DEVELOPING SPECIFICATIONS FOR WASTE GLASS, MUNICIPAL WASTE COMBUSTOR ASH AND WASTE TIRES AS HIGHWAY FILL MATERIALS (CONTINUATION)

FINAL REPORT

PB98-144199

VOLUME 1–MUNICIPAL WASTE COMBUSTOR ASH

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WPI 0510650
State Job No. 99700-7601-119
Contract No. B-9940

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Technical Report Documentation Page

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

4. Title and Subtitle	5. Report Date
DEVOLOPING SPECIFICATIONS FOR WASTE GLASS, MUNICIPAL WASTE COMBUSTOR ASH AND WASTE TIRES AS HIGHWAY FILL MATERIALS (CONTINUATION) Volume 1 of 3 (Municipal Waste Combustor Ash)	APRIL 1995
	6. Performing Organization Code
7. Author's	8. Performing Organization Report No.
P. J. Cosentino, E. H. Kalajian, C-S. Shieh and H. H. Heck	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Florida Institute of Technology (407) 674-7555 Civil Engineering Program 150 West University Blvd. Melbourne, FL 32901-6988	11. Contract or Grant No. B-9940 WPA # 0510650
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Florida Department of Transportation 605 Suwannee Street Tallahassee, Florida 32399-0450	Final Report October 1995 to October 1997
	14. Sponsoring Agency Code 99700-7601-119

15. Supplementary Notes

16. Abstract

A two year study was conducted as a continuation project for the Florida Department of Transportation (FDOT) to evaluate Municipal Waste Combustor (MWC) ash, Waste Glass, and Waste Tires for use as general highway fill. Initial studies conducted at Florida Tech concluded that MWC ash and waste glass possess engineering properties required for highway applications and the environmental characteristics were satisfactory for field deployment. The results of these studies are presented in three volumes. Volume I summarizes the findings for MWC Ash, Volume II summarizes findings for Waste Glass and Volume III summarizes findings for Waste Tires.

During this continuation study field demonstration projects using MWC ash and waste glass indicated that conventional construction methods and techniques were applicable. A comprehensive literature review was completed on the waste tires and their use as highway fill by state DOT's. It revealed that waste tires are highly compressible, but with adequate processing they can be used as highway fill.

For the field demonstration project involving the MWC ash a 82 foot (25 m) long, 32 foot (9.8 m) wide, 4 foot (1.2 m) high embankment was constructed using treated combined ash. A runoff and leachate collection system were installed for environmental monitoring. The geotechnical properties showed that combined ash exhibits high strength while being relatively free draining. An environmental analysis of 8 metals (arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver) indicated that the leachate and runoff concentrations were below surface water standards and below drinking water standards for all elements except an initial peak of selenium.

Laboratory studies conducted on combined ash from all 12 Florida waste-to-energy facilities indicated it would classify as either a well graded or poorly graded sand (SW or SP according to United Soil Classification System). The combined ash meets engineering criteria established by FDOT for use as a highway subgrade material.

The investigation of the environmental properties of waste glass revealed it can be cleaned to meet EPA drinking water standards at a reasonable cost. An outdoor reactor system was used to evaluate the environmental characteristics of waste glass leachate and waste glass cleaning methods. Prior to handling, the waste glass was crushed at a materials recovery facility. The waste glass was cleaned using two methods; direct rainfall and recirculating rinse water. Leachate from the system was analyzed for BOD5, TKN, and Phosphorus. These techniques produced leachate that initially exceeded drinking water standards, but that became clean within a reasonably short time.

For the field demonstration project involving the waste glass a 300 foot (91.5 m) section of subgrade was stabilized to a depth of 6 inches (2.4 cm) on a residential street using approximately 15% waste glass by volume. The subgrade stabilization was accomplished by mixing the waste glass with both the highly deteriorated pavement surface plus the existing base. Subgrade CBR, density and moisture contents data were collected. The construction process produced an acceptable subgrade.

Shredded tires exhibit engineering properties that are favorable for use in highway construction. They are a lightweight, free draining material, however, they undergo large initial displacements upon loading. The waste tire literature indicated that a major concern with waste tire fills was combustion. Fills in Washington and Colorado have combusted, causing numerous environmental concerns and hazards. Combustion can be avoided by proper sizing and placement. The state wide survey revealed that less than 1% of the nearly 14 million scrap tires generated yearly in Florida are available for use as highway fill. The majority of the tires are burned in either waste-to-energy facilities or in the tire-derived-fuel facility.

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

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified	161	

Form DOT 1700.7 (8-72)

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LIST OF ABBREVIATIONS

A........Pasco County Solid Waste Resource Recovery Facility.

B........Dade County Resources Recovery Facility.

C........Lake County Resource Recovery Facility.

D........North Broward Resource Recovery Facility.

E........South Broward Resource Recovery Facility.

F........Hillsborough County Solid Waste Energy Recovery Facility.

G........North County Regional Resource Recovery Facility.

H........Lee County Solid Waste Resource Recovery Facility.

I........Pinellas County Solid Waste Resource Recovery Facility.

J........McKay Bay Refuse to Energy Project.

K.......Bay County Resource Recovery Facility.

L.......Southernmost Waste-to-Energy Facility.

Acknowledgements

The researchers would like to thank the Florida Department of Transportation for funding this research under contract number B-9940. Additionally, our gratitude goes out to the City of Palm Bay, the Palm Beach recycling facility and the Pinellas County Department of Solid Waste Operations for their assistance in obtaining materials and construction of the field sites. Special thanks are also given to Mr. Mike Rudd and Mr. Bob Peacock for their assistance. FDOT's guidance from Dr. Robert K. H. Ho was invaluable. The help of Dr. David Horhota and Mr. Ron Lewis was also appreciated. The diligent efforts of the following graduate students made timely completion of this project possible: Heather Audet, James Egan, Mohammed Hai, Tomas Montemayor, Hasashi Takahashi and Minghshou Tang.

Abstract

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1. Introduction

A two-year study was conducted to determine the feasibility of using municipal waste combustor (MWC) ash in highway applications. Research was carried out to evaluate the geotechnical properties and the environmental acceptability of the MWC ash used to construct an embankment. The study was conducted by researchers at the Division of Engineering Sciences and the Research Center for Waste Utilization at the Florida Institute of Technology in Melbourne, Florida. Study findings will be used to revise the suggested specifications for using MWC combined ash for road construction developed in Phase 1 of the study for the Florida Department of Transportation (DOT).

This report first provides background information on MWC ash and then presents objectives and results of the embankment study, including ash characterization and site location; construction and environmental monitoring of the ash embankment; geotechnical properties of the MWC ash; and conclusions and recommendations. Finally, revised developmental specifications for the Florida DOT "Standard Specifications for Road and Bridge Construction" are proposed. Ash used in the study was MWC combined ash. For the embankment construction treated "WES-PHix" combined ash was collected from the Pinellas County Solid Waste Resource Recovery facility located in St. Petersburg, Florida. To evaluate variations in geotechnical properties of the MWC ash, samples were collected from 12 WTE facilities in Florida.

1.1 Background

1.1.1 Highway Applications Using MWC Ash

MWC combined ash utilization as a road construction aggregate has been shown to be a viable material for road construction (Jones, Hartman, Kort, and Rapues, 1994).

Utilization of MWC ashes has been, and is being considered for a variety of applications in the United States. Ash can be utilized as embankment fill material, highway base course material, landfill cover, and as aggregate for concrete mixtures used to make concrete block. Various investigations have focused on the use of either bottom, fly, or combined ash. The discussions presented here focus on the use of bottom or combined ash.

Reutilization of bottom ash residue has been carried out extensively, particularly in western Europe. In Denmark, size fractioned, processed bottom ash has been used for development of granular subbase for parking lots, bicycle paths, and paved and unpaved roads (World Resource Foundation [WRF], 1995). Similar granular subbase paving applications have also been carried out in Germany (WRF, 1995).

The use of bottom ash for construction of granular base, or as fill in embankments, and as noise or wind barriers has been carried out in the Netherlands. The Dutch have also used bottom ash as an aggregate in asphalt and concrete and have used fly ash as a fine aggregate in asphalt. Sweden has used bottom ash in pavement applications (WRF, 1995). Bottom ash has been used experimentally as an aggregate in bituminous pavement and Portland cement and directly as a road base material in Germany (Kosson,van der Sloot, and Eighmy, 1996).

The U. S. Environmental Protection Agency (EPA), the U. S. Department of Energy (DOE), and the Federal Highway Administration (FHWA) have partially funded several projects for the use of combined ash in road base or subbase courses (Chesner, 1993). Combined ash applications used in road base, subbase courses, and surface pavements within the United States are summarized in Table 1-1 and Table 1-2.

Current practice at WTE facilities in the United States is to dispose of combined ash in monofills or to use it as daily cover in landfills. The engineering and environmental characteristics of ash have been evaluated in the laboratory and results suggest its strong potential for use as a highway construction material (Cosentino, Kalajian, Heck, and Shieh, 1995).

1.1.2 Environmental Concerns

One disadvantage of combustion of municipal solid waste (MSW) is that every year in the United States it produces 4.5 millions tons of ash rich in heavy metals (Sandell, 1996). This volume can be expected to increase as landfill space becomes more limited. Currently, 85-90 % of the ash produced is disposed of directly in monofills (Buchholz, 1995). Most of the remainder is codisposed with raw MSW, often as a cover.

Landfill space is becoming ever more limited, producing a growing need to increase the utilization of the ash. A major concern is that the ash contains high concentrations of metals (Buchholz, 1995). Kosson et al., (1996) identified metals of environmental concern and total dissolved solids from salts (e.g. chloride, sodium, and potassium) to be the important constituents of ash that could potentially cause environmental harm. A major issue is whether these elements will leach out of the ash into surface and ground water. Laboratory extractions designed to simulate leachate often produce concentrations exceeding drinking water and sometimes toxicity standards (Andrews, 1991; Shaub, 1990). The concentrations predicted by the extractions varied markedly from method to method and often were contradicted by actual leachate concentrations in the few instances where field results were available (Shaub, 1990).

1.1.3 Availability of MWC Ash

Americans generated 209 million tons, or 4.4 pounds per person per day, of MSW in 1994 (United States Environmental Protection Agency, 1995). An estimated 49 million tons, or 24 percent of MSW, was recycled or composted in 1994; an estimated 32 million tons, or 15 percent, was combusted (nearly all with energy recovery); and the remainder, 127 million tons (61%), was landfilled (small amounts may have been littered or self disposed) (U. S. EPA, 1995). After materials recovery for recycling or composting, discards were 3.4 pounds per person per day. The generation of MSW within the United States is projected to be 223 million tons by the year 2000 (U. S. EPA, 1995). In Florida alone, over 5 million tons of waste was combusted in 1995 (Hinkley, 1996).

The combustion of MSW in WTE facilities to generate electricity and reduce the volume of waste is a widespread practice in the United States. There is a 70% reduction in weight and a 90% reduction in volume (Sandell et al., 1996). As of October 1995, there were 116 WTE facilities marketing energy in the United States, with a combined capacity of burning more than 1,000,000 tons of MSW per day. The six states with the largest amount of capacity (Florida, New York, Massachusetts, Pennsylvania, Virginia, and Connecticut) represent almost 60% of the total capacity in the nation (Carlin, 1995).

WTE facilities generally fall into four categories: mass burn, refused-derived fuel (RDF), modular controlled air, and pyrolysis (Carlin, 1995). Total WTE capacity in the United States by process type is shown in Figure 1-1.

Mass-burn facilities combust waste without recovery of recyclable materials prior to combustion, while refuse derived fuel (RDF) facilities remove recyclables prior to combustion. Many of the mass burn facilities process the ash for metals recovery. A schematic of the operation of a typical MSW fired mass burn power plant is shown in Figure 1-2 (Carlin, 1995).

At present in the United States, the MWC ash produced is typically combined ash, with approximately 80-90% of it being bottom ash that represents the residue collected in the combustor after the MWC is burned. The remaining 10-20% is referred to as fly ash and represents the ash that escaped the combustor and was trapped in air pollution control devices. Combustion produces bottom ash and fly ash as waste materials. Most WTE facilities in the United States mix the bottom ash and the fly ash to form a combustor ash (called combined ash) that typically passes the toxicity test and is not classified as hazardous waste (Ellen and Cannett, 1995).

MWC combined ash from different facilities displays a high degree of variability in both physical and engineering properties. Combustion of MSW yields ash containing combustible and non-combustible materials. Combustible materials are typically paper, wood, plastic, tires, textile, yard waste, food, etc. Non-combustible materials are ferrous and non-ferrous metals, glass, brick, ceramic, rock, etc. (Collins, 1979). Some of the non-combustible materials, such as glass and metal, bind to form clinker that is glassy and weighty.

1.2 Study Objectives

The objectives of this research project were to identify the geotechnical and environmental properties of MWC combined ash for proposed use as a highway fill material and to produce specifications for inclusion in the Florida DOT Standard Specifications.

The following tasks were conducted to evaluate the geotechnical properties of the MWC combined ash:

1. Design and construct an embankment using MWC combined ash as the fill material
2. Evaluate the field performance of the embankment specifically California Bearing Ratios (CBR), infiltration, pressuremeter, and cone penetrometer
3. Collect combined ash from each of the 12 WTE facilities in Florida to determine physical composition, moisture competition, grain size distribution, moisture density characteristics, and California Bearing Ratio/Limerock Bearing Ratio (CBR/LBR)
4. Determine the suitability of MWC combined ash for use as highway fill material
5. Revise the existing draft specification

The following tasks were conducted to evaluate the environmental characteristics of the ash embankment:

1. Determine the concentrations of the eight selected elements: arsenic (As), barium (Ba), cadmium (Cd), chromium (Cr), lead (Pb), mercury (Hg), silver (Ag), and selenium (Se) present in the ash used to construct the ash embankment
2. Determine the ash embankment's leachate and runoff concentrations of As, Ba, Cd, Cr, Pb, Hg, Ag, and Se over time for comparison with drinking water and toxicity standards
3. Determine field pH and conductivity of the leachate, runoff, and rainwater over time and compare these trends with element metal concentrations
4. Determine the volumes of major inputs and outputs to the embankment, including rainfall, leachate, and runoff quantities, to ensure no extraneous gains or losses of water were occurring to the ash embankment
5. Determine the environmental suitability of MWC combined ash as a highway fill material
6. Revise the existing draft specification

2. Embankment Study

Previous studies conducted for the Florida DOT demonstrated that MWC bottom ash has the physical and geotechnical properties necessary for highway fill applications and meets existing environmental acceptability regulations (Cosentino et al. 1995). Researchers in these studies concluded that a field demonstration of the ash would be very beneficial to evaluate the major concerns of constructability and environmental behavior. Since the WTE facilities are now producing combined ash instead of bottom ash, the demonstration project was constructed using combined ash.

The objectives of constructing the combined ash highway embankment as a field demonstration were

- to evaluate conventional construction methods and quality control procedures, and
- to determine the physical and environmental acceptability of MWC combined ash as a fill material.

2.1.1 Ash characteristics

The combined ash used for embankment construction was obtained from Pinellas County's Refuse-to-Energy facility. This plant, which began operation in 1983, is operated by Wheelabrator, Inc. The design capacity for waste processing of the refuse-to-energy plant is 3,000 tons per day, and the plant produces 645 tons of combined ash per day (Hinkley, 1997). Combustion of MSW occurs on moveable grates, and the heat is used to generate electricity. The combined ash was processed by Resource Recovery, Inc., to remove metals from the ash and sieved through the 5/8 inch trammel sieve before stockpiling.

A total of 150 cubic meters (200 cubic yards) of treated "WES-PHix" combined ash was transported and discharged in piles as shown in Figure 2-1. The stockpiling rate was approximately 11.5 cubic meters per truck per day. It was planned to age the ash for a minimum period of 30 days to allow for chemical modification of the physical properties of the ash as recommended by Shieh and Kalajian (1995). Samples of the combined ash were collected over a 13 day period for grain size, moisture content, and chemical analysis. The ash was aged for 44 days, as counted from the dumping of the last truck load.

The engineering and environmental indicator properties of the Pinellas ash samples taken from the 13 day period were studied. A statistical analysis was performed to evaluate typical day-to-day variations in these MWC ash properties. Figure 2-2 shows the grain size variations for the 13 days. Based on the uniformity coefficient (C_u) and coefficient of curvature (C_c) ranges, it was concluded that the combined ash would classify as a well graded sand (SW). The uniformity coefficient and coefficient of curvature for each of the sample dates are presented in Table 2-1. Both the diameter at 10% passing (D_{10}) and percent passing the number 200 sieve indicate that the combined ash would possess good drainage characteristics.

The top 0.2 m (6 in) surface of stockpiled ash desiccated during the aging period. The ash within a depth of 0.3-0.5 m (1-1.5 ft) showed moisture contents of 11-17%. These moisture contents are similar to the range of moisture contents of ash collected directly from the plant (Cosentino et al., 1995).

To characterize the chemical properties of the ash, the elemental metals were extracted from the solid matrix, using HF and nitric acids, in a procedure suggested by Silberman (1979). The digests were then analyzed for selected metals using the Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). In the ICP-MS analysis, a number of mass-to-charge ratios for the elements of interest (i.e., Cr 52, Ar 75, Se 78, and Se 82) were found to have interferences from other compounds (i.e., ArC13, ArCl, ArClH, Kryton, and Ar_2H_2). By analyzing for more then one mass-to-charge ratio for each element, it was possible to confirm the quantities for most of the elements. The concentrations of these elements were also confirmed by Graphite Furnace Atomic Absorption Spectrometry (AAGF).

