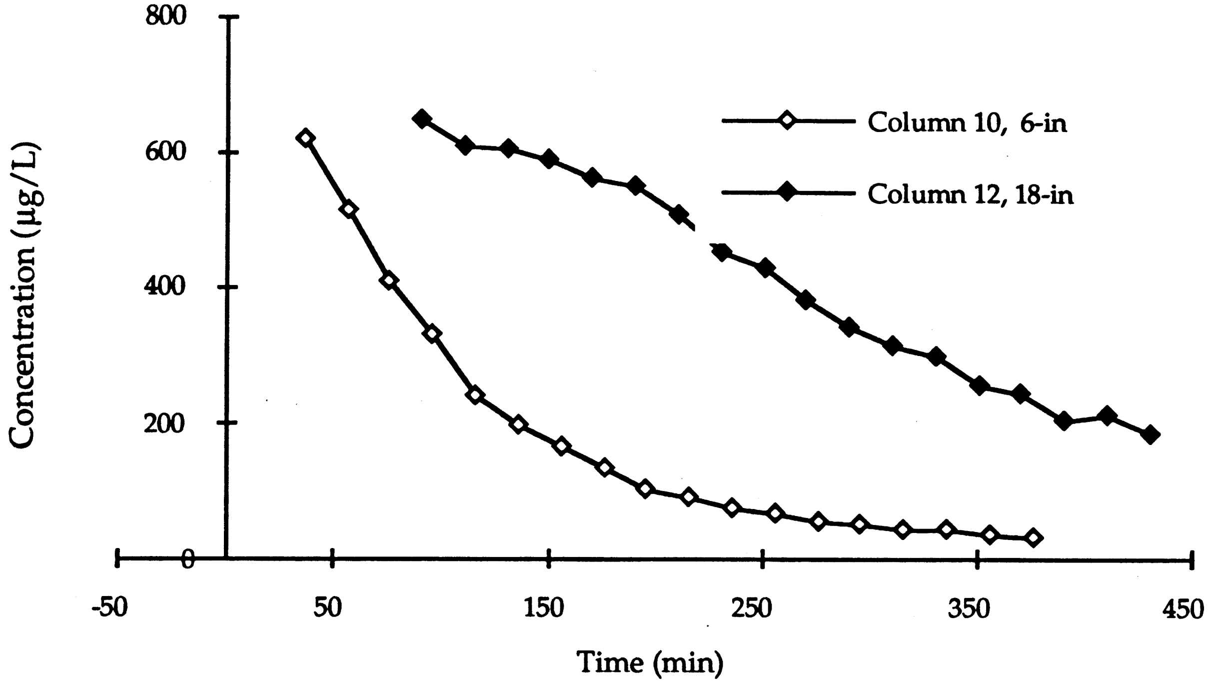

Figure 4.55 Variation in chromium leaching from 15.2-cm and 45.7-cm columns subjected to SAR

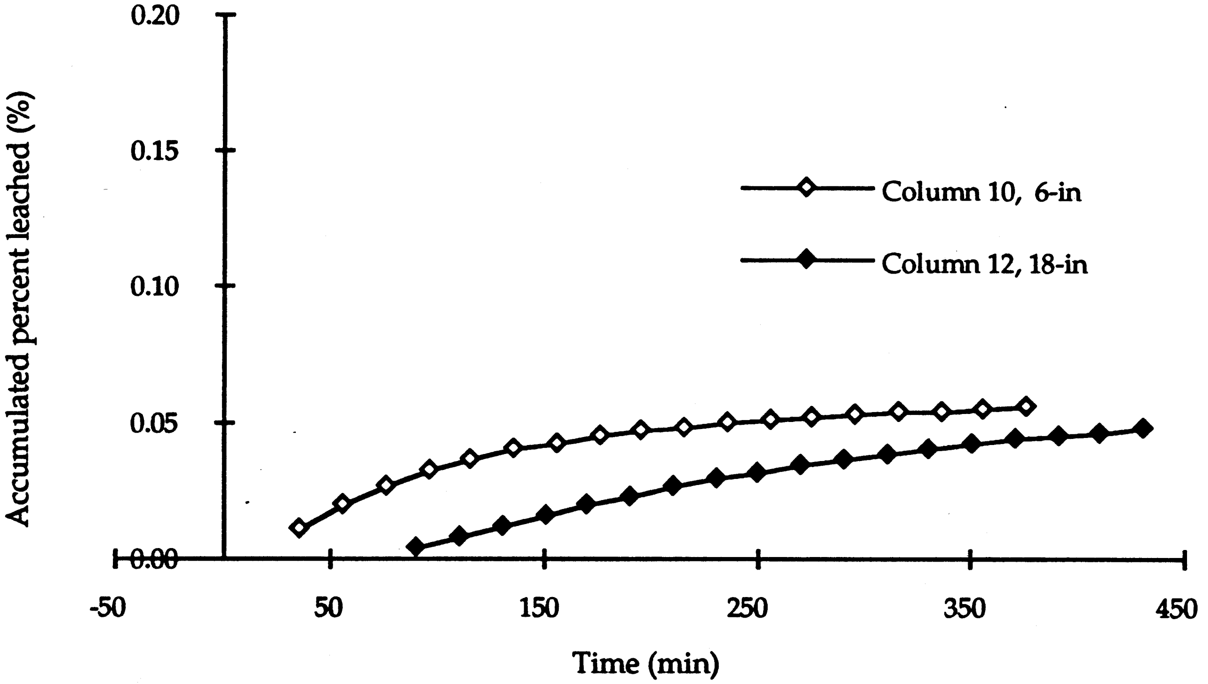

Figure 4.56 Accumulated percent of chromium leached from 15.2-cm and 45.7-cm columns subjected to SAR

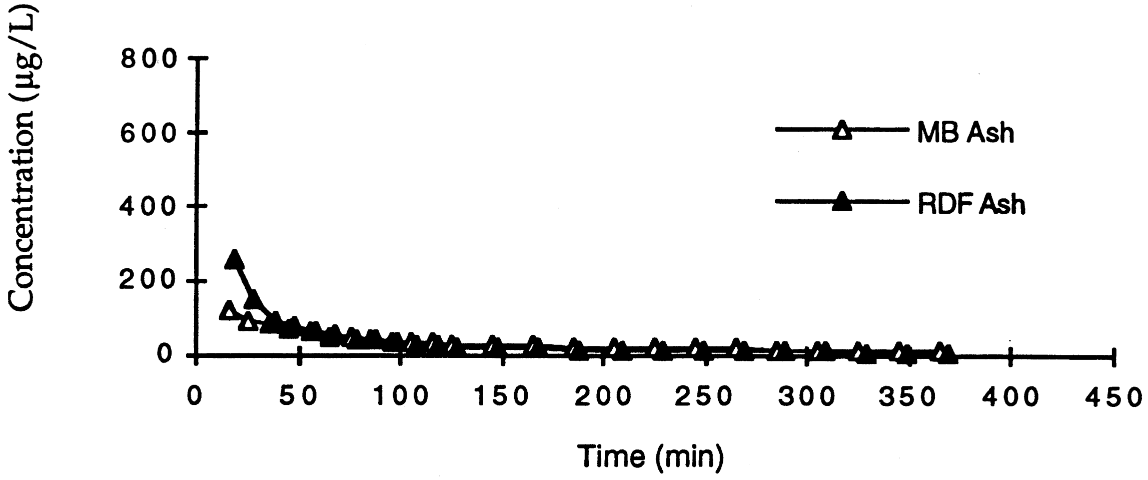

Figure 4.57 Variation in chromium leaching from 6-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

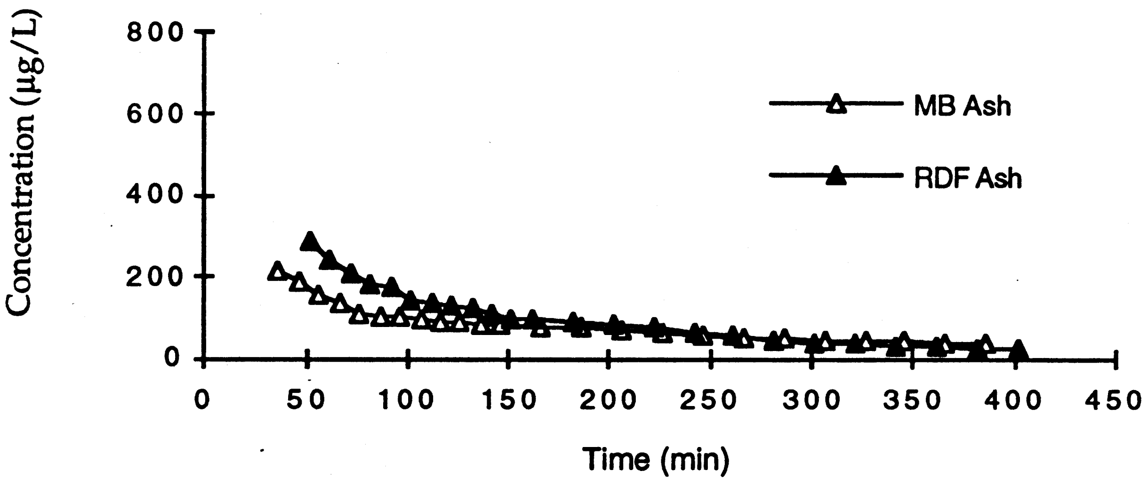

Figure 4.58 Variation in chromium leaching from 18-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

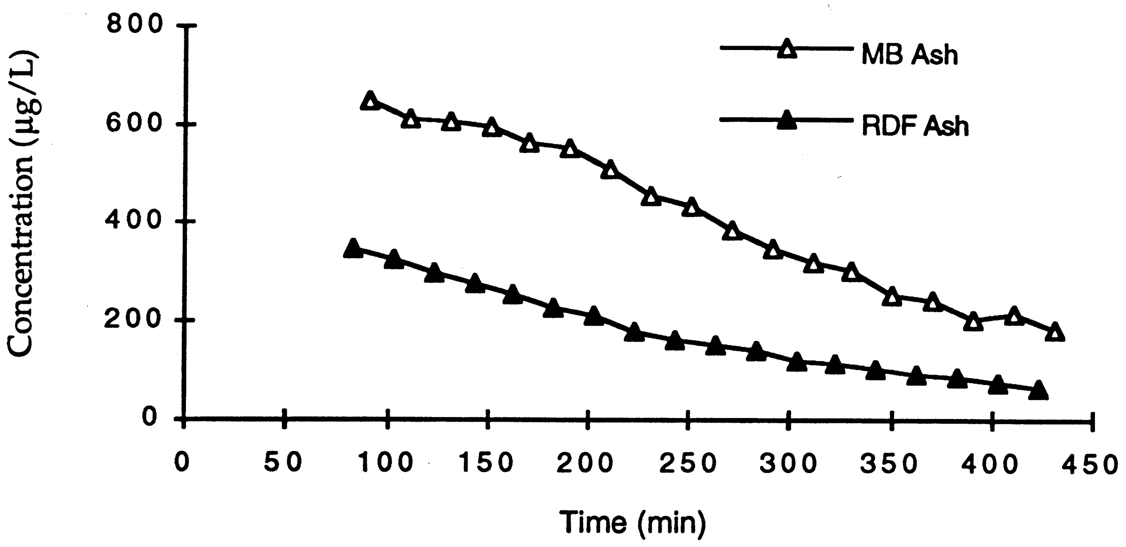

Figure 4.59 Variation in chromium leaching from 18-in columns subjected to SAR using Pinellas County MB ash and Palm Beach County RDF ash