Figure 2-3 shows a log plot of selected element concentrations, as determined by ICP-MS analysis as a function of the date of ash production in March 1996. Figure 2-4 shows a similar plot using data from AAGF analysis of the same extracts. The concentrations of the extracts were multiplied by the dilution factor to determine the concentrations of the eight selected elements in the dried ash. For lead, barium, cadmium, and arsenic, the variation during the 13 day sampling period was relatively small. Chromium displayed little variation until a high concentration occurred on March 28. This peak was exaggerated in Figure 2-3 since the concentration of a 50-fold dilution still exceeded the optimum accuracy (5 mg/kg maximum) of the ICP-MS. The corresponding peak in Figure 2-4 measured by AAGF was a better representation of the magnitude of this peak. This peak did not correspond with increases in any of the other elements of interest; however, analysis for titanium showed a 200-fold increase on this date over the day before and day after. This could reflect a chance inclusion of a fragment high in those metals in the portion of the ash being extracted, or an actual variation in the supply of material to the MSW combustor. Mercury showed the least tendency to hold a constant value over time, followed by silver. Both of these elements are present in the ash in a smaller quantity than the others and have fewer sources so variation would be expected. Selenium concentrations were below detection limits by AAGF analysis, except for the March 23, sample which was 220 g/kg.

Concentrations of all the elements determined in the ash fall close to the mean of typical combined ash values reported by Buchholtz (1995) and summarized in Table 2-2. The average concentration and standard deviation of elements in the ash determined by ICP-MS analysis is given in the second column of Table 2-3. The standard deviation for chromium was much greater than the other elements primarily due to the two orders of magnitude increase that occurred on March 28.

2.1.2 Site location

The MWC combined ash embankment site is located within the slurry wall of the 730 acre Pinellas County Department of Solid Waste Management landfill in St. Petersburg, Florida. This landfill is naturally lined with a clay layer, and leachate is confined by a man-made slurry wall constructed along the perimeter of the entire facility. The embankment site is adjacent to the county bomb-disposal area.

The existing construction site was previously graded to an elevation of 1.5 m (5 ft) above the original ground surface with a gravely clay fill. The ground surface at the site was fairly leveled and relatively compacted. An undisturbed natural area with vegetation is located adjacent to the construction site with some water holding areas. The top level of water surface is about 2.8 m (9 ft) below the filled ground surface.

The ground surface at the site was cleared and grubbed one month prior to construction. The construction site had not been used as a landfill, however, it is within 500 meters of the bomb disposal area. Combined ash, collected for a 13 day period during March 1996, was stored within 100 meters of the construction site. The embankment was located far enough away from the stockpile area to avoid contamination from runoff during the collection and aging period.

2.2 Embankment Construction

The embankment was constructed according to the drawing shown in Figure 2-5 and was 25 m (82 ft) long and 9.8 m (32 ft) wide at the base and 1.2 m (4 ft) in height. The top of the embankment was 15.2 m (50 ft) long and 3.1 m (10 ft) wide. Four side slopes were chosen for the embankment. In the longitudinal direction, the side slopes were (5:1) and (3:1); in the transverse direction, the side slopes were (2.5:1) and (3:1). The specifications required that the ash be placed in loose-layer thickness of less than 0.15 m (6 in) and be uniformly compacted to a density of not less than 100% of the maximum density, as determined by AASHTO T-99 (FDOT, 1991). Based on laboratory moisture density testing, this required a field dry density of 116 lb/ft^3 (18.2 kN/m^3). The ash was placed in eight lifts to achieve the design height of the embankment. A leachate and runoff collection system (shown in Figure 2-5), was designed to capture leachate and runoff from rain across a section of the embankment.

A cross section of the embankment across the leachate collection and runoff collection systems is shown in Figure 2-6. The collection system consisted of a sand cushion, geomembrane, perforated polyvinyl chloride (PVC) collection pipes, gravel, geotextile, and ash. Leachate and runoff were captured and collected in separate 55 gallon PVC drums, which could be sampled at specified intervals. The geomembrane isolated the leachate collection system from the ground water at the site and trapped the leachate generated within the leachate collection system. To avoid possible migration of fines, the perforated pipe was wrapped in a geotextile, and the geotextile was spread on top of a gravel layer before placing the combined ash.

2.2.1 Construction Procedure

The construction process began by laying out the embankment using a transit, level, measuring tape, and stakes. A temporary bench mark, which was assigned an elevation of

2.8 m (9 ft) was used as a backsite to determine the elevation of each layer of embankment during construction. The embankment outline was marked with lime to delineate the base dimensions as shown in Figure 2-7.

The following equipment was used in the construction of the embankment:

- 2 cubic yard front-end loader (John Deere model 588) provided by Pinellas County
- small front-end Merloe skid steer loader (Bobcat model 753)
- vibratory compactor (Ingersoll Rand Model SD -40D), 5 tons / 54 inch / single smooth roller
- small (20 in) plate compactor (MQ : MCV 90L)
- water truck (100 gallon capacity) with hose and sprinkler provided by Pinellas County
- Troxler nuclear density meter from FDOT

The construction procedure consisted of:

1. Moving the ash from the stockpiles to the site using the front-end loader
2. Spreading the ash in 0.2 m (6 in) lifts using the loader and manual labor
3. Distributing water over each ash lift using a sprinkler hose from the water truck
4. Compacting the ash lift with approximately 10 passes of the vibratory roller
5. Measuring field density and moisture content using the Troxler nuclear density meter

The first lift of combined ash of 18 cm (7 in) was spread over the base dimension of embankment. A front-end loader (see Figure 2-8) was used to move the ash from the ash stockpile and spread over the site by back blading with the bucket and manual spreading with rakes. No additional water was added to the first lift. The vibrating smooth-wheel compactor as shown in Figure 2-9 ran six passes over the first ash lift. The nuclear density meter (see Figure 2-10) was then used to check the field density and moisture at three locations in this lift. The density of the lift had a relative compaction of 85% with a moisture content of 9%. The compacted lift surface was loosened using rakes, and water was spread uniformly over the compacted lift of combined ash. The permeability of the ash allowed the water to drain freely into the ash. Watering was continued until the color of the ash was similar to the color of the ash on the dry side of optimum moisture content as found in previous laboratory tests of the ash. After six passes of the roller, the field density reached 97% relative compaction. An additional five roller passes increased the field density to a relative compaction of 100%. The second, third, and fourth ash lifts were spread the same way as the first lift; however, the ash was watered before rolling with the vibratory compaction equipment. The required number of passes of vibrator roller to obtain the 100% relative compaction for the second, third, and fourth lifts were twelve, ten and ten, respectively. The field density data is summarized in Table 2-4.

The only problems encountered during measurement of field density and moisture content were with the use of the Speedy moisture tester. This device was found to be unreliable for use on ash as it yielded moisture contents that were higher than the nuclear density meter. A short study conducted by Mr. Ron Lewis of the Florida DOT State Materials office yielded the data presented in Table 2-5 and the results plotted in Figure 2-11. The Speedy moisture tester tended to overestimate the moisture content for ash that had moisture contents less than 16%. It is believed that chemical compounds present in the ash may affect the results of the Speedy moisture tester.

Gravel and sand were used in the construction of the leachate and runoff collection systems of the embankment. These materials were purchased from Florida Rock and Minerals of St. Petersburg. The gravel was a rounded to subrounded washed brown river rock with a maximum grain size of 2 cm (3/4 in). The material was visually classified according to USCS as poorly graded gravel (GP). The sand was a white masonry sand passing the number 10 sieve and was visually classified according to USCS as a poorly graded sand (SP). The sand was used as a cushion for the geomembrane in the leachate and runoff collection system of the combined ash embankment.

Combined ash was removed after completion of the fourth lift to construct the leachate and runoff collection system. The small front-end loader was used to remove the compacted combined ash from the designated section (see Figure 2-5). Prior to spreading the first lift of ash a 3 m (10 ft) long by 1.2 m (4 ft) wide trough was excavated and filled with sand to allow for the toe drain construction for the runoff collection section. Excess sand was removed from the toe drain section, and a 0.1 m (4 in) thickness sand cushion was built at a slope of 2% toward the collection point. A 3.7 m (12 ft) long by 1.8 m (6 ft) wide geomembrane was placed over the sand cushion and 3.1 m (10 ft) long and 0.1 m (4 in) diameter perforated PVC pipe was placed at the center of the runoff collection section before placing the gravel as a cover. The specified side slopes of the leachate and runoff collection system were manually graded. A 0.1 m (4 in) sand cushion was spread out with a 2% slope toward the collection system. The geomembrane was then placed over the sand cushion.

A 4.9 m (16 ft) long and 0.1 m (4 in) diameter perforated PVC pipe wrapped in geotextile was placed at the center of the leachate collection section. The perforated PVC pipe slope of 2% was checked by using the leveling instrument before placing a 0.1 m (4 in) thickness of gravel. Geotextile was then spread out on the top of the gravel layer. Finally, combined ash was distributed by the front-end loader on top of geotextile (see Figure 2-12), watered, and compacted by vibrator compactor. Ash was added in lifts and watered and compacted until reaching the existing top surface of the embankment. Field compaction tests were performed on each lift of ash in the leachate collection section and each achieved 100% relative compaction.

The next four ash lifts were placed in the same manner described for the second lift of ash until the required 1.2 m (4 ft) height of combined ash embankment was reached. The combined ash used for the embankment construction was directly from the stockpiles. Some pieces of oversize plastic, rubber, wood, and metal (see Figure 2-13) were manually removed during spreading of each lift of combined ash embankment construction. The total volume of these materials was less than 0.06 cubic meter (2 cubic feet), which was approximately 0.03% of the total fill for construction of the embankment. Based on the small percentage of oversize materials, it can be assumed that the ash was very clean of debris.

To install the drums for collection of the leachate, a 3.1 m (10 ft) long by 0.1 m (3 ft) wide and 1.5 m (5 ft) deep trench was dug by backhoe at a distance of 1.5 m (5 ft) from the edge of the embankment. Four drums were then placed in the trench (see Figure 2-14). All pipes were joined using PVC primer and glue. The trench was then back filled. The completed combined ash embankment is shown in Figure 2-15.

The construction of the ash embankment was accomplished using conventional construction equipment and methods. The moisture content of the ash could be easily controlled due to its free draining capability. Compaction time or number of passes could be reduced by increasing the weight of the roller and adjusting the moisture content approximately 2% less than optimum.

2.2.2 Leachate Collection System

The leachate collection area was situated toward one end of the ash embankment to prevent any disturbance by planned engineering evaluations. Figure 2-6 shows a transverse cross section of the embankment and the leachate and runoff collection systems. The geotextile below the ash layer prevented the migration of ash particles into the gravel below, but allowed rainwater that had infiltrated the ash to freely pass to the gravel section. This infiltrated water could not pass below the gravel layer due to the underlying impermeable 0.06 mil geomembrane. The 0.1 m (4 inch) sand layer below the geomembrane acted as a cushion for the geomembrane. The gravel layer was sloped toward the center of the collection area where leachate could collect in a perforated pipe, as well as toward the collection drums. The perforated pipe was wrapped in geotextile, which allowed water to pass through but prevented clogging by the gravel. Before exiting the leachate collection area, the perforated pipe was connected to a solid PVC pipe that was sloped to allow the leachate to move by gravity to buried drums.

2.2.3 Runoff Collection System

Depending on the permeability of the ash and the rate of precipitation, a significant percentage of the rainwater falling on the collection area did not infiltrate the ash, and instead "ran off" the sides of the embankment toward the adjacent ground. To account for the effects on the water exposed to the ash as runoff, a 2% slope was given to the top surface of the embankment to ensure flow toward a toe drain situated at the bottom edge of the side of the embankment. Any rainfall that infiltrated the ash up to the base of the slope passed downward to the leachate collection system. A geomembrane prevented leachate from moving laterally to where the toe drain was located (see Figure 2-6). The toe drain consisted of a gravel section lined by geomembrane with a perforated pipe that collected only the water that made it to the bottom of the slope via surface runoff. This perforated pipe was connected to a solid PVC pipe, that was sloped to allow it to drain by gravity to buried PVC drums, allowing the leachate and runoff water from the same area to be collected simultaneously in separate collection drums (see Figure 2-6).

2.2.4 Collection Drum Design

Both leachate and surface runoff were collected in separate but identical systems consisting of a solid PVC pipe connected to a primary collection drum that was, in turn, connected to an overflow drum. As illustrated in Figure 2-6, the configuration allowed an unobstructed access to each drum from the ground surface for the purpose of monthly sampling, volume measurement, and evacuation of the contents. Each drum was identical in capacity and dimension, made of PVC, and installed level. Each drum was also calibrated so a measurement of total liquid height from the pipe access was directly convertible into liters collected. The drums were sealed to the atmosphere (except during sampling) to eliminate appreciable evaporative loss.

2.2.5 Rain Water Collection and Measurement

A 30-gallon PVC drum was placed on site for direct rainwater collection. The rain gauge was modified to allow the water collected to pass through into the drum below. Since the rain gauge was open to the atmosphere, any contribution of material due to washout or dry fallout on the embankment was also reflected in the rainwater. Rainfall was recorded to the hundredth of an inch using a digital recorder. Monthly sampling, volume measurement, and evacuation took place through a pipe access.

A tilting bucket rain gauge, also placed on site, was used to measure the volume of rainwater collected and account for any evaporation that might have taken place in the rainwater drum. A backup confirmation of rainfall was available with a rain gauge situated less then a half mile away at the Department of Solid Waste Operations, Pinellas County offices.

2.3 Environmental Analysis

2.3.1 Arsenic Concentrations

Figure 2-16 shows leachate, runoff and rainfall concentrations of arsenic as a function of time. Time elapsed refers to the number of days after the completion of construction of the ash embankment and leachate collection system. The first set of data points at 20 days represents the first sampling date of the leachate and runoff that had collected for the previous 20 days. The leachate concentrations of arsenic were two orders of magnitude below toxicity standards and below the drinking water standard. The concentration in the leachate showed a general downward trend over time. Runoff concentrations of arsenic were three orders of magnitude below toxicity standards and an order of magnitude below drinking water standards. The runoff concentrations were slightly elevated over rainwater concentrations and show no downward trend with time, eventually matching the concentrations in the leachate after 135 days elapsed. In general, arsenic is found in both the fly ash and bottom ash portions of combined ash, though to a greater extent in the fly ash portion (Buchholz, 1995).

2.3.2 Barium Concentrations

Figure 2-17 shows the concentration of barium in the leachate, runoff, and rainwater as a function of time elapsed. Barium concentrations in both the leachate and runoff were well below both toxicity and drinking water standards and showed general downward trends in the concentrations of both over time. Barium concentrations in both the leachate and runoff were clearly elevated over rainwater concentrations. Ninety nine percent of barium present in the rainwater was in dissolved form (capable of passing through a 45 μm filter (see Table 2-6). Ninety five percent of barium in the runoff and 97% of the barium in the leachate were also in dissolved form.

The runoff results allow some inferences to be drawn directly from the field data. Runoff concentrations showed barium levels above that of the rainwater. Because very little of the barium was transported as a particulate and because the runoff was not subject to displacement of pore water volumes or leaching, the major mechanism for barium release in the runoff was either washout or rapid dissolution.

Barium concentrations in all the leachate and runoff samples exceeded the concentrations of the other eight toxicity elements by at least an order of magnitude. Laboratory studies have found barium in both the fly ash and bottom ash portions of combined ash, and usually concentrated near the surface of ash particles (Buchholz, 1995), making it much more available for leaching or rapid dissolution.

2.3.3 Cadmium Concentrations

Figure 2-18 shows the concentration of cadmium in the leachate, runoff, and rainwater as a function of time. Cadmium concentrations in both leachate and runoff were well below both toxicity and drinking water standards throughout the period of the study.

Cadmium concentrations in laboratory leachate studies were found to decrease when pH was reduced from 10 to 9 and then sharply increase until leveling out at pH 6 (Eighmy, 1995). Since the pH of the leachate changed from 6.95 to 7.04, the initial high concentration of cadmium in the leachate could be pH-related since the leachate during the first sampling interval was at the lowest pH level (6.63). Eighty-nine percent of the cadmium in the rainwater was in dissolved form (passing a 45 μm filter); the remaining 11% could be contributed by washout and dry fallout of particulates. Forty-one percent of the cadmium in the runoff was in dissolved form. All of the dissolved cadmium in the runoff could be accounted for simply from the dissolved portion of the rainwater concentrations, while the particulate cadmium in the runoff was found to be in excess of the rainwater particulate concentrations. This suggests that the major mechanism of cadmium release in the runoff was particulate transport. Ninety two percent of cadmium in the leachate was in dissolved form; therefore, particulate transport could only play a minor role. This suggests that the most likely mechanisms for cadmium release in the leachate was leaching or displacement of pore water. Laboratory studies have found cadmium to be a water-leachable constituent of the MSW fly ash portion of the combined ash though found to a lessor extent in the bottom ash portion as well (Buchholz, 1995). Volatile or semi-volatile heavy metals (such as cadmium) are deposited near the surface of particles in the fly ash portion of combined ash and are more readily leached (Buchholz, 1995).