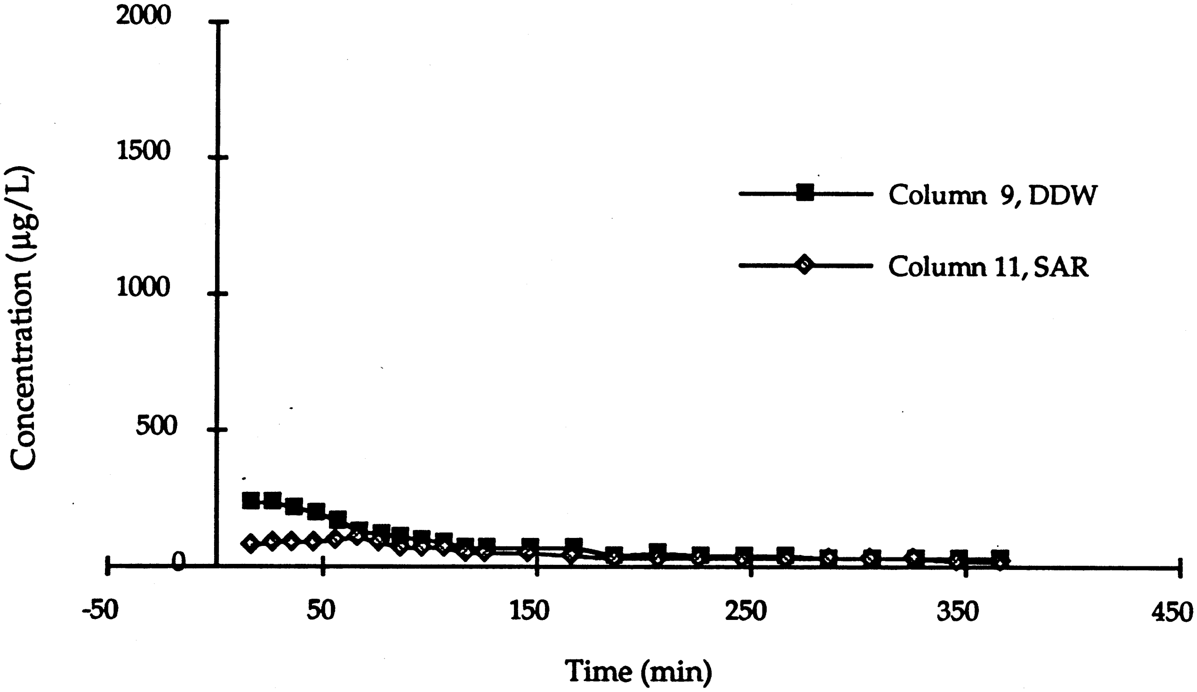

Figure 4.60 Leaching of lead using DDW and SAR as leaching fluids

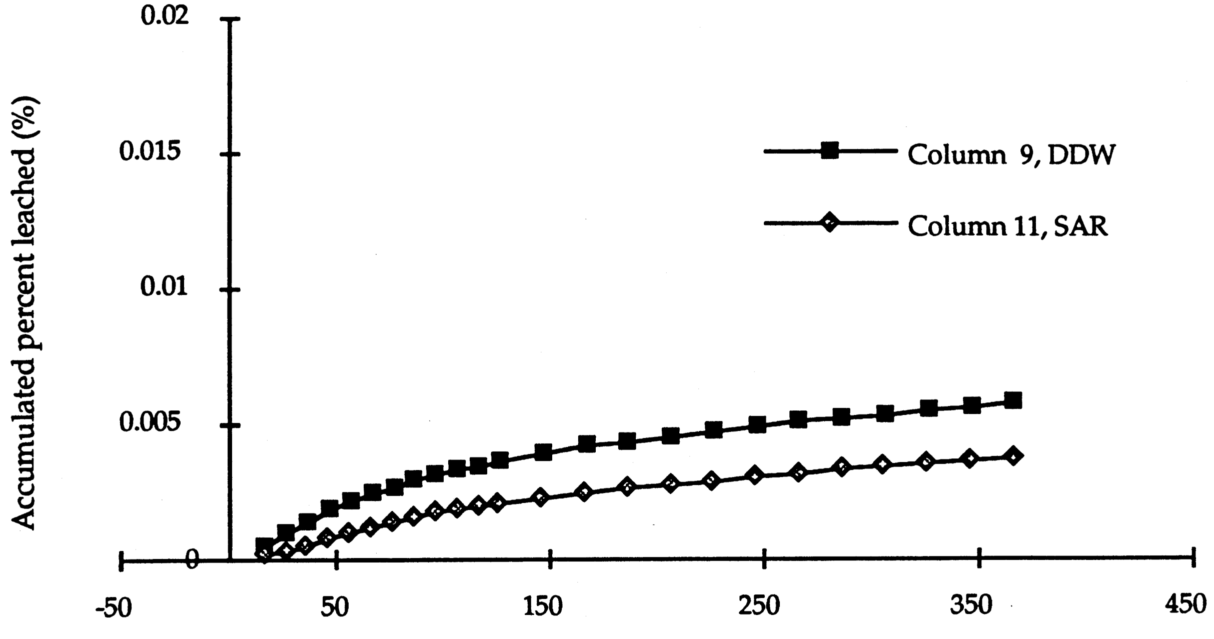

Figure 4.61 Accumulated percent leaching of lead using DDW and SAR as leaching fluids

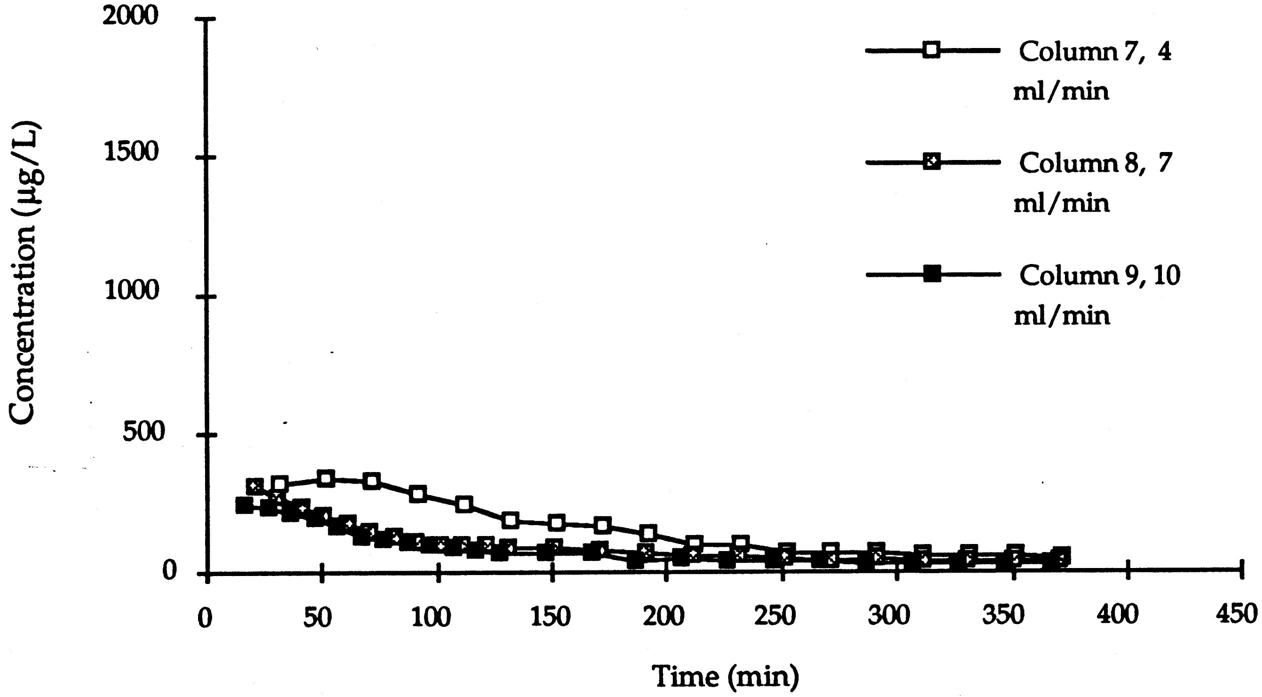

Figure 4.62 Leaching of lead using DDW at different flow rate

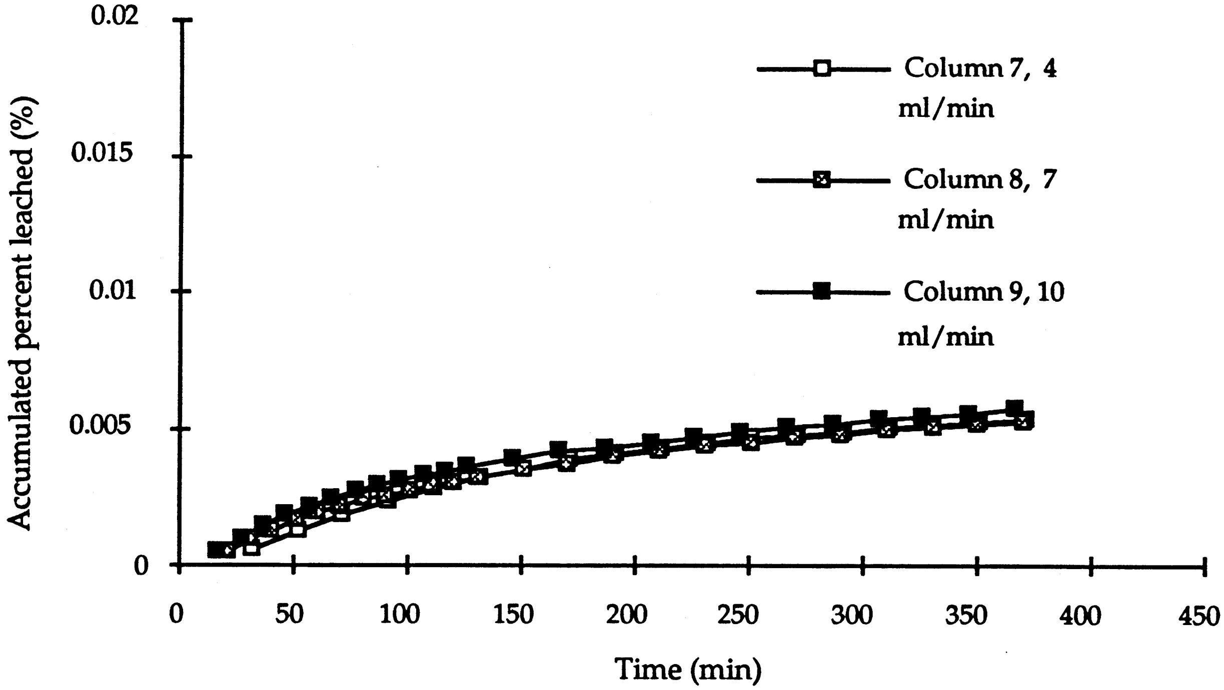

Figure 4.63 Accumulated percent leaching of lead using DDW at different flow rate