2.3.4 Chromium Concentrations

Figure 2-19 shows chromium concentrations in the leachate and runoff as a function of time. The concentrations of chromium in the leachate and the runoff were below the drinking water standard and three orders of magnitude below the toxicity standard. The trend of the concentration of the leachate was generally downward, though that is not clearly shown on a log plot. Both leachate and runoff concentrations were elevated above rainwater concentrations.

Laboratory leachate studies have found chromium to decrease in concentration as the leachate moves from pH 10 to pH 6 and then increases rapidly in concentration as pH decreases below 6 (Eighmy, 1995). Since the leachate during the first sampling interval was at its lowest pH level (6.63) the initial high concentration of chromium could be pH-related.

Eighty-nine percent of chromium in the rainwater was found to be in dissolved form (passing a 45 μm filter). Forty-four percent of chromium concentration in the runoff and

80% of the chromium concentration in the leachate was in dissolved form. The 56% of chromium in the runoff transported as a particulate accounts for almost all of the chromium in the runoff above the rainwater levels. Twenty percent of the chromium in the leachate was transported as a particulate. Because there was no evidence for washout or rapid dissolution occurring in the runoff, the remaining 80% of chromium was more likely released by leaching or displacement of porewater volume. Laboratory studies indicate that chromium is a water-leachable constituent of the fly ash portion of combined ash, though present to a larger extent in the bottom ash portion (Buchholz, 1995).

2.3.5 Lead Concentrations

Figure 2-20 shows leachate, runoff, and rainfall concentrations of lead as a function of time. Both the leachate and runoff concentrations were an order of magnitude below the drinking water standards and three orders of magnitude below the toxicity standards. Both the leachate and runoff concentrations of lead closely approximated the concentrations of lead in the rainwater.

Sixty one percent (61%) of the lead concentration in the rainwater was in dissolved form (passing a 45 μm filter); the remaining 39% was in particulate form consistent with washout or dry fallout of particles. Eight percent of lead in the runoff and 100% of the lead in the leachate were in dissolved form. The dissolved portion of the rainwater can account for the entire dissolved portion of the runoff; therefore, transport of particles appears to be the primary mechanism for lead transport in the runoff. No evidence of particulate transport occurred in the leachate. The most likely mechanisms, then, are leaching or porewater displacement. In laboratory studies, lead was present in large concentrations in both the fly ash and bottom ash portions of the combined ash (Buchholz, 1995).

2.3.6 Mercury Concentrations

Figure 2-21 shows the mercury concentrations in leachate, runoff, and rainwater as a function of time elapsed. Both the leachate and runoff concentrations were several orders of magnitude lower than toxicity standards, as well as being below the drinking water standard. For the first 100 days the leachate and runoff concentrations were higher then the rainwater level, and then both dropped off until they fell below detection limits at 135 days. The mostly neutral pHs found in the leachate inhibit release of mercury that is facilitated in alkaline conditions (Buchholz, 1995). Mercury was not detected in either dissolved or particulate form in any of the samples during the sampling periods when the samples were being filtered. In general, mercury is found in highest concentration in the fly ash portion of the combined ash, though it is present in the bottom ash as well (Buchholz, 1995).

2.3.7 Selenium Concentrations

Figure 2-22 shows concentrations of selenium in the leachate, runoff, and rainwater as a function of time. Although the selenium concentrations in the leachate were on average two orders of magnitude below toxicity standards, the initial value for selenium in the leachate (0.013 mg/l) slightly exceeded the drinking water standard (0.010 mg/l). The selenium concentration in the leachate dropped rapidly and after 70 days elapsed remained an order of magnitude below drinking water standards. The selenium concentration of the runoff was an order of magnitude below drinking water standards and three orders of magnitude below toxicity standards. While the selenium concentration in the leachate was elevated above rainwater concentration, the concentration in the runoff roughly approximated rainwater concentrations.

Concentrations of selenium in the filtered and unfiltered rainwater and runoff were close to or below detection limits; the percent dissolved must be interpreted very conservatively. One-hundred percent of the selenium found in the rainwater was in particulate form. Twenty percent (20%) of the selenium found in the runoff was in particulate form. Concentrations of selenium in the leachate were well within detection limits. Ninety-two percent of the selenium in the leachate was in dissolved form, suggesting that particulate transport was not a major mechanism. Leachate concentrations were greater than an order of magnitude over runoff concentrations, suggesting the major mechanism would likely be leaching or displacement of pore water volumes because they would occur preferentially in the leachate. In laboratory leaching studies, selenium has been found to be a water-leachable constituent of the MWC fly ash portion of the combined ash (Buchholz, 1995).

2.3.8 Silver Concentrations

Figure 2-23 shows concentrations of silver in the leachate, runoff, and rainwater as a function of time. The leachate concentrations were an order of magnitude below the drinking water standards and three orders of magnitude below the toxicity standards. Initially, the leachate concentration of silver was elevated above the rainwater levels, but after 45 days elapsed, the concentration dropped sharply until it fell below detection limits by 135 days elapsed. The concentrations of silver in the runoff were two orders of magnitude below the drinking water standard and four orders of magnitude below the toxicity standards. The silver concentrations in the rainwater varied over time. The concentration of silver in the runoff mirrored the variations in rainwater and rarely exceeded them. Silver was not detected in particulate or dissolved forms in any of the samples during the sampling periods when samples were being filtered. In laboratory studies, silver was found to a greater extent, and observed to leach more readily, from the fly ash portion then the bottom ash portion of the combined ash (Buchholz, 1995).

In summary, Figure 2-24 shows a linear plot of the presented elements, except Barium, elements in the leachate as a function of time. The linear plot shows the general trend of the concentrations over time more apparently then the log plot. Although barium also shows a similar downward trend, it was not included in this figure since the barium concentrations were a magnitude higher than that of the other elements.

2.3.9 Percent of Selected Elements in Dissolved Form

Some of the leachate, runoff and rainwater samples were filtered through a 45 μm filter to determine the percent of the elements in dissolved form. In Table 2-6, the concentration of several elements (As, Ag, Ba, Cd, Cr, Hg, Pb, and Se) in the leachate, runoff and rainwater at 204 days elapsed, with and without filtration and the percent dissolved are given. Silver and mercury were found to be not detectable and, therefore, the percent dissolved could not be calculated. Selenium values for rainwater and runoff approach or are below the detection limits for the instrument but are included for comparison purposes.

2.3.10 Concentrations of Selected Elements as a Function of Leachate and Runoff Volumes

The measured volume of ash in the leachate collection area (19.7 m^3 or 700 ft^3) was multiplied by the dry density of the ash when compacted (18.2 kN/m^3 or 116 lb/ft^3) to obtain the weight of ash in the leachate collection area. This approximate weight (36,600 kg or 81,200 lbs) was multiplied by the concentrations of each element measured in the ash itself to give an approximate total weight of elements present in the ash matrix of the leachate collection area. The average concentrations and total weight in the leachate collection area for each element are given in Table 2-7.

Concentration caused by heavy rainfall washing out spikes of elements of concern or light rainfall concentrating the elements in the smaller quantity of water changes could have conceivably occurred in the leachate or runoff. To determine if this was the case, the leachate concentration was plotted as a function of leachate volume in Figure 2-25. No statistically significant relationship (r= <0.4) was found.

Figure 2-26 is a linear plot of runoff concentration as a function of runoff volume. It also shows no statistically significant relationship (r= <0.3) between any concentration changes of selected elements in the runoff and the runoff volume. Concentrations of elements in the leachate and runoff showed no statistically significant relationship (r= <.5) to changes in the rainfall volumes as well.

2.3.11 Cumulative Weight of Selected Elements in Leachate and Runoff as a Function of Time

Figure 2-27 shows the cumulative weight of elements in the leachate as a function of time. The cumulative weight was calculated by multiplying the concentration in weight per volume by the volume of leachate collected for that period. The resulting weight was added cumulatively to the weight of the element observed up to that period. The flattening out of the curves as they approach the 70-110 day interval reflected the drop in leached concentration with time contributing less and less to the cumulative weight. Figure 2-28 is an identical plot to Figure 2-27 excluding barium so that the other elements could be significantly shown. Note that the flattening out of the curve of silver occurred early at the 45 day interval, whereas mercury and lead flattened out at 75 days and 110 days, respectively. The curves for cadmium, arsenic, selenium, and chromium appear to begin to flatten out by 110 days. Because the total cumulative weight of these elements was not large, small releases caused a slight increase in the slope of the curves at that time.

Most of the elements reached steady percentages earlier than would be suggested by Figure 2-28 due to the increases over time being insignificant compared to the percentage of the element in the ash. Mercury, selenium, and silver showed higher percentages due to their disproportionally low concentration in the ash (two orders of magnitude less than chromium), which exaggerated very small cumulative changes. Also apparent on Table 2-8, the small percentages in the last column indicate that greater than 99.99% of these elements were retained in the ash after 173 days.

Figure 2-29 is the cumulative weight of selected elements in the runoff as a function of time. The cumulative weight was calculated by multiplying the concentration of runoff in weight per volume by the volume of runoff collected for that period. The resulting weight was added cumulatively to the weight of the element observed up to that period. Like the cumulative weight of elements in the leachate, the cumulative weight of the elements in the runoff tended to flatten out, particularly after 110 days.

2.4 Field Engineering Properties

Field tests were conducted on the MWC ash embankment in Pinellas County after construction in May 1996. Figure 2-30 shows that the combined ash embankment is holding its shape very well and no major signs of slope or surface degradation were visible during this visit. Double ring infiltration, cone penetrometer, field CBR and pressuremeter tests were performed after the environmental studies were completed in May 1997. The cone penetrometer and field CBR/LBR tests were conducted with the assistance of the Florida DOT State Materials Office.

Three double ring infiltrometer tests were performed (see Figure 2-31). The infiltration rate for the compacted MWC ash in the embankment was approximately 0.2 ft/day (0.06 m/day). Only one cone penetrometer test was done because of equipment difficulties.

Three field CBR tests and three pressuremeter tests were also performed. The results from these tests are listed in Table 2-9. The N values in Table 2-9 were derived from CPT relationships and were not field values.

The results of the cone penetrometer test with N values ranging from 31 to 87 indicate that the ash exhibits excellent performance in the unbound pavement layers, with respect to strength and deformation. The lower value, which occurred at the surface, resulted both from a lack of confining stress and desiccation of the top surface. The value at the base of the embankment was due to the softer sandy soil below the embankment.

The CBR tests results, which were lower than expected in comparison to the Qc cone penetrometer values, were most likely due to the fact that the embankment had not been compacted in 14 months and the surficial ash was unconfined and desiccated. The surface of the embankment was exposed to wetting and drying cycles and the CBR tests should have been performed at least six inches below the surface. However, CPT equipment problems during field testing prevented testing below the surface.

Elastic moduli from pressuremeter testing ranged from 9,000 to 75,000 psi (62-517 MPa), with an average of 32,200 psi (222 MPa). These values also indicate that the ash is an excellent base/subbase/subgrade material. The limit pressures (i.e., similar to ultimate soil strengths) were extremely high. Because they exceeded the limit of the pressure gages, they could not be accurately estimated. A conservative estimate of 300 psi or 22 tsf (2070 kPa) given in the table, indicates that the ultimate strength of the combined ash is comparable to very high strength base course material.

3. Geotechnical Properties of MWC Ash in Florida

The geotechnical properties studied for this investigation include moisture content, grain size distribution, moisture density, and CBR/LBR. These properties were previously studied using bottom ash, and the following results were obtained:

- The ranges of moisture content on bottom ash reported in investigations conducted at the Florida Institute of Technology yielded moisture contents from 10.6% to 26% (Wu, 1990; Nevin, 1991; Jain, 1992; Pandeline, 1994).
- Bottom ash classifies as well graded sand. Sieve analysis results on bottom ash yielded a coefficient of uniformity (C_U) value ranging from 4.6 to 13.7 and coefficient of curvature (C_C) value ranging from 1.1 to 1.80 (Wu, 1990; Nevin, 1991; Jain, 1992; Chavez, 1993).
- Dry unit weights (ASTM D-698) of mass burn bottom ash were 114.8 pcf for material passing the #4 sieve and 104.9 pcf passing the < #8 sieve. RDF bottom ash values were 98.0 pcf for material passing the < #4 sieve and 82 pcf for material passing the #8 sieve (Cosentino et al., 1995).
- The mass burn bottom ash and RDF bottom ash exhibited an unsoaked CBR (ASTM D-1557) value of 194 at moisture content of 13.5% for material passing the #4 sieve and an unsoaked CBR value of 80 at moisture content of 15.6%, respectively, for material passing the # 4 sieve (Pandeline, 1994).
- The LBR also measures the shearing resistance of a soil at controlled moisture and unit weight condition. LBR is used to evaluate limerock and other soils for base, stabilized subgrade, and subgrade in Florida. In Florida, limerock material used in construction of limerock base in Florida shall have an average LBR value of not less than 100 (FDOT, 1991).
- The mass burn bottom ash exhibited an unsoaked LBR (ASTM D-1557) value of 183 at moisture content of 13.5% on the wet side of optimum for material passing the #4 sieve. The RDF bottom ash exhibited an unsoaked LBR (ASTM D-1557) value of 92 at moisture content of 15.6% on the dry side of optimum for material passing the #4 sieve (Pandeline, 1994).

3.1 Physical Composition

The combined ashes used in this part of the investigation to evaluate the selected highway geotechnical properties were collected from 12 WTE facilities in Florida. The facilities that provided the combined ash are listed in Table 3-1 (Hinkley, 1996). Ash from the facility named "Ridge Generation Station" was not used in this study because it only combusts waste tires and waste wood to produce electricity; therefore, it is not included in the table.

In July 1996, the director of each of the 12 facilities listed in Table 3-1 was contacted and asked to provide samples of combined ash for this investigation. It was originally planned to have the ash sampled over a one week period, however, this was not possible to coordinate. Plant operators collected and shipped 4 to 5 five gallon buckets of combined ash to the Florida Institute of Technology, Melbourne, FL, between the last week of August and the last week of November 1996.

An applicable ASTM standard for analysis of the physical composition of the combined ash was not found. The procedure followed in this part of the investigation is described herein. A representative combined ash sample of one kilogram (1 kg) was chosen from each WTE facility for sieving using U. S. Standard sieves (1/2 in [12.5 mm], 3/8 in [9.5 mm], 1/4 in [6.3 mm], #4 [4.75 mm], #8 [2.36 mm]) after twenty four hours oven drying. The material retained on each sieve was visually sorted into the following categories, metals, glass, plastic, wood, paper, ceramic, and clinker. Two categories, which were not able to be visually sorted, were categorized as unclassified less than the #4 sieve but greater than the #8 sieve (referred to as unclassified > #8) and material passing the #8 sieve (referred to as unclassified < #8). Clinker was described as non-combustible materials, such as glass and metal, melted to form a glassy and weighty material.

The material retained on the #8 sieve was weighed, shaken for 18 hours in a water bottle to better identify the components, and then washed through a #100 sieve. Once washed, the material was oven dried for a twenty-four hour period, weighed again, and sorted visually. The materials lost due to washing and that remaining after sorting as unclassified < #8 sieve were added to obtain the weight of unclassified > #8 sieve category. Ferrous materials were identified using a magnet while non ferrous materials were sorted visually. Both metals (ferrous and non-ferrous) were added to get actual metal content. The percentage was calculated and summarized into the following categories: metal, glass, paper-wood-plastic (PWP), ceramic, clinker, unclassified < #8 sieve, and unclassified > #8 sieve.

The physical composition of the mass burn bottom ash from the Pinellas County Solid Waste Resource Recovery facility was reported to contain 48% clinker and miscellaneous, 32% metal, 16% glass, and 4% fines (Pandeline, 1994). The same analysis conducted on RDF bottom ash provided by the North County Regional Resource Recovery facility, showed 60% clinker and miscellaneous, 16% metals, 20% glass, and 4% fines.

MWC combined ash typically consists of a mixture of granular and fine grain materials and contains very small amounts of unburned paper and cloth. Some metal pieces could be visually identified as pieces of nails, wires, cans, and coins, while other pieces could not be identified. Broken pieces of glass were characterized by color as clear, brown, blue, and other. PWP were typically very small in quantity. The amount of ceramic pieces occupied a small portion of combined ash and could be visually identified among particles larger than the > # 8 sieve size. Clinker, mostly glassy and weighty materials consisting of melted glass, metal, and soil particles, could be visually identified. Unclassified materials less than the #4 sieve but greater than the # 8 sieve and unclassified materials passing the # 8 sieve could not be easily identified in composition.

The physical composition data of the MWC combined ash from each facility is presented in Appendix A. The physical composition of the MWC combined ash was categorized as metal, glass, paper, wood, plastic, ceramic, clinker, unclassified < # 8 sieve, and unclassified > # 8 sieve, and graphical presentation of the physical composition of the MWC ash for each facility is provided in Appendix B. The PWP quantities were combined due to their small amounts and their common ability to degrade with time for presentation and discussion purposes. The combined ash from four of the facilities (Pasco County, Lake County, Dade County, and Lee County) contained material greater than the # 3/4 in sieve size. The percentages by weight of materials greater than the #3/4 in sieve were 6%;, 24%;, 10%; and, 2%, respectively. The physical composition of combined ash from the 12 WTE facilities are summarized and presented in Table 3-2. The percentage of each component, along with the mean value and standard deviation for each component is given.