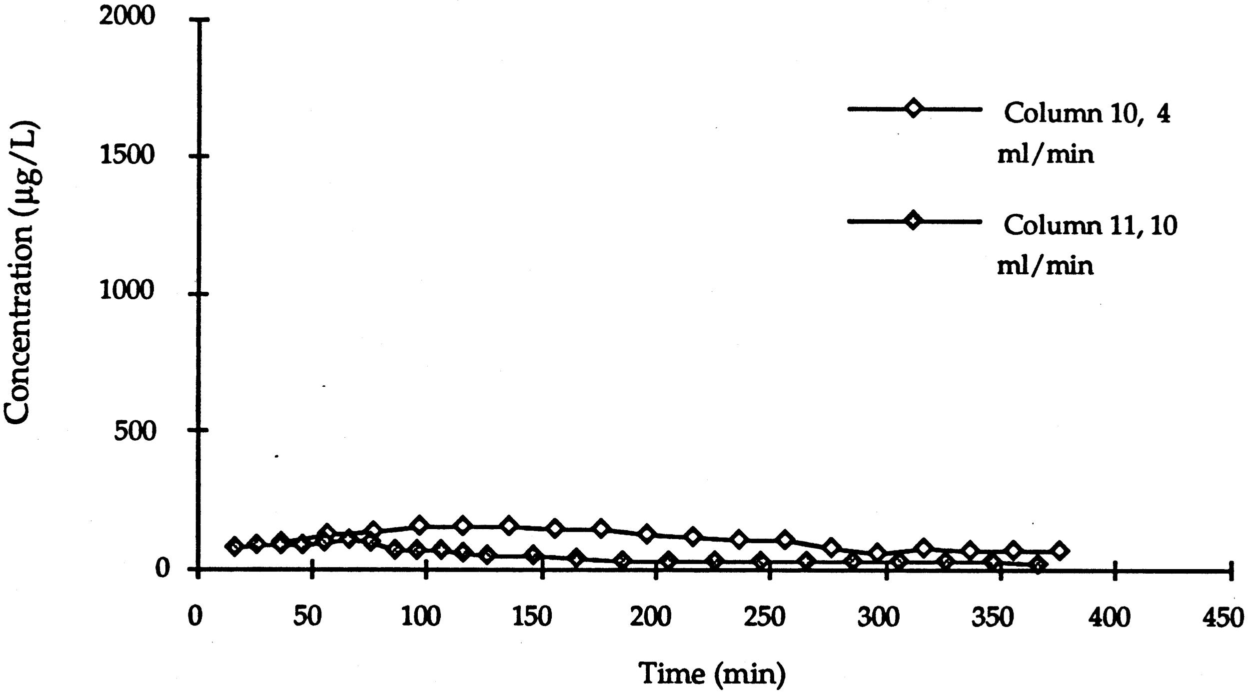

Figure 4.64 Leaching of lead using SAR at different flow rate

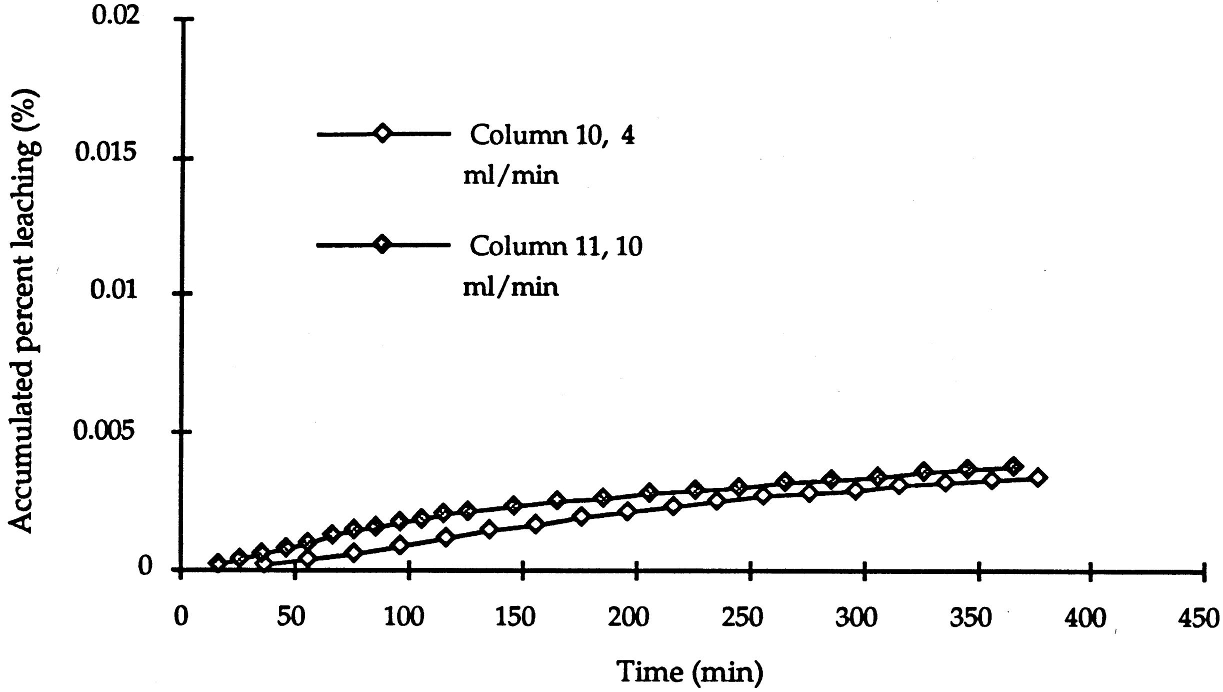

Figure 4.65 Accumulated percent leaching of lead using SAR at different flow rate

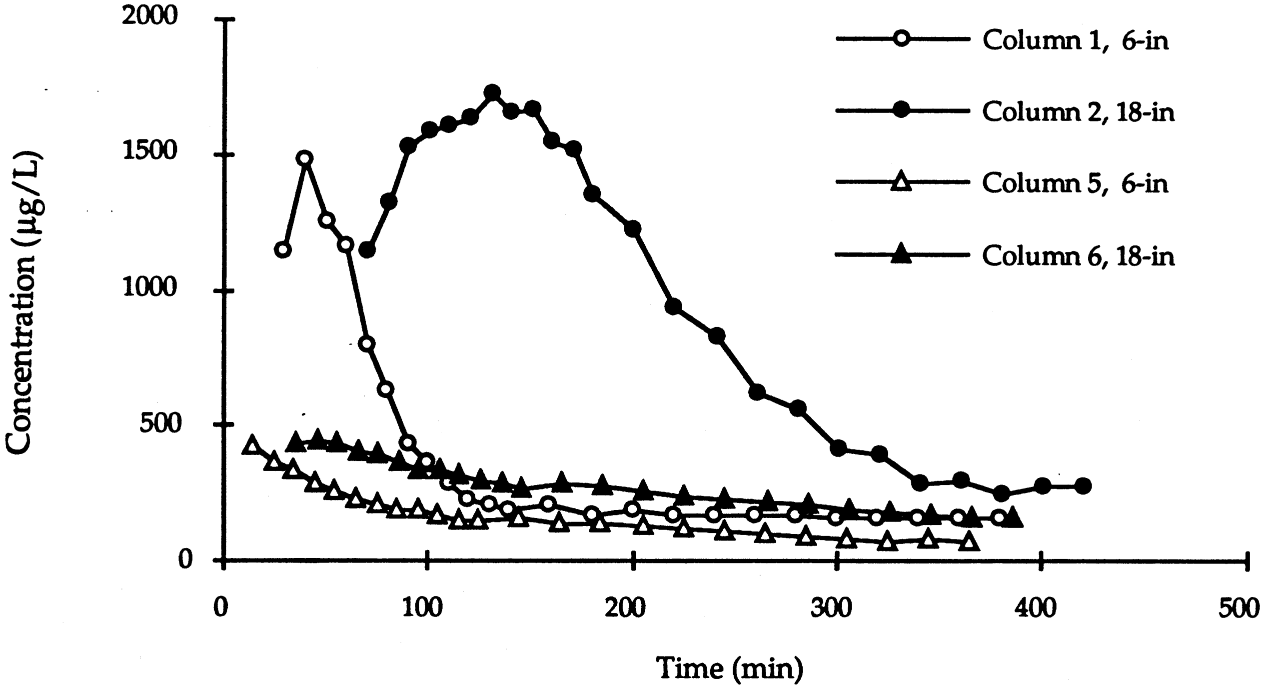

Figure 4.66 Variation in lead leaching from 15.2-cm and 45.7-cm columns subjected to DDW

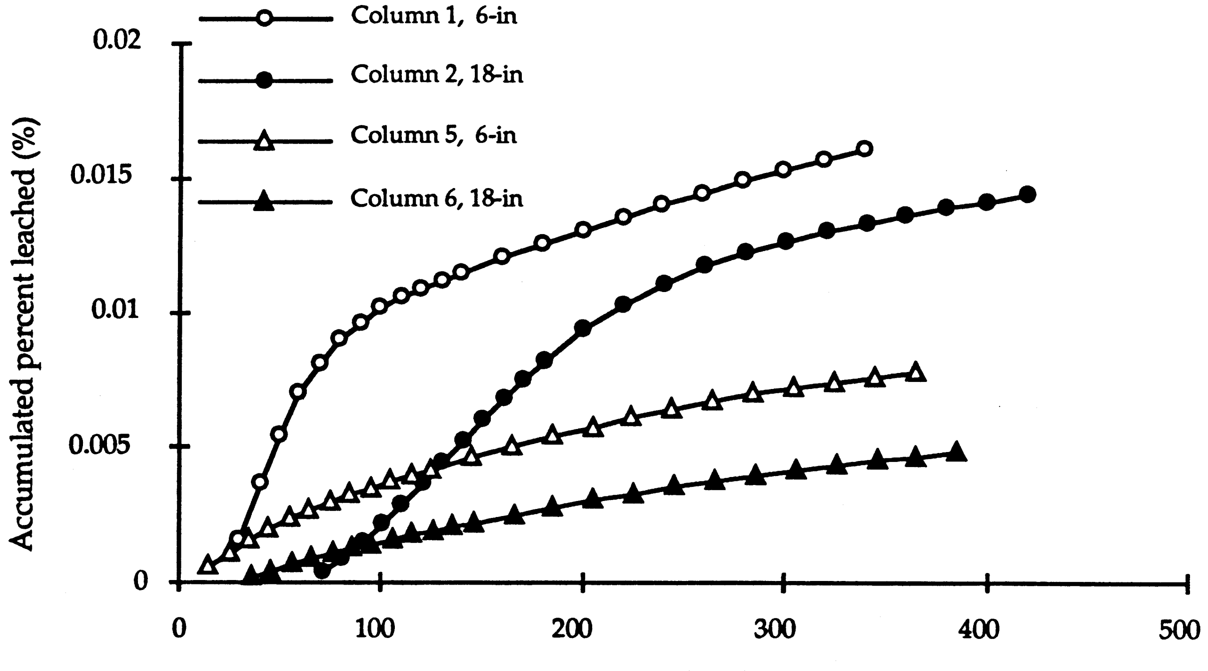

Figure 4.67 Accumulated percent of lead leached from 15.2-cm and 45.7-cm columns subjected to DDW

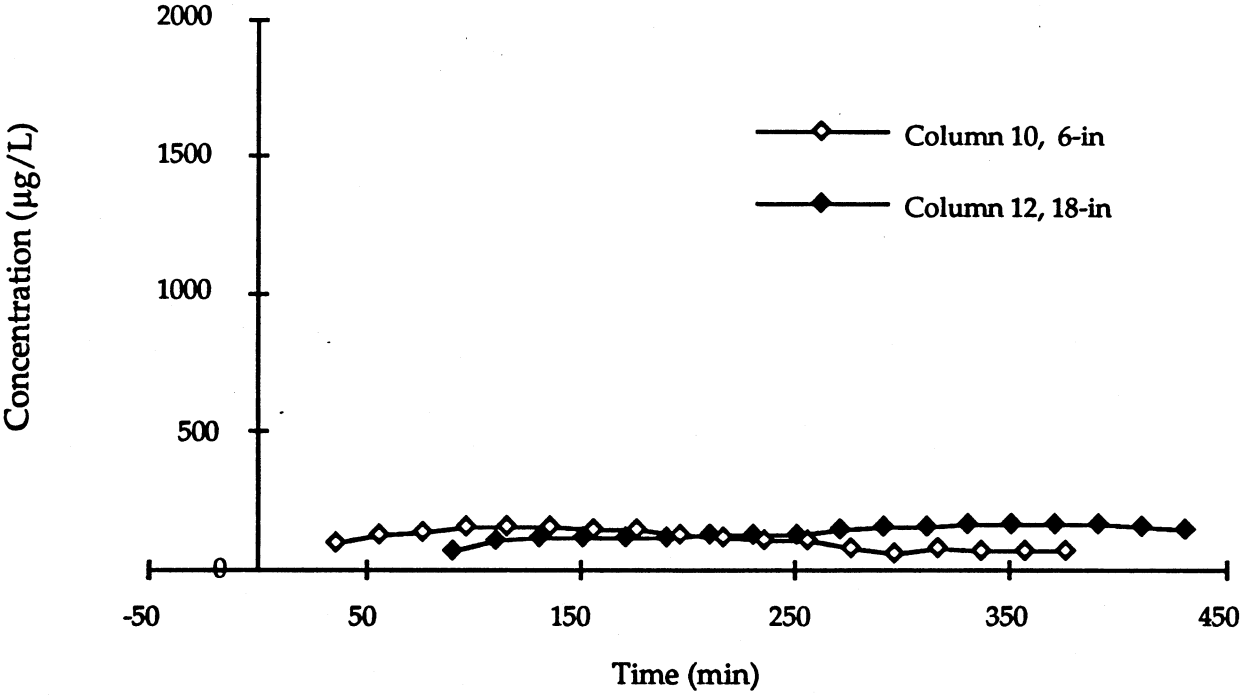

Figure 4.68 Variation in lead leaching from 15.2-cm and 45.7-cm columns subjected to SAR

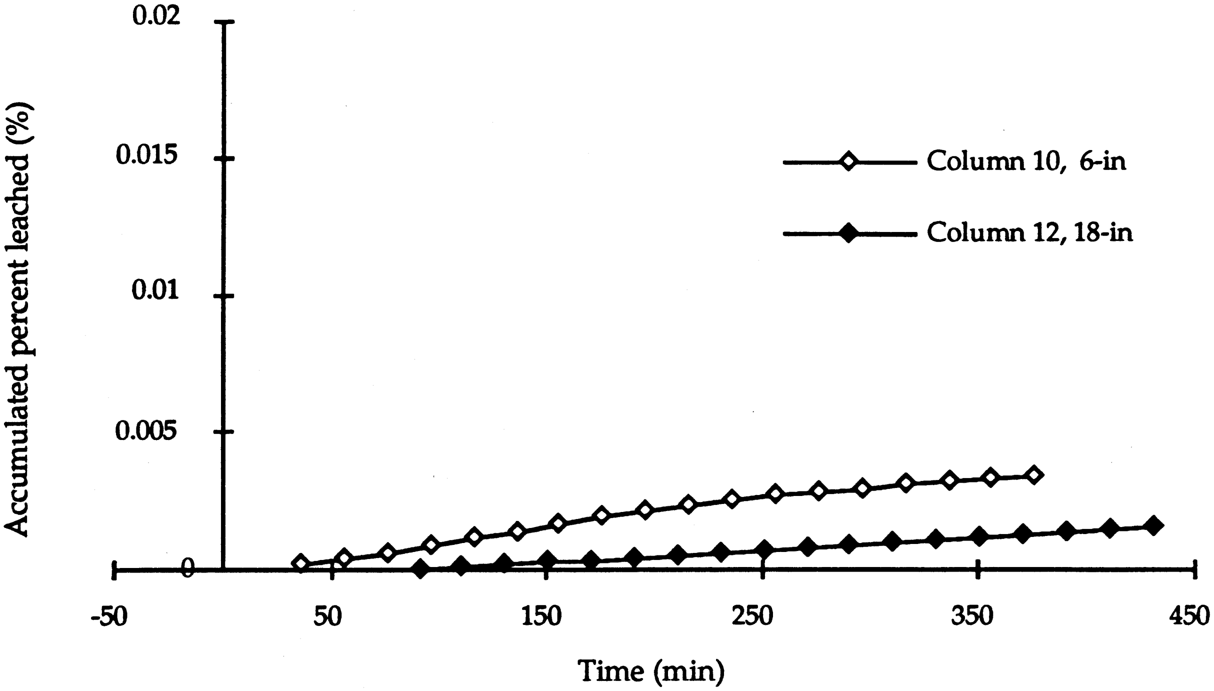

Figure 4.69 Accumulated percent of lead leached from 15.2-cm and 45.7-cm columns subjected to SAR