The mean values of each component, a Florida composite ash is presented in Figure 3-1. From this figure it can be concluded that a major component of MWC ash is unclassified materials. The metals, glass, ceramic, clinker, and PWP had a range of values and all had a large standard deviation.

The PWP content represents a low percentage of the combined ash and the only material that may biologically degrade. The major components that could change with time either biologically or chemically are metal and PWP. If the metals degrade, they would form oxides, which typically occupy a volume equivalent to the original volume of material. The PWP percentage is small, with a maximum of 4.4% and a mean of 1.18%. While these components could decrease with time, they should have a minimal effect on using the combined ash as a fill material.

3.2 Moisture Content

Moisture content tests were conducted in accordance with ASTM D 2216-80, "Laboratory Determination of Moisture Content of Soil, Rock, and Soil Aggregate Mixture" (ASTM, 1990). A thermostatically controlled, ventilated drying oven was used to dry all the samples at a temperature of 110 ± 5^0 C. Two samples were used to determine the average moisture content.

The moisture contents of the combined ash received from the 12 WTE facilities in 1996 are given in Table 3-3. The moisture content values ranged from 7-75%, with a mean value of 26% and a standard deviation of 20.

The method of ash collection at the facilities, (i.e., with or without free water) was not specified and resulted in excess free water in some of the ash samples delivered to the Florida Institute of Technology. The combined ash received with excess free water showed an expected higher moisture content, which is attributed to the quenching of the bottom ash in water after combustion of the MSW.

Since the method of ash collection was not specified, it is difficult to draw conclusions about the variability of the moisture content of the ash collected from the 12 facilities. Eight of the 12 facilities provided ash with a moisture content of 21% or less. Ash from these facilities (with a moisture content of 7-21%) could be used as highway fill materials. Since it is necessary to age the ash for a month, the moisture contents would reduce during the aging process.

3.3 Grain Size Distribution and Classification

The grain size distribution study of the combined ash was conducted in according with ASTM C 136-84a, " Standard Method for Sieve Analysis of Fine and Coarse Aggregate" (ASTM, 1990). A 2 kg sample of combined ash was oven dried at 110 ± 5^0 C for 24 hours before being sieved in a mechanical sieve shaker for 15 minutes. A series of U. S. standard sieves were used: 1 in (25.4 mm), 3/4 in (19 mm), 1/2 in (12.5 mm), 3/8 in (9.5 mm), 1/4 in (6.3 mm), #4 (4.75 mm), #8 (2.36 mm), #16 (1.18 mm), #30 (0.60 mm), #60 (0.25 mm), #100 (0.15 mm), #200 (0.08 mm), #325 (0.05 mm).

The variability of the grain size curves of combined ash from the 12 WTE facilities is shown in Figure 3-2. The uniformity coefficient, coefficient of curvature, and fineness modulus values, USCS, and AASHTO classifications are summarized in Table 3-4 for each combined ash sample from the 12 WTE facilities. Individual grain size curves for each facility, along with D_{10}, D_{30}, and D_{60} values are provided in Appendix C and show variation from facility to facility. The combined ash from any of the 12 WTE facilities would be classified as a coarse grained soil. The uniformity coefficient (C_u) values ranged between 7.1 to 45, and the values of the range of coefficient of curvature (C_c) values ranged between 0.4 to 11.4. Fineness modulus (F. M.) values ranged between 4 to 6.3.

The MWC combined ashes from Florida were classified as well graded and poorly graded sand, with group symbols SW and SP, respectively (Unified Soil Classification System [USCS]). Some of the combined ashes were identified as poorly graded sand because the coefficient of curvature (C_c) values were either less than 1 or greater than 3. However, the (C_u) coefficient of uniformity values for ash from any of the facilities exceeded the requirements for a well graded sandy soil. Because the fines were non plastic materials the combined ashes would be classified as A-1-a (granular materials) and group indices 0 (zero), (AASHTO M 145-87 Soil Classification System). The ash was found to be free of oversize materials or paper, wood or plastics that could degrade. Based on USCS and AASHTO soil classification, it can be concluded that ashes from the 12 WTE facilities in Florida have potential for use as fill materials.

3.4 Moisture Density

Moisture density relationships were determined for the combined ash by using ASTM D 698-78, method C or method D, "Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures using 5.5 lb (2.49 kg) Rammer and 12 in (305 mm) Drop." Method C was used if less than 10% combined ash was retained on the 3/4 in (19.0 mm) sieve, while Method D was used when 10% or greater amount of combined ash was retained on 3/4 in (19.0 mm) sieve. The combined ash needed for moisture density and CBR/LBR testing, (approximately 2 buckets) was allowed to air dry for 48-72 hours. The ash was sieved through a # 3/4 inch sieve. The combined ash was thoroughly mixed and samples were taken for moisture content determination. If the average moisture content of the air dried ash was 12% or less, samples were prepared for moisture density and CBR/LBR testing. The combined ash was then separated into five plastic storage bags for making moisture density samples. Five specimens were fabricated using ash from each facility at varying moisture contents according to either Method C or Method D.

Samples of 5.25 kg combined ash for each facility were mixed and stored in plastic bags after adding increasing amounts of water to each sample. The moisture contents were selected to vary from sample to sample by approximately 1.5%. Twenty-four hours were allowed for absorption and distribution of the water among particles. The desired moisture content ranges for testing were 12%, 13.5%, 15%, 16.5%, and 18%. The samples were remixed prior to compaction.

Based on both the grain size of the combined ash and the ASTM recommendations, a 6 in compaction mold was chosen. Compaction was conducted in three layers using a manually operated 5.5 lb (2.49 kg) rammer with a 12 in (304.8 mm) free fall. Each layer received 56 blows with the third compaction layer as close as possible to the top of the mold to follow the intent of the test criteria. The compacted specimens were carefully trimmed and patched with smaller particles to fill any large voids produced by removal of coarse particles during trimming. The mold and compacted combined ash were then weighed.

Since the same samples would also be used for determining the CBR, representative samples greater than 500 g were taken for moisture content determination after completion of the CBR testing.

The moisture content versus dry unit weight relationship for the combined ash from each of the 12 WTE facilities is presented in Appendix D. The shape of the compaction curves are similar to the parabolic Type A compaction curve for conventional soils as found in typical laboratory investigation (Winterkorn et al., 1975).

The significant parameters of optimum moisture content (OMC) and maximum dry unit weight (γ_{dry}) are tabulated in Table 3-5. The moisture density data of the combined ash from the 12 Florida WTE facilities are presented in Appendix E. The maximum dry unit weight of the combined ash ranged from 11.6 kN/m^3 to 17.53 kN/m^3 (74.0 pcf to 111.7 pcf), with the corresponding OMCs ranging from 13.7-17.8%. The highest maximum dry unit weight occurred with combined ash from the Lake County Resource Recovery facility. This ash contained the highest percentage of metal and clinker and had the highest fineness modulus (F. M.) with only 1% of the combined ash retained on a #200 sieve. The lowest maximum dry unit weight occurred with combined ash from the Bay County Resource Recovery facility. This ash contained the lowest percentage of metal and clinker and had the lowest F. M., with 3% of the combined ash retained on a #200 sieve.

The effect of grain size distribution on the moisture density relationship can be clearly observed from Figures 3-3 and 3-4. As the grain size distribution curve shifts to the right, which yields a decrease in the F.M. the compacted dry unit weight decreases. Thus, the F.M. may be used as a preliminary indicator of the maximum dry unit weight of the compacted ash.

3.5 California Bearing Ratio/Limerock Bearing Ratio

California bearing ratio tests were conducted on each of the five specimens prepared for the moisture density relationship test. These tests were performed in accordance with ASTM D 1883-73 (reapproved 1978), "Standard Test Method for Bearing Ratio of Laboratory Compacted Soils" using the compactive energy as described in ASTM D 698 -78 (ASTM, 1987).

A surcharge of 15 lb (6.82 kg) was applied to the sample to produce an intensity of loading equal to the weight of the base material and pavement within 5 lb (2.27 kg) but not less than 10 lb (4.54 kg). The penetration piston was initially seated with a load of less than 10 lb (4.55 kg) (which is considered a zero loading) before starting the actual loading test on each of the specimens. The piston penetration rate was 0.05 in (1.27 mm)/min. The load readings were taken at penetrations of 0.025 in (0.64 mm), 0.050 in (1.27 mm), 0.075 in (1.91 mm), 0.100 in (2.54 mm), 0.125 in (3.18 mm), 0.150 in (3.81 mm), 0.175 in (4.45 mm), 0.200 in (5.08 mm), 0.300 in (7.62 mm), 0.400 in (10.16 mm), and 0.500 in (12.70 mm). The LBR value was obtained by dividing the value of corrected stress at 0.1 in deflection of the CBR test by the standard load of 800 psi of crushed limerock and multiplying by 100.

The unsoaked CBR and LBR values of the combined ash passing the #3/4 in sieve from the 12 WTE facilities are summarized in Appendix E. A graphical presentation of CBR and LBR values as a function of moisture content is provided in Appendix D, along with the corresponding moisture density relationship curves. The CBR/LBR values associated with the respective maximum dry unit weight and the maximum CBR/LBR values for each ash were tabulated and are presented in Table 3-5. Results from 10 of the 12 plants indicated that the maximum LBR and CBR values occured either at OMC or dry of OMC.

The combined ash yielded CBR values ranging from 32 to 64, which are suitable values for base and subbase beneath pavements of roads and airfields. The Lake County Resource Recovery facility and the Pinellas County Solid Waste Resource Recovery facility combined ashes showed CBR values greater than 50. Combined ash with a CBR value ranging from 20 to 50 is applicable for use as base and subbase. Combined ashes with CBR values greater than 50 are excellent for use as bases beneath pavements of roads and airfields for soil classified as SW or SP (USCS) (Bowles, 1986). The CBR values of combined ash are sensitive to the compaction moisture content. The combined ash exhibited lower CBR values on the wet side of OMC than the dry side. Generally the CBR value was lower on the wet side than the CBR value at OMC, except for the ash from two facilities.

The LBR values of combined ash ranged between 35 to 62. The LBR values on the dry sides of OMC were greater than the LBR values on the wet sides. LBR values are greater than CBR values of combined ashes from the 12 WTE facilities. However, they did not meet FDOT specifications for use as base materials of roads (LBR values primarily used for limerock materials in Florida require a value greater than 100 [FDOT, 1991]).

3.6 Empirical Relationships

One task in this investigation was to determine the suitability of Florida-produced MWC combined ash for use as a highway fill. To evaluate these ashes usability of these empirical relationships between the physical properties and the geotechnical properties of the ash were examined. Table 3-6 lists the various properties that were examined and presents the sample correlation coefficients (r) for each relationship. In the analysis, only linear relationships were considered.

The value of r is independent of the units in which the parameter on the X and Y axes are measured. The sample correlation is considered weak if $0 \leq | r | \leq 0.5$, moderate if $0.5 < | r | < 0.8$, and strong if $0.8 \leq | r | \leq 1$. The square of the sample correlation coefficient (r^2) implies that the percentage of the observed Y axis value can be explained by the sample correlation model in a regression of Y axis value on X axis value (Devore, 1987).

The empirical relationships shown in Table 3-6 yield some strong, moderate, and weak values of the correlation coefficient between physical properties and engineering properties. The empirical relationships between physical properties and CBR/LBR, and between two different physical properties of the ash, are weak and will not be discussed. Strong and moderate empirical relationships between different engineering properties are presented and will be discussed. All correlation coefficients are tabulated in Table 3-6.

Based on the behavior of combined ashes, the fineness modulus versus maximum dry unit weight was plotted and is presented in Figure 3-5. A strong sample correlation ($r = 0.8$) existed between those variables; the F.M. increased linearly with an increase in the maximum dry unit weight. A $r^2 = 0.6122$ values implies that 61% of the maximum dry unit weight values followed this strong relationship, showing the influence of larger grain size material in the ash on the maximum dry unit weight for ash classified as sand size.

The relationship between maximum dry unit weight versus percent finer than # 8 sieve is plotted in Figure 3-6. The sample correlation coefficient value of $r = 0.8$ signifies a strong relationship, with 63% of maximum dry unit weight values following this strong relationship. Figure 3-6 shows that as the percent of ash finer than # 8 sieve increased, there was a linear decrease in the maximum dry unit weight.

The grain size (D_{60}) of the ash versus maximum dry unit weight relationship is plotted in Figure 3-7. The sample correlation coefficient value of r = 0.8 signifies a strong relationship, with 57% of maximum dry unit weight values following this strong relationship. Figure 3-7 shows that as the grain size (D_{60}) of the ash increased, there was a linear increase in the maximum dry unit weight.

CBR values at OMC for the combined ash are plotted as a function of the maximum dry unit weight of the ash and are shown in Figure 3-8. The sample correlation coefficient (r) value of maximum dry unit weight versus the corresponding CBR values of combined ash from 12 WTE facilities was 0.74 and exhibiting a moderate relationship.

All dry unit weights versus all CBR values of combined ash from 12 Florida WTE facilities were plotted and are shown in Figure 3-9. The sample correlation coefficient (r) value was 0.74, exhibiting a moderate relationship. As would be expected in conventional soils, as the maximum dry unit weight increased, there was an increase in the CBR values of the compacted MWC combined ash.

4. Conclusions

The following conclusions on the suitability of MWC combined ash for use as highway fill material were found as a result of this investigation:

- Combined ash can be used as highway fill using conventional construction equipment and methods.

- The percent of the eight elements in the ash lost to leachate or runoff after one year of exposure to natural rainfall was determined to be less than 0.01% and 0.005%, respectively, of their original weight. This indicates that greater then 99.99% of each of the eight elements was retained in the ash.

- The largest concentrations of soluble salts were removed from the combined ash in the first 110 days, though soluble salts continued to be removed to a lesser extent after that point. Toxicity limits were not exceeded or approached for any of the eight elements in the leachate or runoff during the first six months. Drinking water standards were not exceeded for any of the eight metals in the leachate except for an initial peak of selenium (0.13 mg/l), which slightly exceeded the drinking water standard (0.10 mg/l). Drinking water standards were not exceeded by any of the eight elements in the runoff. Concentrations of all eight elements in the leachate and runoff generally decreased as a function of time. Concentrations of Ag, Cd, Hg, and Pb in the leachate and runoff approximated or were less than the rainwater concentrations at 140 days of elapsed time.

- Ba, Cd, Cr, and Pb were predominantly in dissolved form in the leachate of the combined ash. In the runoff, Ba was predominately in dissolved form and Cd, Cr, and Pb were predominantly in particulate form. Rapid dissolution or washout were the major mechanisms of barium transport in both the leachate and runoff. Particulate transport was the major mechanism of transport of Cd, Cr, and Pb in the runoff. Leaching, dissolution, or displacement of pore water volume were the major mechanisms of transport of Cd, Cr, and Pb in the leachate.

- The combined ash from any of the 12 Florida WTE facilities would be classified as either a well graded or a poorly graded sand. The ash was found to be free of oversize materials or paper, wood or plastic that could degrade.

- The moisture density relationships of combined ash were similar to conventional soil. The moisture content affects the magnitude of the dry unit weight of combined ash.

- The grain size distribution curve of combined ash indicated some variation from facility to facility. Maximum dry unit weight (ASTM D -698-78) of the combined ash increased linearly as the fineness modulus of the combined ash increased.

- The maximum dry unit weight (ASTM D-698-78) of the combined ash increased linearly as the D_{60} grain size of the combined ash increased.

- The CBR values of the combined ash increased linearly as the maximum dry unit weight of the combined ash increased. Based on typical CBR values for compacted soil, the combined ash from any of 12 Florida WTE facilities could be used as base and subbase materials

5. Recommendations

Combined ash was found to be acceptable for use as highway fill material. It is, therefore, recommended that the proposed specification in Section 6 of this report be adopted by Florida DOT for incorporation into "Standard Specifications for Roads and Bridge Construction." The Florida DOT should coordinate a joint effort with the Florida Department of Environmental Protection to ensure that the State of Florida can develop MWC reuse procedures.

6. Developmental Specifications for using MWC Combined 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" (1996) from the Florida Department of Transportation. Section number 180 was developed such that any new specification for use of waste materials can be added at the end of the section as it is approved.

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 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 Ash.

180-2.1 Composition: Ash shall consist of the solid material remaining after combustion of municipal solid waste at a Department of Environmental Protection (DEP) approved Waste-to-Energy plant. The facility shall process the solid waste for metals recovery (using the best available technology) before combustion, or process the ash for metals recovery after combustion.

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

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

180-2.4 Furnishing and Stockpiling: All ash shall be furnished for a specific project from one facility. The 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 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 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 12 inches of topsoil over the 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 ash shall be coated with a bitumen or rubberized compound or separated with an inert borrow.

180-2.7.4 *Water table:* Ash shall be placed at a minimum of 12 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.

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Project	Max. Particle size Ash % in mix	Site Used	Monitoring Activities
FHWA, 1974 Houston	1 in 100% ash	Road base, 6 in, 200 ft of access roadway	Engineering performance
FHWA, 1977 Houston	1 in 70% ash	Road base, 4.5 in, 400 ft to residential street	Engineering performance
RESCO, 1980 Lynn, MA	1 in 60% ash	Three binder courses, 3/4 mile of Route 129	Engineering performance (4 years)
Los Angeles 1990 pilot (1991 full size)	2 in ash 12% PC with fly ash 15% water added to treated mix	Subbase for landfilled roads	California WET test, Engineering performance

Table 1-1 Combined ash used in road base and subbase structures. (PC = Portland Cement) (Chesner, 1993)

Project	Max. Particle size Ash % in mix	Site used	Monitoring Activities
FHWA, 1975 Delaware County, PA	1/2 in 50% ash	60 ft entrance road 1.5 in	Engineering performance
FHWA, 1975 Philadelphia, PA	5/8 in 50% ash	108 ft pavement 1.5 in	Engineering performance
FHWA, 1975 Harrisburg, PA	1/2 in 50% ash	260 ft of Wayne Street 1.5 in	Engineering performance
FHWA, 1976 Harrisburg, PA	1/2 in 100% ash	180 ft of Route 22, 1.5 in	Engineering performance
RESCO, 1980 Lynn, MA	1 in 50% ash	750 ft of Route 129	Engineering performance
Tampa, FL 1987	McKaynite aggregate, 5, 10, 15%	Three 250 ft sections	Engineering performance, runoff
Tampa, FL 1987	McKaynite aggregate, 15% blend	1/4 acre surface, 4 in	Ground water leachate

Table 1-2 Field tests of municipal waste combustor combined ash in surface asphalt (Chesner, 1993)

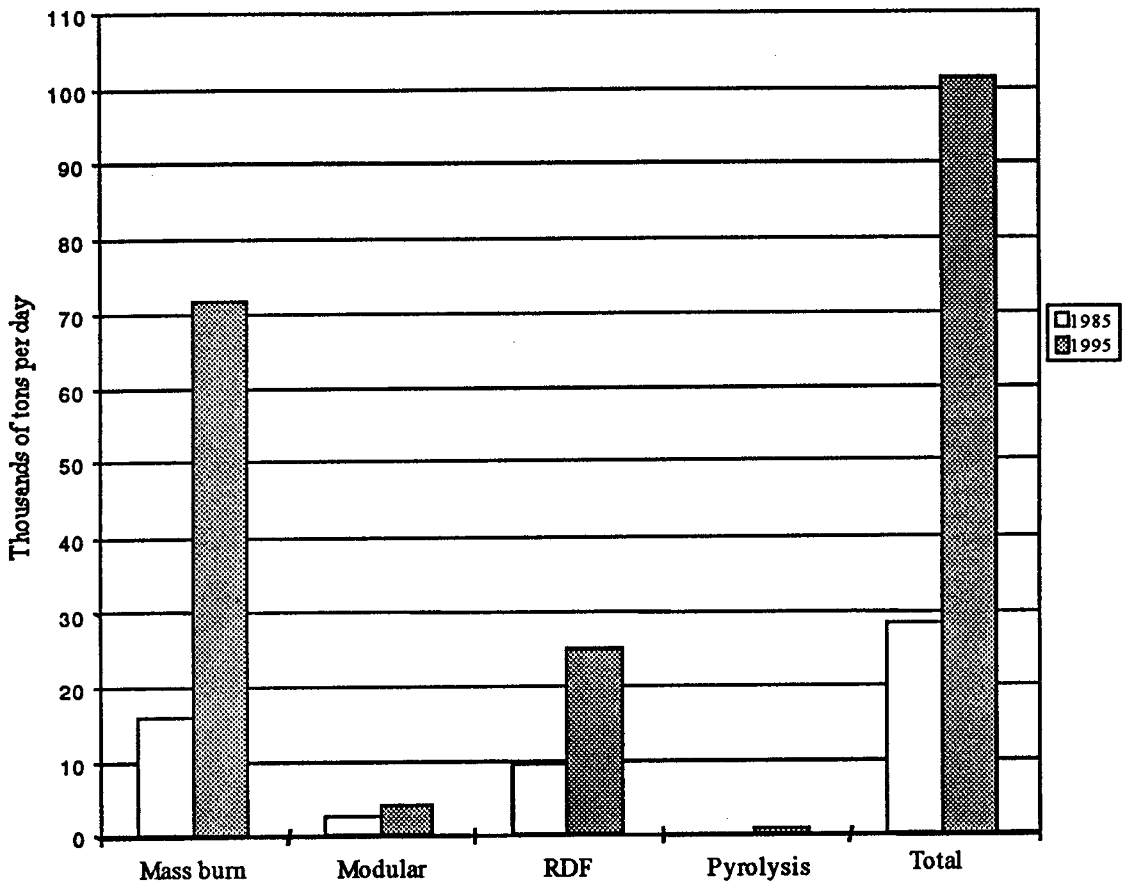


Figure 1-1 Total waste-to-energy capacity by process type, 1985 and 1995 (Carlin, 1995)

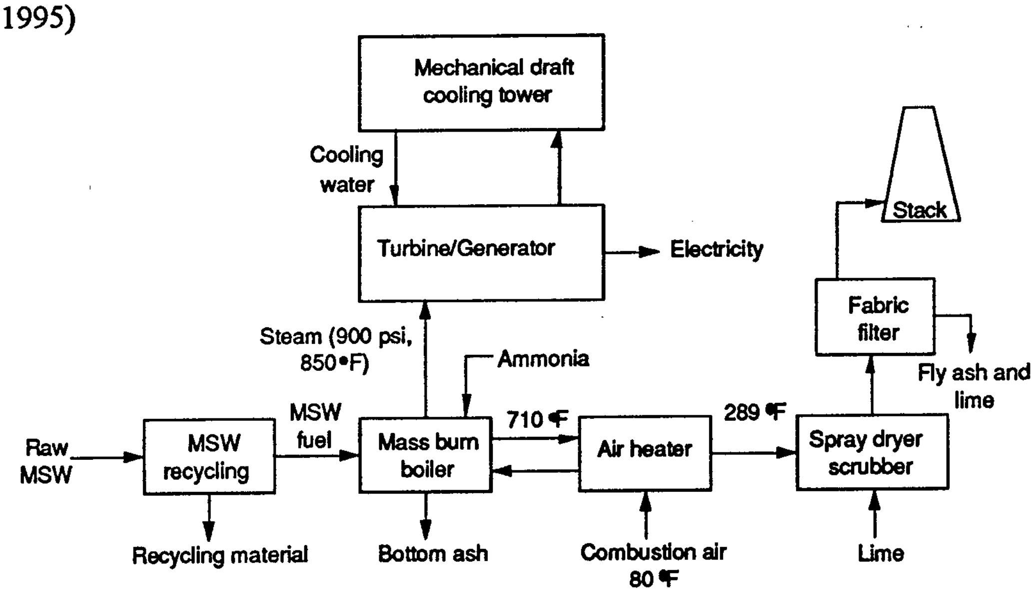


Figure 1-2 Schematic of a typical municipal solid waste mass burn boiler power plant. (Carlin, 1995)

Figure 2-1 Ash stockpile adjacent to the embankment construction site

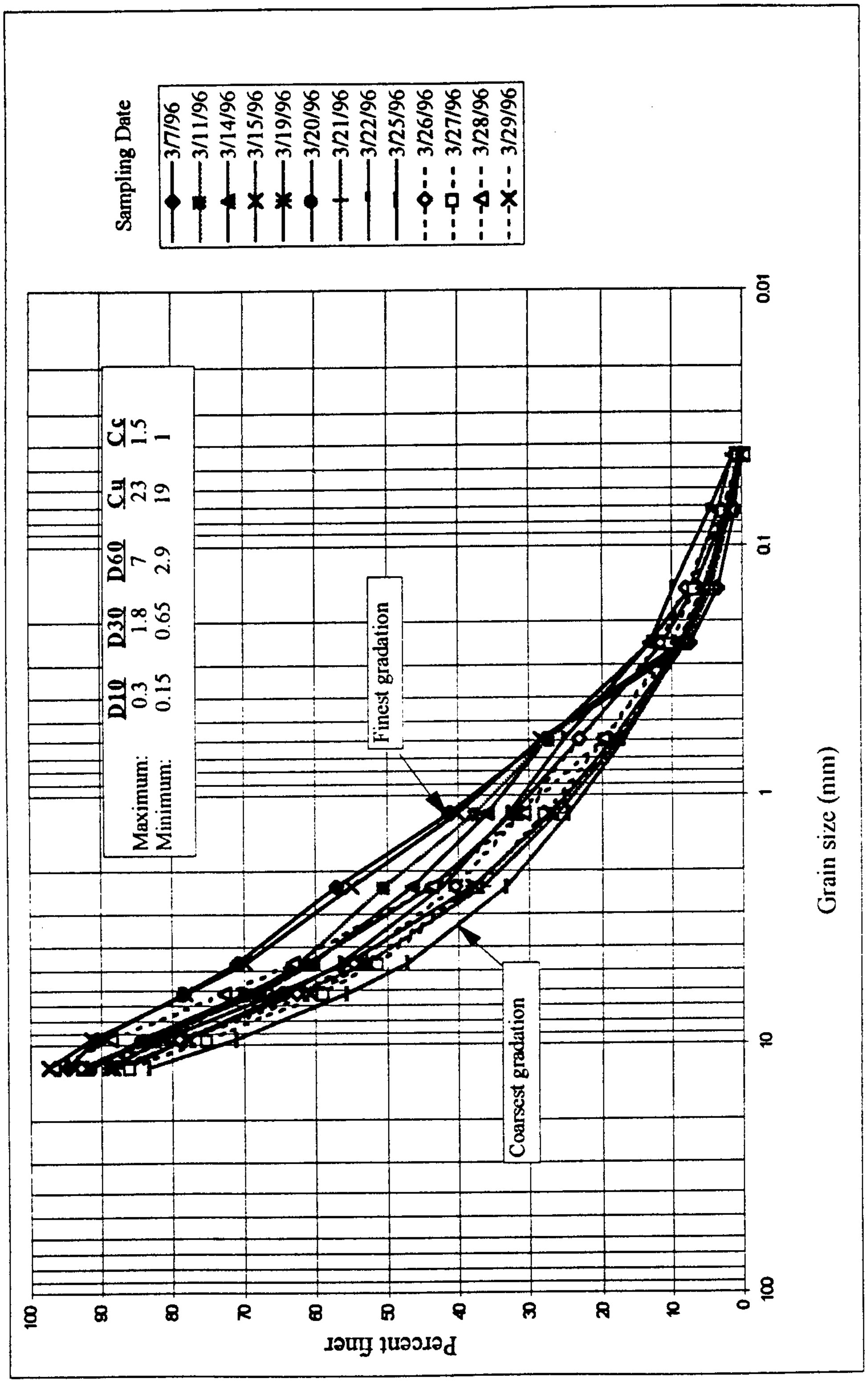


Figure 2-2 Grain size distribution of MWC combined ash for the embankment at various sampling dates

Sample date	Cc	Cu
Mar-7	0.5	10.0
Mar-11	1.1	17.6
Mar-14	1.4	21.0
Mar-15	0.5	11.1
Mar-19	1.5	20.4
Mar-21	1.0	20.5
Mar-22	1.4	20.0
Mar-25	1.0	36.7
Mar-26	1.5	23.3
Mar-27	1.3	28.0
Mar-28	1.2	26.0
Mar-29	1.5	24.0
Mean	1.2	21.5
Standard deviation	0.4	7.2

Table 2-1 Coefficients of curvature and uniformity of the combined ash for the 13 days

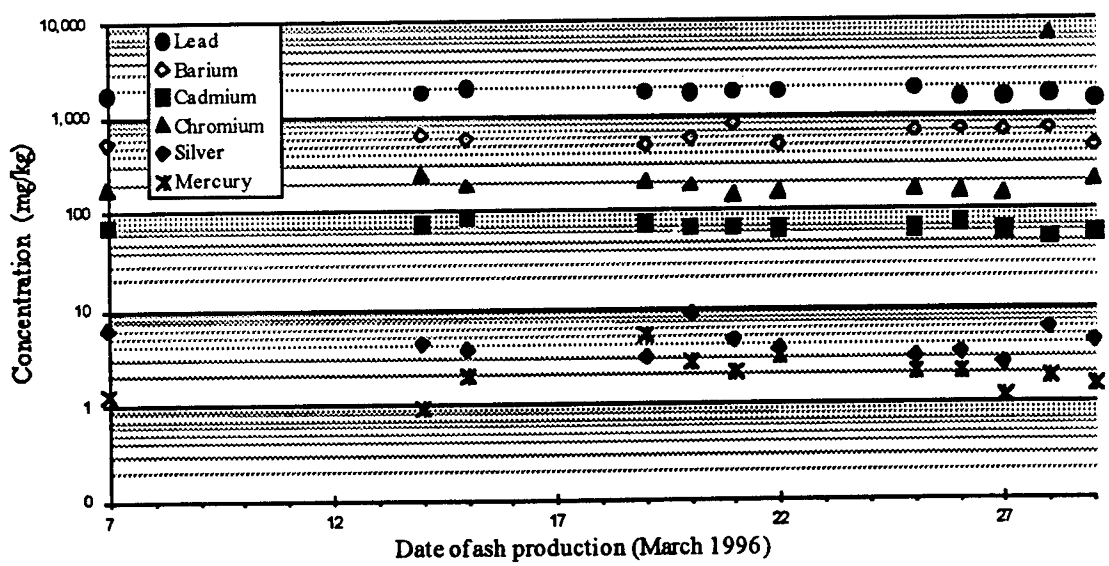


Figure 2-3 Concentration of selected elements in combined ash determined by ICP-MS as a function of the day produced

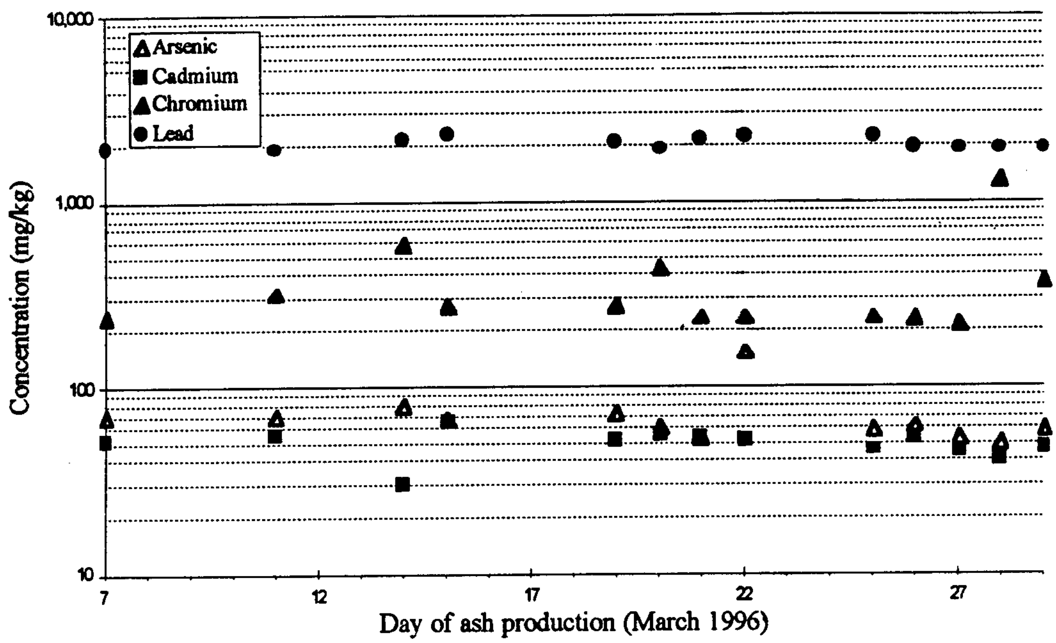


Figure 2-4 Concentration of selected elements in combined ash determined by AAGF as a function of the day produced

Element	Fly Ash	Bottom Ash	Combined Ash	Soil
Arsenic	269 - 355	47.2 - 52.0	48.6 - 57.0	6
Barium	< 700	710 - 720	1090 - 1120	500
Cadmium	246 - 266	47.6 - 65.5	39.9 - 49.2	0.06
Chromium	146 - 169	623 - 807	325 - 416	100
Lead	3200 - 4320	2090 - 2890	1850 -2490	10
Mercury	59.1-65.0	9.1-9.7	15.7-17.0	0.03
Selenium	6.7 - 11.2	< 2.52	< 2.36	0.2
Silver	46.1 - 55.3	17.5 - 28.5	10.1 - 12.1	0.1

Table 2-2 Elemental abundances in typical municipal waste combustion fly, bottom, combined ash, and soil in mg/kg (ppm) unless indicated by % (Buchholz, 1995)

Element	Average Ash Concentration (mg/kg)	Total Weight in leachate area (g)	Primary Analysis Instrument
Arsenic	70 ± 27	2,450	AAGF
Barium	609 ± 104	213,450	ICP-MS
Cadmium	68 ± 10	2,390	ICP-MS
Chromium	752 ± 1,990	26,340	ICP-MS
Lead	1,710 ± 160	59,880	ICP-MS
Mercury	2.17 ± 1.13	76	ICP-MS
Selenium	< 3	100	AAGF
Silver	4.38 ± 1.68	150	ICP-MS