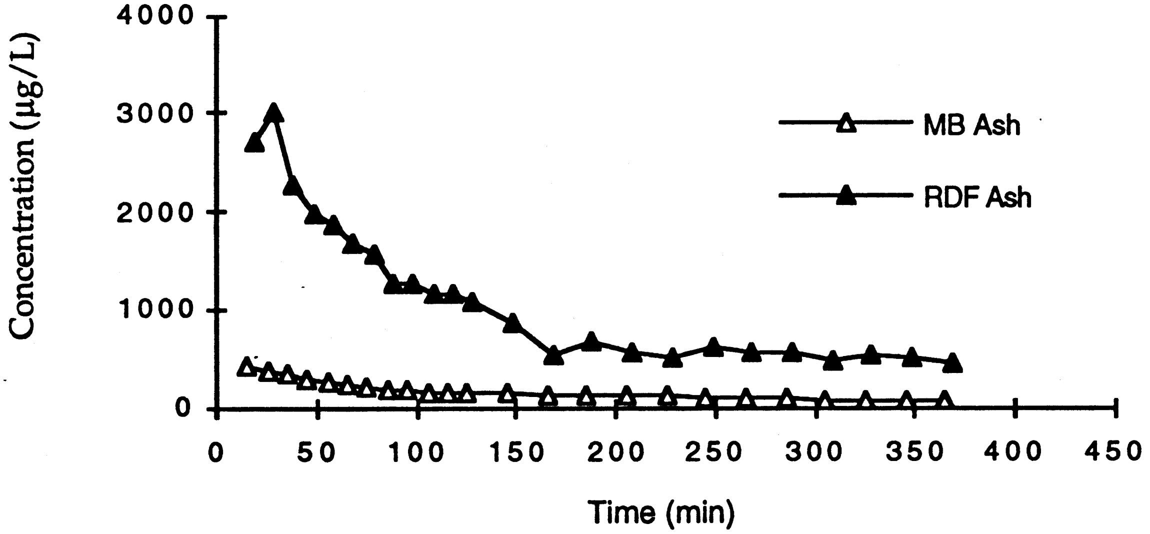

Figure 4.70 Variation in lead leaching from 6-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

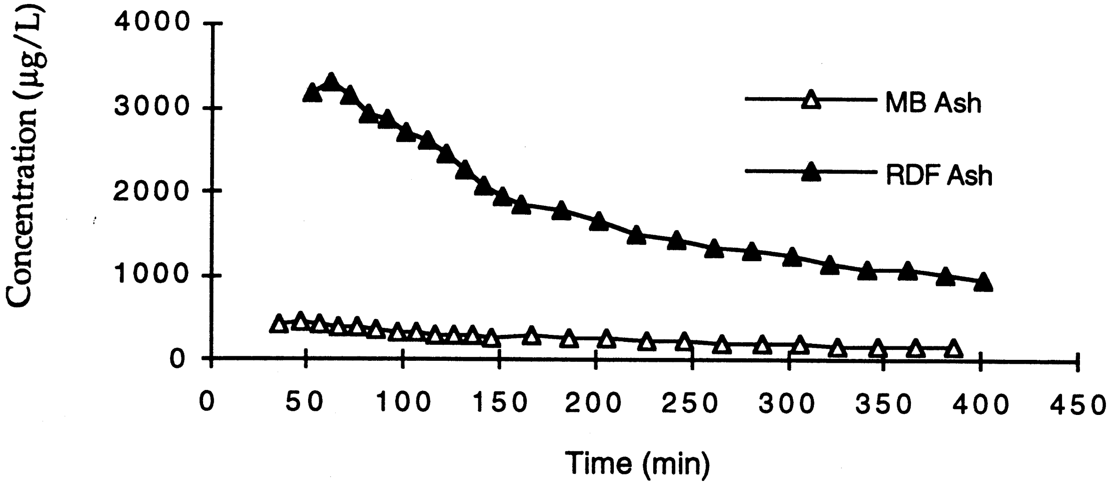

Figure 4.71 Variation in lead leaching from 18-in columns subjected to DDW using Pinellas County MB ash and Palm Beach County RDF ash

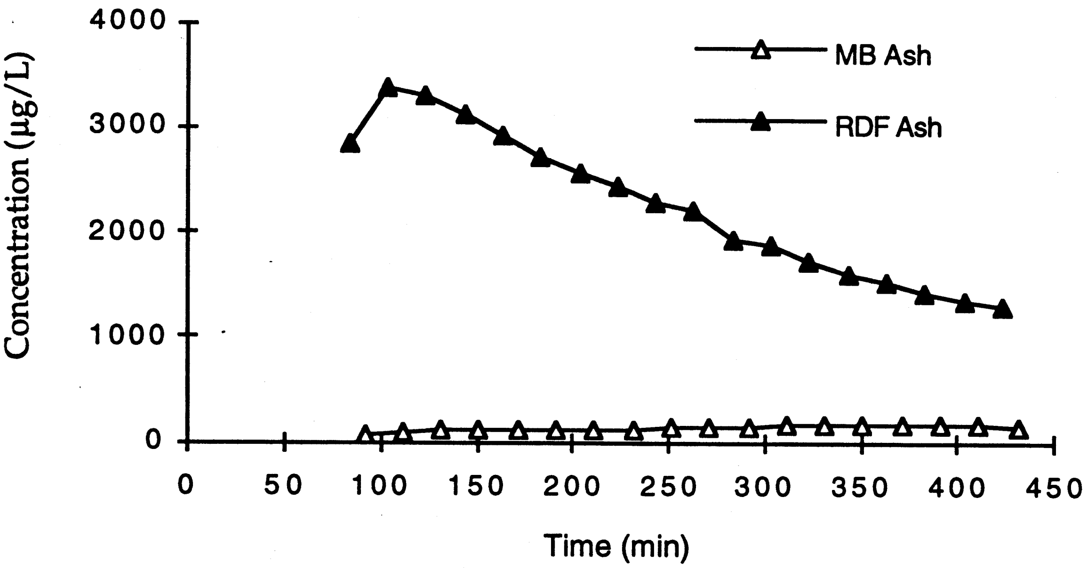

Figure 4.72. Variation in lead leaching from 18-in columns subjected to SAR using Pinellas County MB ash and Palm Beach County RDF ash

5.0 CONCLUSIONS

The results of this study show that MWC bottom ash has the physical and geotechnical properties necessary for application as a highway fill material and meets existing environmental acceptability regulations. As a result of various changes in ash management practice, a reliable cost estimate for the use of ash can not be developed at this time.

The following specific findings support this conclusion:

- Bottom ash meets the grain size classification criteria for use as a highway fill material. It is classified as A-1a with a group index of zero (predominately stone fragments and gravel size particles, with a well-graded binder of fine material) using the AASHTO classification. The grain size distribution of bottom ash samples showed little variability with time; suggesting that bottom ash can be obtained for use as a fill material at different times.

- MB bottom ash contained a higher percentage of metals than RDF bottom ash. The lower percentage of metals in the RDF bottom ash can be attributed to the processing of the MSW prior to combustion. The specific gravity of the bottom ash was found to be a function of metal content. MB bottom ash exhibited higher specific gravity than RDF bottom ash. A decrease in grain size resulted in a decrease in specific gravity for both ash types.

- The moisture-density relationships in bottom ash behave very similarly to conventional soils. MB bottom ash samples exhibited higher maximum dry densities and lower optimum moisture contents as compared to RDF bottom ash samples. A decrease in bottom ash grain size resulted in a decrease in maximum dry density and an increase in optimum moisture content. Increasing the compaction energy increased the maximum dry density but also decreased the optimum moisture content. The high absorption of water by the ash affects the moisture-density relationship, especially on the wet side of the optimum moisture content.