± represents Standard deviation, N=13

Table 2-3 Average concentrations of selected elements in the combined ash used in the ash embankment

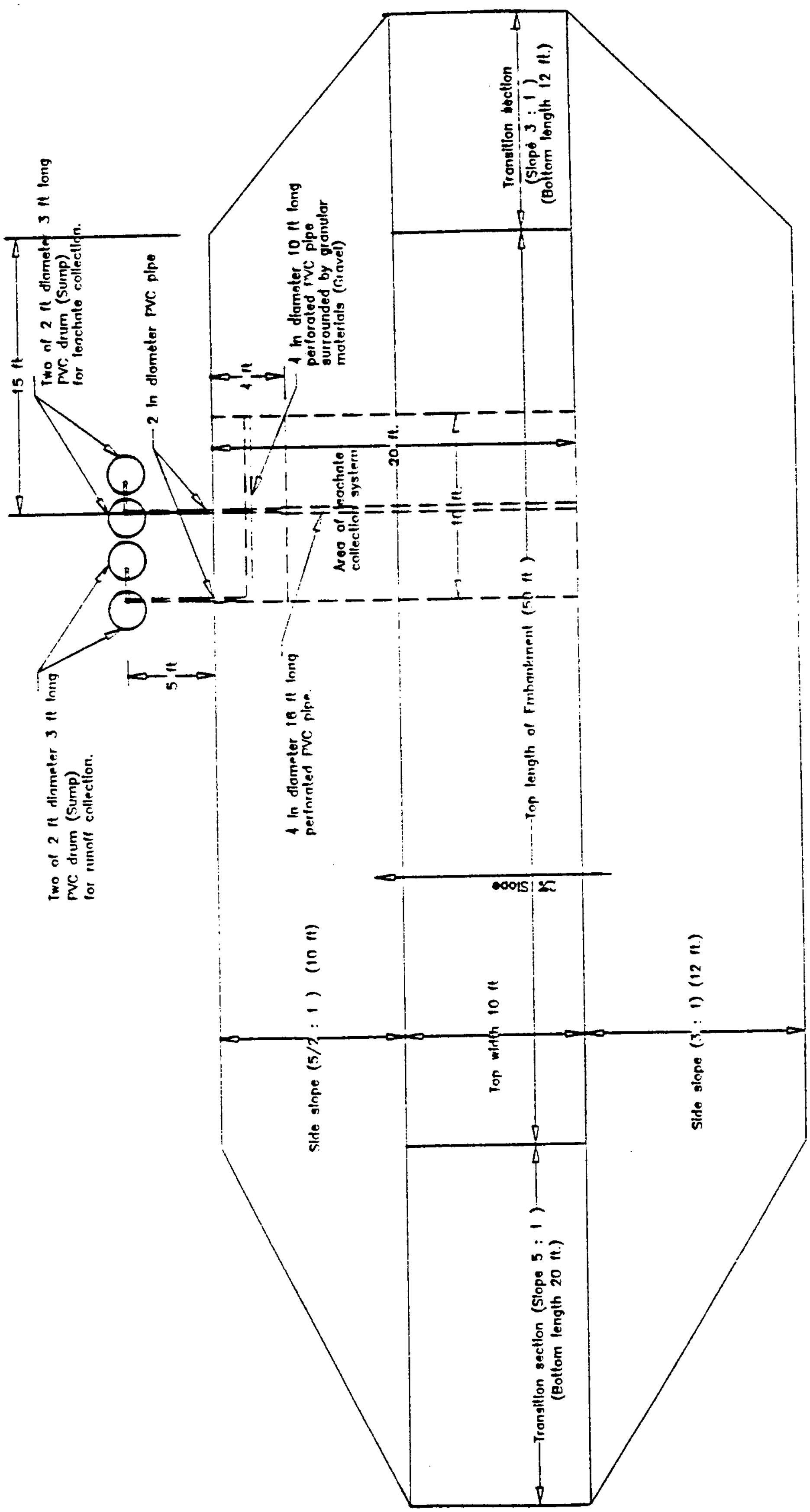


Figure 2-5 Plan view of MWC combined ash embankment

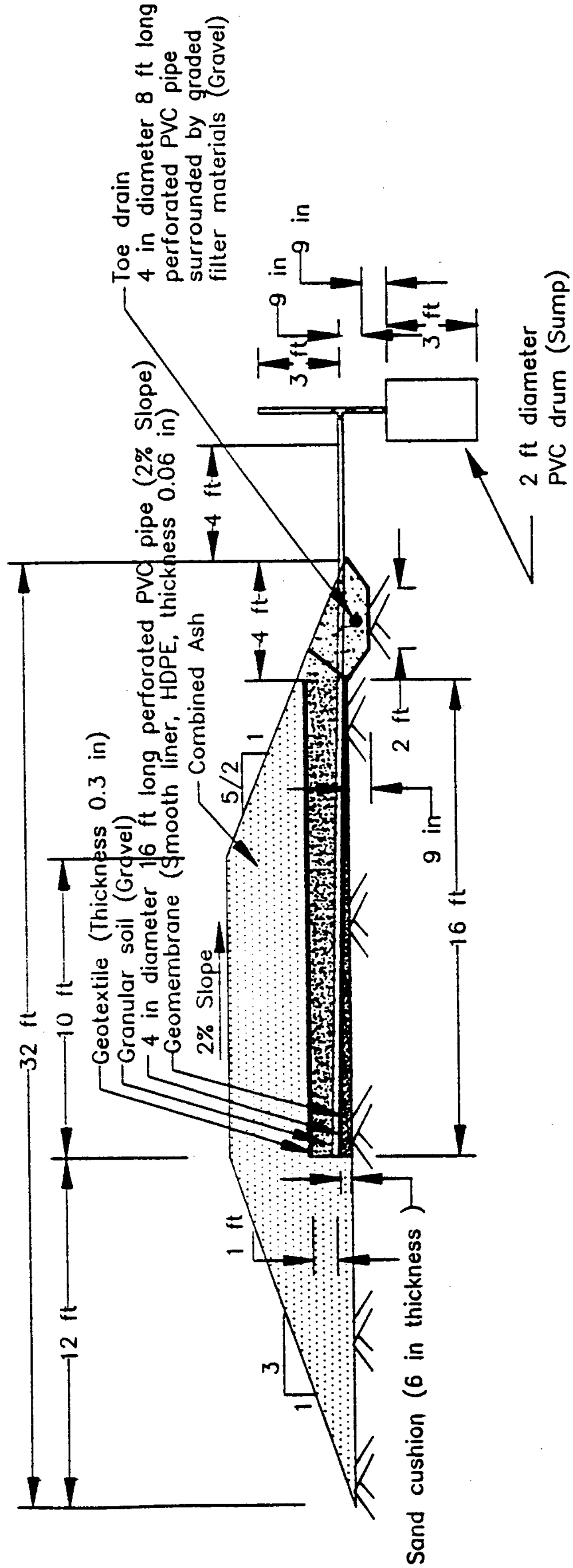


Figure 2-6 Typical embankment cross-section

Figure 2-7 Embankment base outline marked with lime

Figure 2-8 Front-end loader used to spread ash during construction

Figure 2-9 Vibrating smooth wheel roller used for compaction

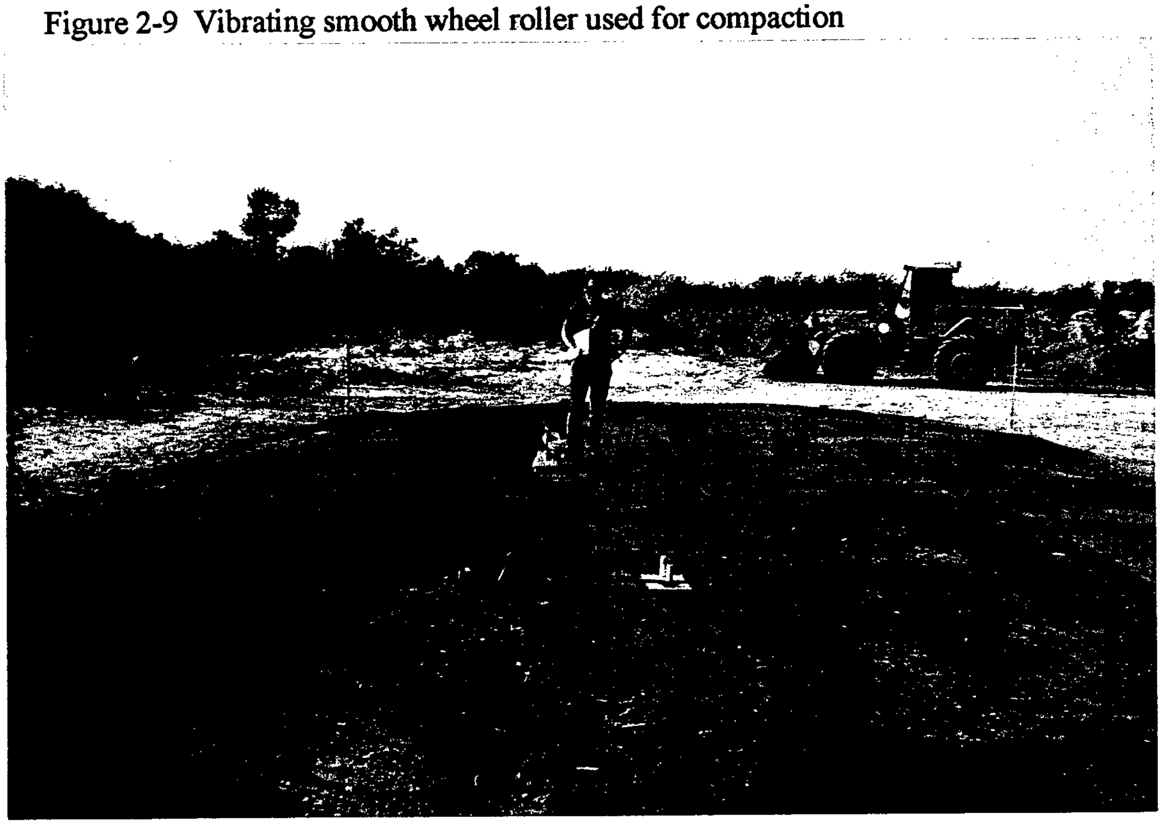


Figure 2-10 Troxler nuclear density meter for field densities and moisture contents

Lift number	Date	Test location	Number of passes	Dry Density		Moisture content	Relative compaction
				(kN/m³)	(lb/ft³)	(%)	(%)
1	5/14/96	North	12	16.37	104.1	7	90
1	5/14/96	Center	12	17.69	112.5	10	97
1	5/14/96	South	12	18.39	117.0	8.5	> 100
1	5/14/96	North	17	17.64	112.2	9.5	97
1	5/14/96	Center	17	17.97	114.3	8.3	99
1	5/14/96	South	17	18.77	119.4	7.5	> 100
2	5/15/96	North	12	19.07	121.3	9.3	> 100
2	5/15/96	Center	12	19.54	124.3	8.2	> 100
2	5/15/96	South	12	18.32	116.5	8.9	> 100
3	5/15/96	North	10	19.23	122.3	5.4	> 100
3	5/15/96	Center	10	19.24	122.4	7.2	> 100
3	5/15/96	South	10	18.68	118.8	6.1	> 100
4	5/15/96	North	10	18.16	115.5	8.2	> 100
4	5/15/96	Center	10	18.98	120.7	8.2	> 100
4	5/15/96	South	10	19.13	121.7	8.4	> 100
5	5/16/96	North	10	18.99	120.8	7.7	> 100
5	5/16/96	Center	10	18.71	119.0	7.6	> 100
5	5/16/96	South	10	18.46	117.4	9.0	> 100
6	5/16/96	North	10	18.50	117.7	8.5	> 100
6	5/16/96	Center	10	18.38	116.9	7.5	> 100
6	5/16/96	South	10	18.68	118.8	7.4	> 100
7	5/17/96	North	10	18.74	119.2	7.8	> 100
7	5/17/96	Center	10	18.47	117.5	7.2	> 100
7	5/17/96	South	10	18.90	120.2	8.1	> 100
8	5/17/96	North	10	18.57	118.1	7.2	> 100
8	5/17/96	Center	10	18.60	118.3	6.4	> 100
8	5/17/96	South	10	19.26	122.5	7.3	> 100

AASHTO T-99 Maximum Dry Density =18.2 kN/cu m (116 lb/cu ft)

Loose Lift Thickness: 15 cm (6 inches)

Compaction Equipment: Ingersoll Rand, 5 ton / 54 inch / single smooth vibratory roller

Moisture Density Field Measurements: Troxler nuclear density meter using 5 inch probe depth for first lift and 6 inch probe depth for the remaining seven lifts

Table 2-4 Field lift densities for the combined ash embankment

Sample Number	Oven Moisture (%)	20 gram Speedy (%)	26 gram Speedy (%)
1	11.9	14.9	16.0
2a	13.2	18.5	17.4
2b	12.7	15.2	14.7
3a	14.3	20.0	19.6
3b	15.0	16.8	15.7
4a	15.8	19.0	17.6
4b	16.2	18.7	16.3
5a	16.0	17.6	17.1
5b	18.2	18.2	16.8
6a	20.3	19.6	18.5
6b	19.7	20.2	19.6

Table 2-5 Results from the Speedy moisture study for combined ash

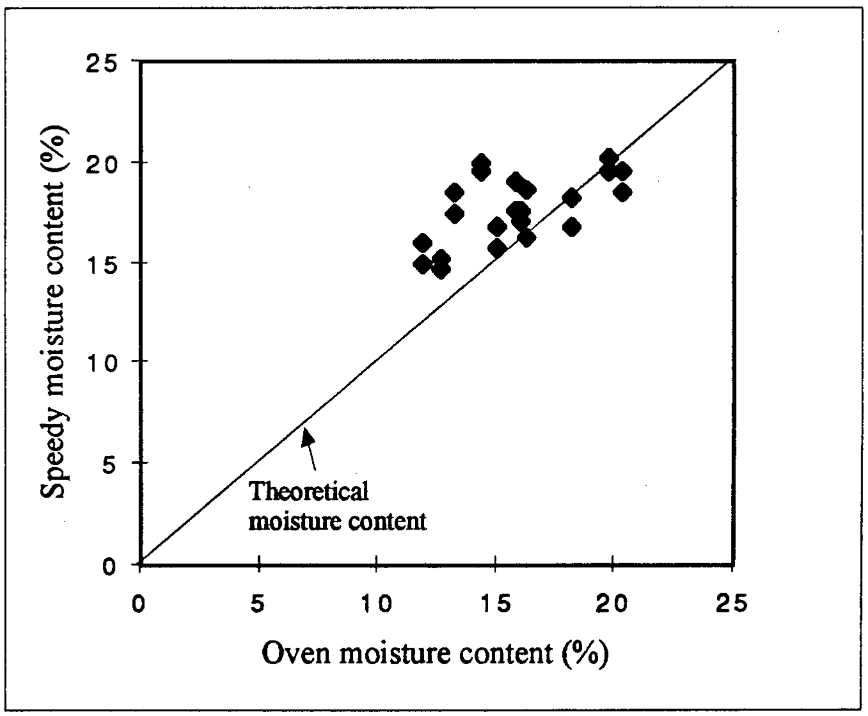


Figure 2-11 Oven moisture contents versus Speedy moisture contents for the MWC combined ash

Figure 2-12 Combined ash over the geotextile in the leachate collection section

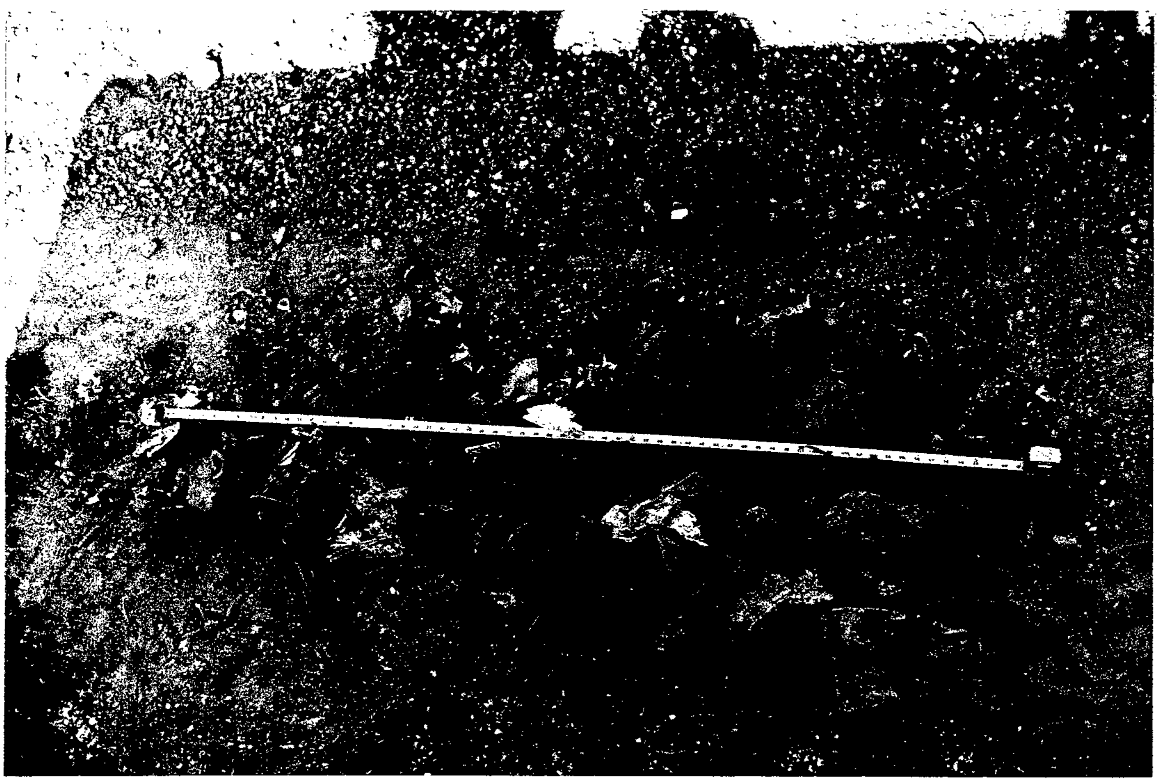


Figure 2-13 Pieces of rubber, plastics, fabric, metal etc. in the MWC ash

Figure 2-14 Leachate and runoff collection drums in the trench next to the embankment edge

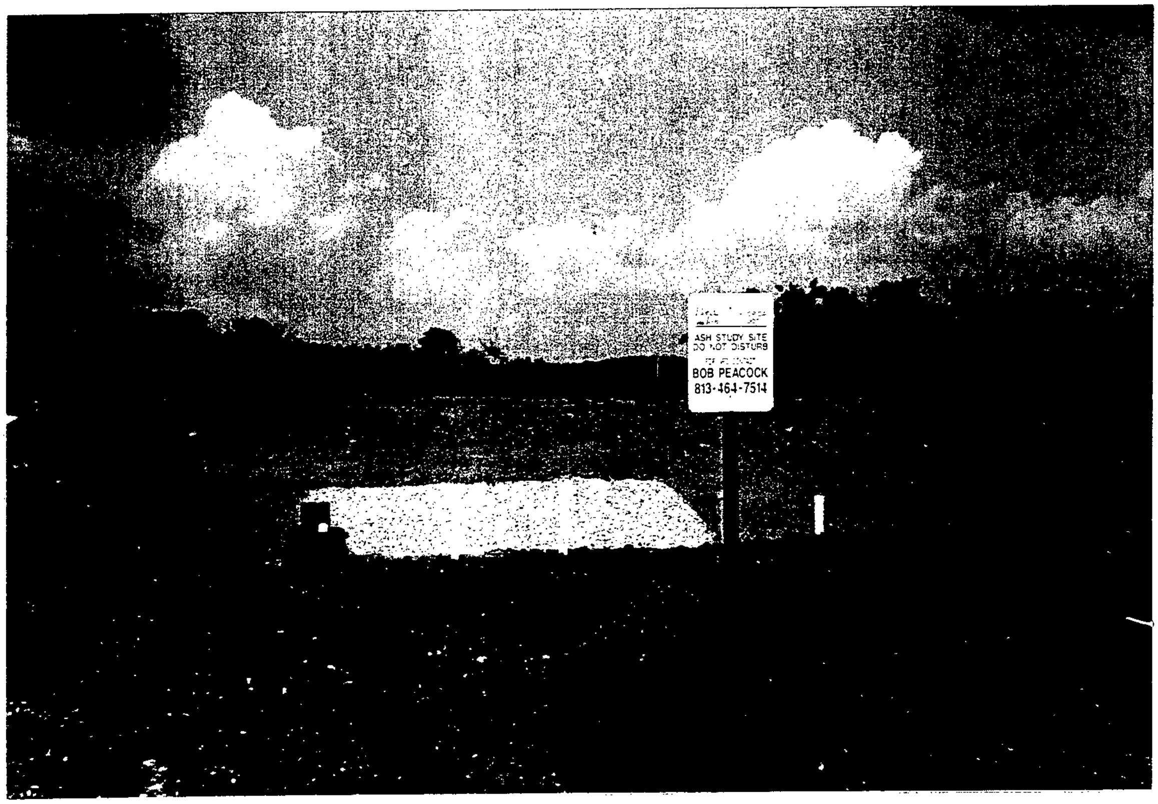


Figure 2-15 Finished combined ash embankment

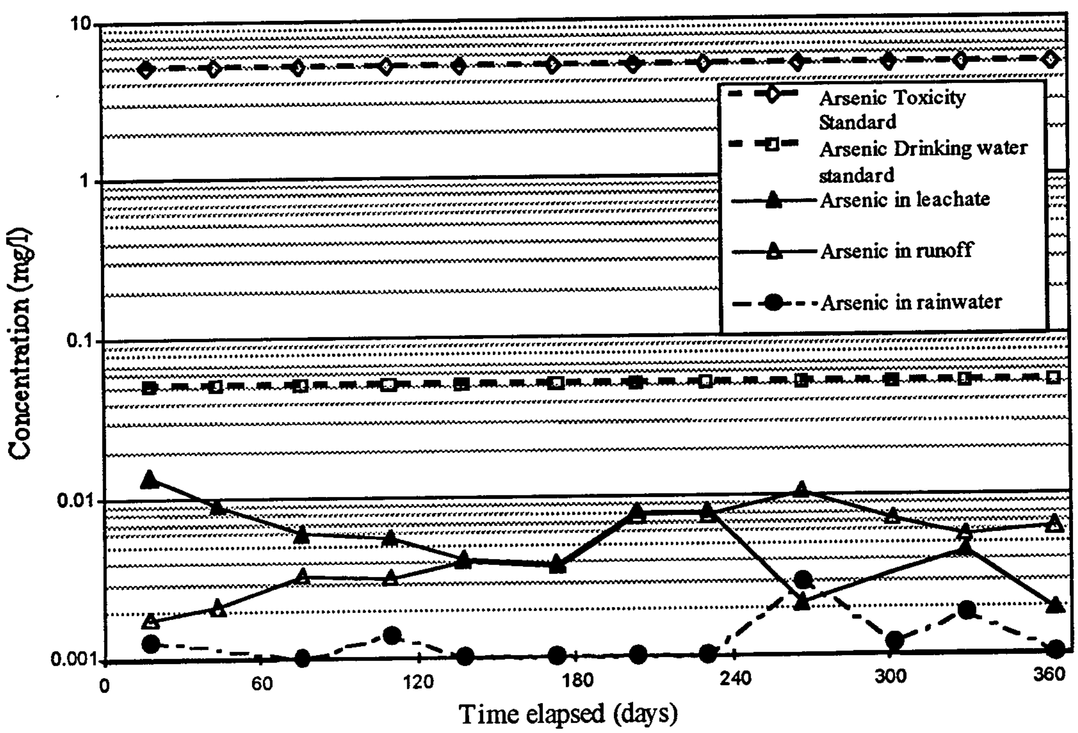


Figure 2-16 Arsenic concentrations in leachate, runoff, and rainwater as a function of time

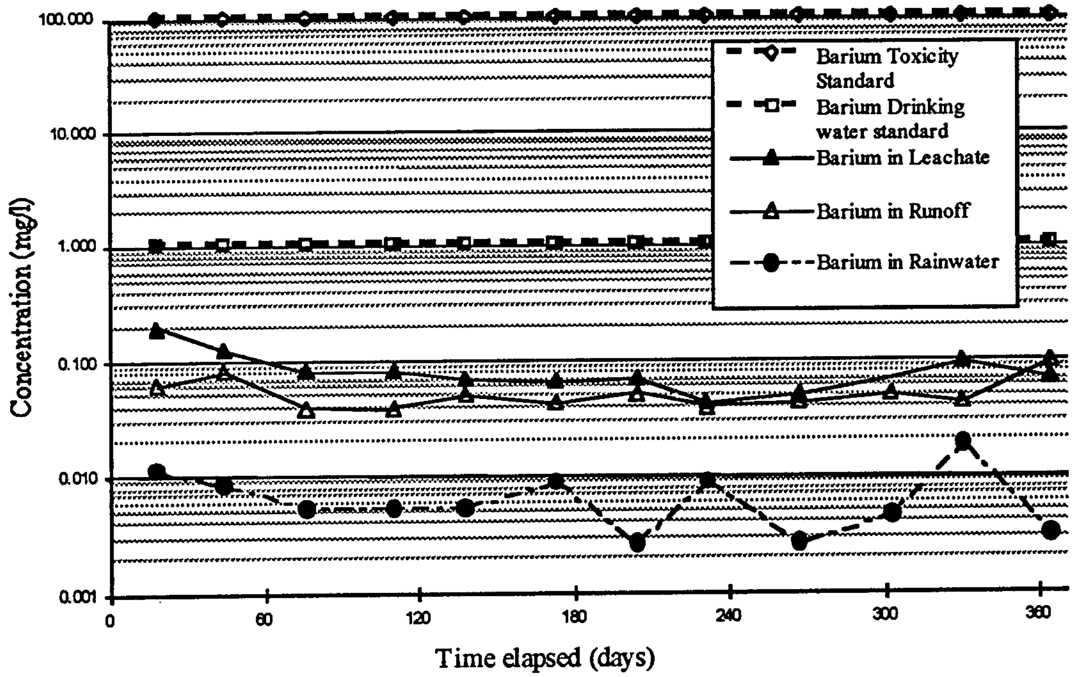


Figure 2-17 Barium concentrations in leachate, runoff, and rainwater as a function of time

	Rainwater filtered (µg/l)	Rainwater unfiltered (µg/l)	% dis.	Runoff filtered (µg/l)	Runoff unfiltered (µg/l)	% dis.	Leachate filtered (µg/l)	Leachate unfiltered (µg/l)	% dis.
As	n/a	n/a	--	n/a	n/a	--	n/a	n/a	--
Ag	N.D.	N.D.	--	N.D.	N.D.	--	N.D.	N.D.	--
Ba	2.5 ± 0.09	2.6 ± 0.04	99	45.5 ± 1.0	48.0 ± 0.6	95	65.8 ± 0.6	68.0 ± 0.2	97
Cd	0.5 ± 0.09	0.6 ± 0.05	89	0.6 ± 0.58	1.5 ± 0.03	41	5.1 ± 0.2	5.6 ± 0.2	92
Cr	0.9 ± 0.12	1.0 ± 0.09	89	2.4 ± 2.6	5.4 ± 0.1	44	4.4 ± 0.3	5.5 ± 0.2	80
Hg	N.D.	N.D.	--	N.D.	N.D.	--	N.D.	N.D.	--
Pb	2.5 ± 0.06	4.2 ± 0.03	61	0.7 ± 0.8	8.4 ± 0.4	8	1.9 ± 0.1	1.2 ± 0.1	100
Se	0 ± 0.2	0.5 ± 0.2	0	0.4 ± 0.1	0.5 ± 0.2	80	7.9 ± 0.5	8.6 ± 1.3	92

N.D. - Not detectable
± represents standard deviation, N=3
n/a - results not available.

Table 2-6 Concentration of elements with and without filtration and the percent in dissolved form

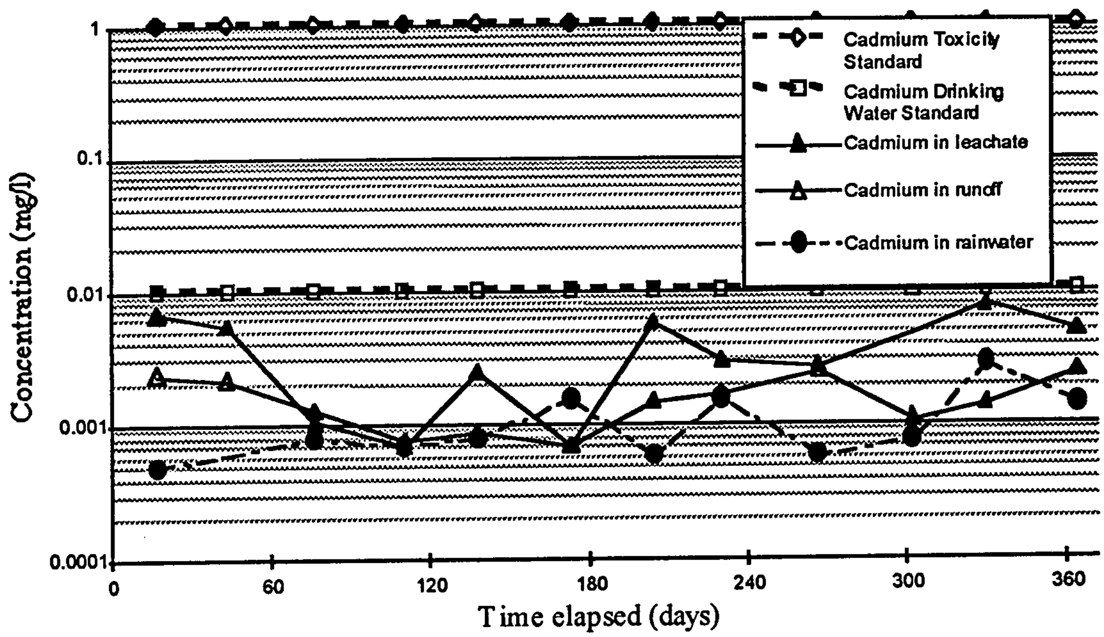


Figure 2-18 Cadmium concentrations in leachate, runoff, and rainwater as a function of time

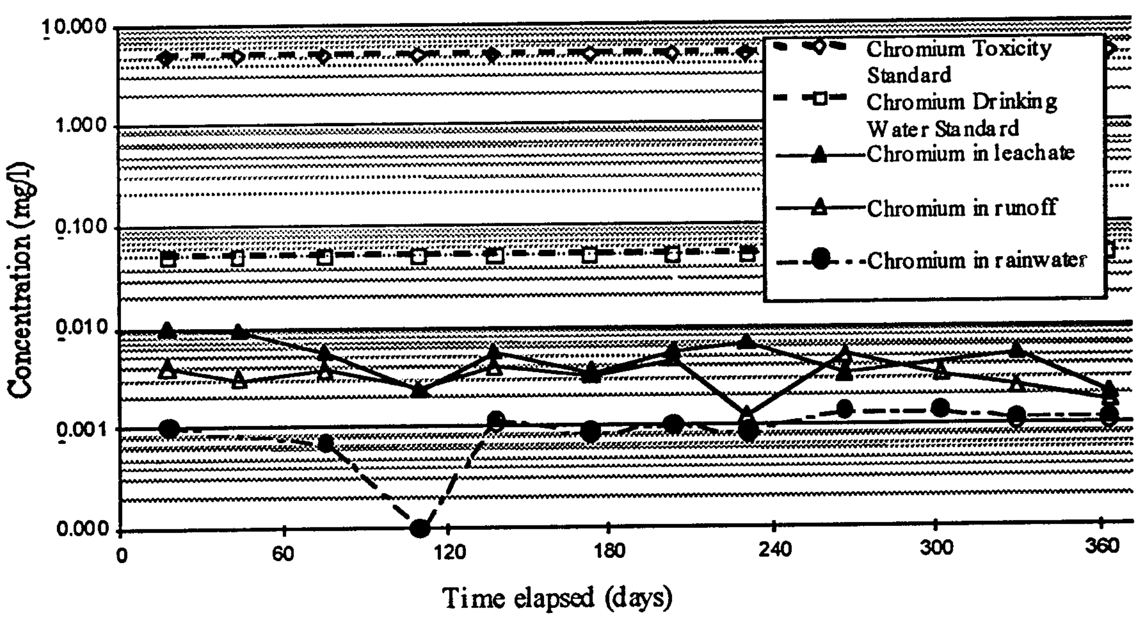


Figure 2-19 Chromium concentrations in leachate, runoff, and rainwater as a function of time

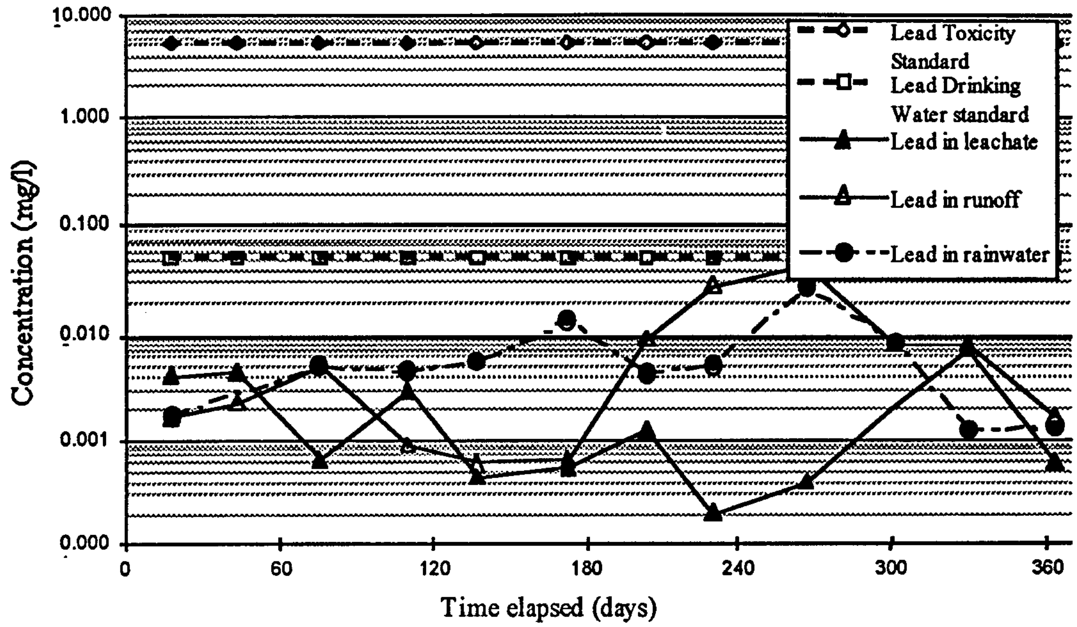


Figure 2-20 Lead concentrations in leachate, runoff, and rainwater as a function of time