- The coefficient of permeability of freshly compacted bottom ash was found to be a function of the initial molding water content—with the highest permeability on the dry side of the optimum moisture content. The coefficient of permeability decreased significantly on the wet side of the optimum moisture content.

- Compacted bottom ash has a negligible shrinkage and swell potential when saturated. The ash swelled when allowed to air dry.

- The unconfined compressive strength of the compacted bottom ash behaves similarly to compacted soils in that the unconfined compressive strength is higher either dry or near optimum moisture content and increases with compaction energy. Thus, compaction moisture content and compaction energy are controlling factors for unconfined compressive strength. Allowing compacted bottom ash to age increases the compressive strength.

- The stress-strain curves of both ash types in loose and dense conditions behave similar to sand. Both ashes develop some cohesion which is attributed to pozzolanic cementing reactions occurring in the bottom ash. The angle of internal friction increases with the density of the compacted bottom ash.

- The elastic moduli for both ash types increase as the dry unit weight and confining pressures increase. The RDF bottom ash was found to be twice as stiff as the MB bottom ash. Both the MB and RDF bottom ashes exhibit elastic moduli within the range of loose sands.

- The CBR/LBR values of both ash types are very sensitive to the compaction moisture content of the sample. MB bottom ash exhibits unsoaked CBR/LBR values that are twice as large as the RDF bottom ash. MB bottom ash also exhibits higher unsoaked CBR/LBR values on the wet side of optimum while RDF bottom ash exhibits higher unsoaked CBR/LBR values on the dry side of optimum. A loss in strength occurs for both MB and RDF bottom ash after soaking.

☛ Concentrations of leaching of trace metals (Ag, As, Cd, Cr, and Pb) in the leachate from compacted ash columns subjected to DDW and SAR were below the EPA toxicity standard and decreased as a function of time. For Ag, As and Cd, most of the leachate concentrations were below the drinking water standard.

☛ The leaching of Ca increased when the rate of rainfall increased. However, the rate of rainfall had no effect on the release of Ag, As, Cd, Cr and Pb from the compacted ash columns. It is concluded that MWC bottom ash does not pose a threat to the environment even under extremely stormy conditions (i.e., 5 cm/hour).

☛ No special concern would be required if compacted MWC bottom ash were exposed to acid rain at pH around 4.

6.0 DEVELOPMENTAL SPECIFICATIONS FOR USING BOTTOM ASH IN HIGHWAY APPLICATIONS

Based on the results from this study, the following developmental specifications are proposed. These specifications have been formatted to fit into the general section on Earthwork and Related Operations in " Standard Specifications for Road and Bridge Construction" (1991) from the Florida Department of Transportation. Section number 1890 was developed such that any new specification fuse of waste materials could be added at the end of the section as they were approved. For completeness of this report the description (Section 180-1) associated with this new section has been presented in both volumes of this final report. Section 180-3 Waste Glass is presented in Volume 2 of 2.

DEVELOPMENTAL SPECIFICATION SECTION 180

REUSE OF DISCARDED MATERIALS AND BYPRODUCTS

180-1 Description

Discarded materials and byproducts shall consist, in general of municipal waste combustor bottom ash and waste glass generated from state mandated recycling quotas. The specification requirements for various discarded materials as contained in this Section are to govern their use only when these materials are used as a source of borrow material.

Sources of supply shall be approved by the Department.

180-2 Municipal Waste Combustor Bottom Ash.

180-2.1 Composition: Bottom ash shall consist of the solid material remaining after combustion of municipal solid waste which is discharged from the grates or stoker of a solid waste combustor at a facility designed to combust waste for electric power generation. The facility shall exclude other combustion residues from being mixed with the bottom ash. The facility shall process the solid waste for metals recovery (using the best available technology) before combustion or process the bottom ash for metals recovery after combustion.

180-2.2 Gradation: Materials classified as bottom ash shall meet the following gradation requirements:

Passing the 3/4-inch sieve	Minimum 97%(max. dimension < 1-inch)
Passing the 3/8-inch sieve	Maximum 80 % (by weight)
Passing the No. 200 sieve	Maximum 5 % (by weight)

180-2.3 Organic Content: Bottom ash shall have a maximum loss on ignition of 6 %.

180-2.4 Furnishing and Stockpiling: All bottom ash shall be furnished for a specific project from one facility. The bottom ash shall be trammeled through a 3/8-inch trammel screen and aged for a minimum of 60 days prior to use to allow aging reactions to occur.

180-2.5 Physical Properties: The dry rodded bulk unit weight (FM 1-T 019) for the bottom ash shall be greater than 65 pounds per cubic foot.

180-2.6 Chemical Properties: Concentrations of silver, arsenic, barium, selenium, cadmium, chromium, mercury and lead in the leachate from bottom ash shall be below the toxicity limits specified by the Environmental Protection Agency. In addition the contractor shall comply with regulatory issues of other environmental regulatory agencies.

180-2.7 Construction Methods: The contractor shall comply with construction methods specified in the DOT Standard Specifications for backfilling.

180-2.7.1 *Support of Vegetation:* Areas to be covered with grass shall be covered with a minimum thickness of twelve inches of topsoil over the bottom ash. For trees and shrubs, the depth of the topsoil shall be adjusted to accommodate the root system.

180-2.7.2 *Use with Metallic Construction:* Buried metallic materials such as culverts shall be coated with a bitumen or rubberized compound or separated with an inert borrow.

180-2.7.3 *Use with Concrete Construction:* Concrete structures constructed using Class I or Class III concrete having contact with bottom ash shall be coated with a bitumen or rubberized compound or separated with an inert borrow.

180-2.7.4 *Watertable:* Bottom ash shall be placed at a minimum of twelve inches above the top of the capillary zone.

180-2.8 Safety and Health: The contractor shall comply with the requirements of Section 7-1.4 of the Florida DOT Standard Specifications.

7.0 RECOMMENDATIONS

This research has yielded valuable information on the use of bottom ash in highway applications. The following continuation studies are suggested:

☛ Stockpile RDF and MB bottom ash and evaluate their *in-situ* environmental and geotechnical properties to ensure they are acceptable.

☛ Evaluate the variation in engineering and physical properties when RDF and MB bottom ash are combined with FDOT conventional base courses.

☛ Construct and monitor a field demonstration project using bottom ash as embankment, base and subbase material. The construction should be performed within a landfill to reduce permitting problems. Emphasis should be placed on construction methods and on how *in-situ* densities will be achieved. Data should be collected on engineering performance of the project and on leachate collected from the constructed site.

☛ Develop an *FDOT Users Manual* explaining when, where, and how waste materials can be used. This document will provide FDOT with needed information on current environmental concerns.

☛ Expand the current data base on the engineering and environmental characteristics of waste materials in highway applications.

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