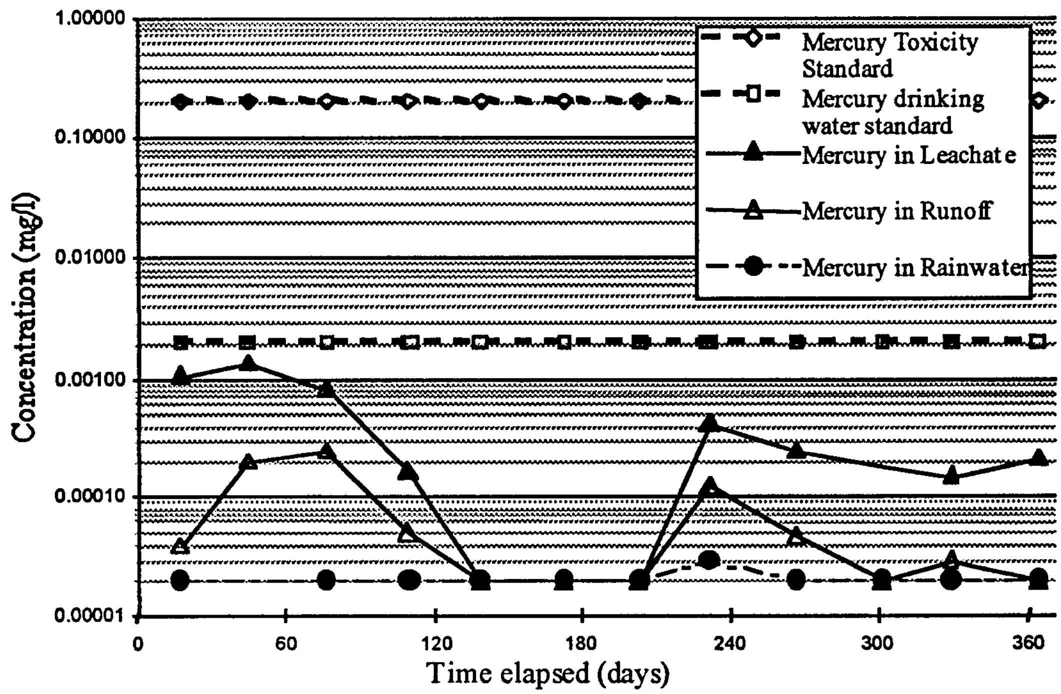


Figure 2-21 Mercury concentrations in leachate, runoff, and rainwater as a function of time

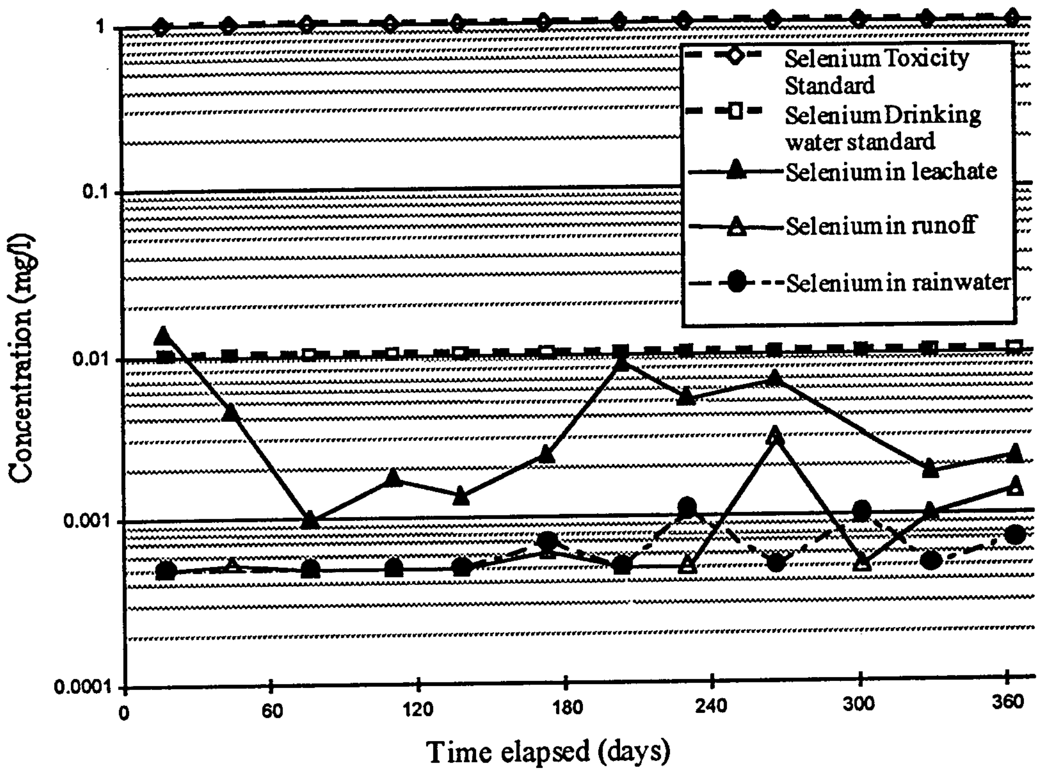


Figure 2-22 Selenium concentrations in leachate, runoff, and rainwater as a function of time

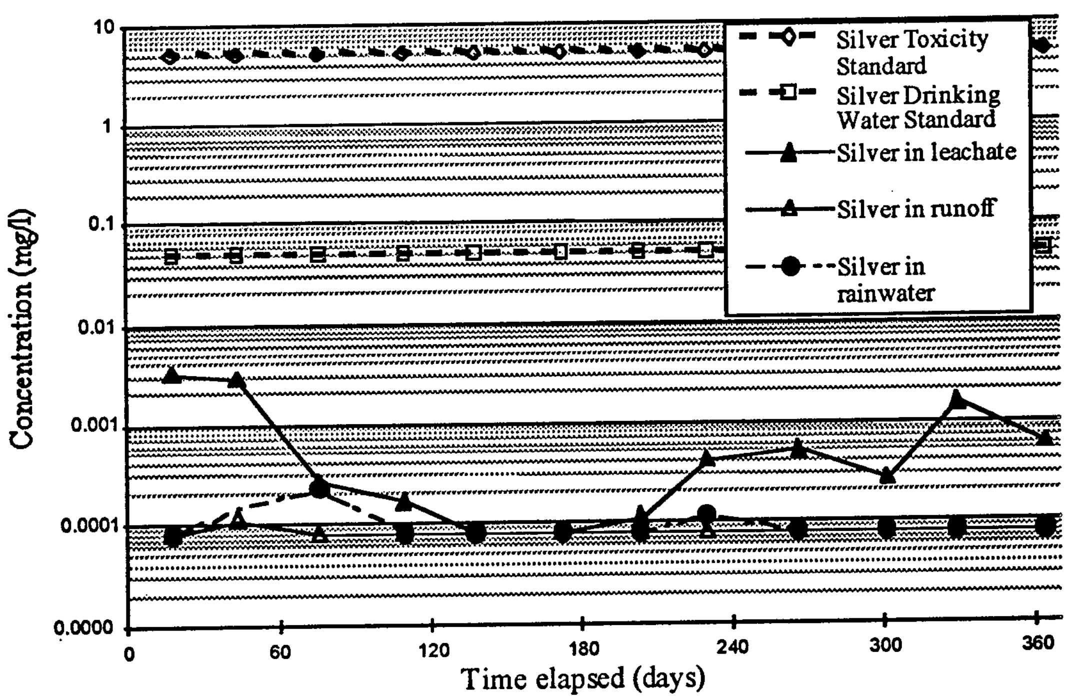


Figure 2-23 Silver concentrations in leachate, runoff, and rainwater as a function of time

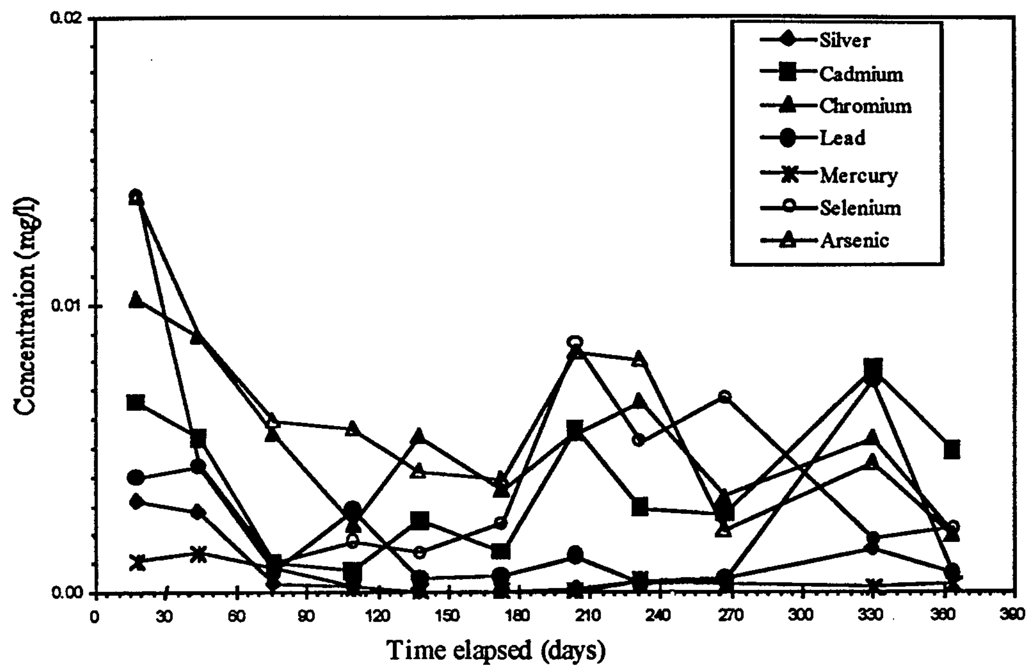


Figure 2-24 Concentrations of selected elements in the leachate as a function of time

Element	Average Ash Concentration (mg/kg)	Total Weight in leachate area (g)
Arsenic	70 ± 27	2,450
Barium	609 ± 104	213,450
Cadmium	68 ± 10	2,390
Chromium	752 ± 1,990	26,340
Lead	1,710 ± 160	59,880
Mercury	2.17 ± 1.13	76
Selenium	< 3	100
Silver	4.38 ± 1.68	150

± represents Standard deviation, N=13

Table 2-7 Average concentrations of selected elements in the combined ash used in the ash embankment

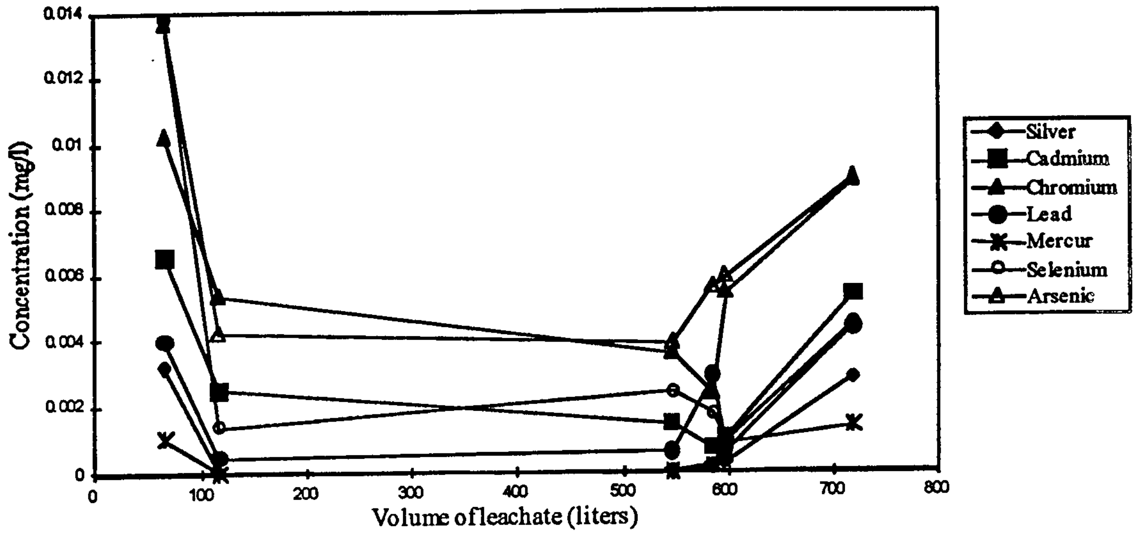


Figure 2-25 Concentration of selected elements in the leachate as a function of volume

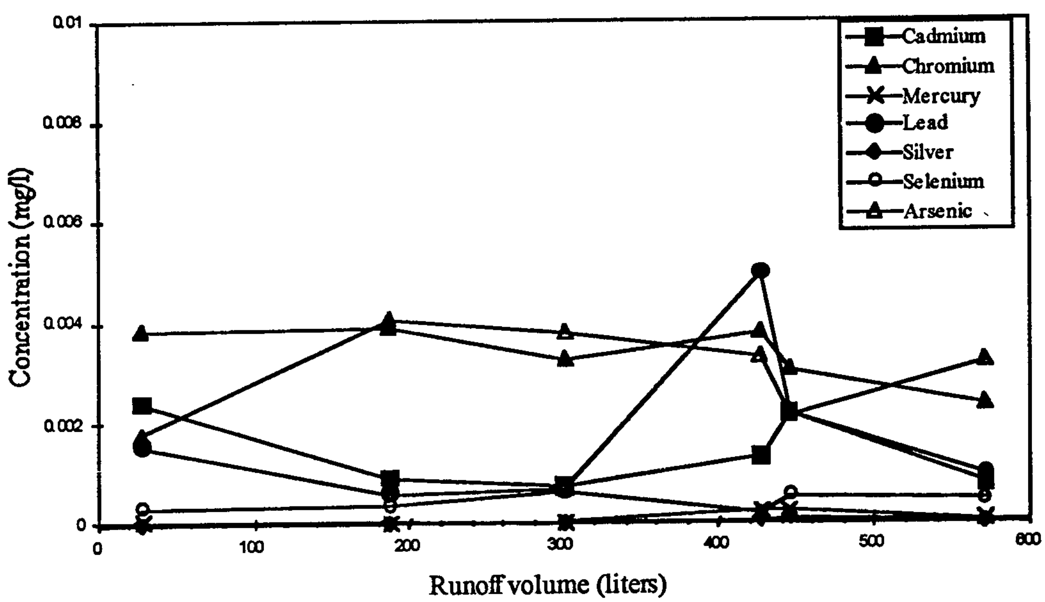


Figure 2-26 Concentration of selected elements in the runoff as a function of runoff volume

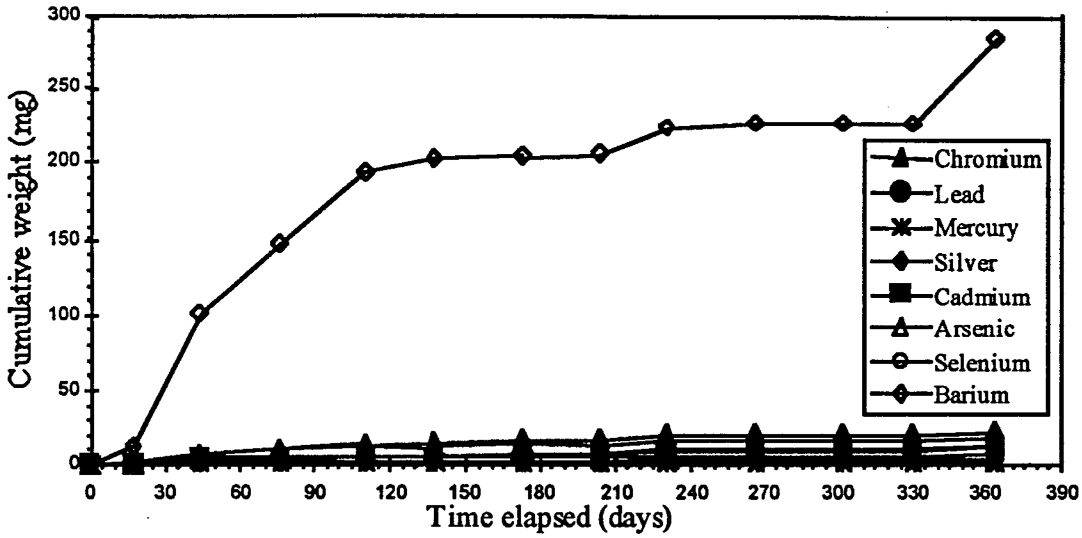


Figure 2-27 Cumulative weights of selected elements in the leachate as a function of time

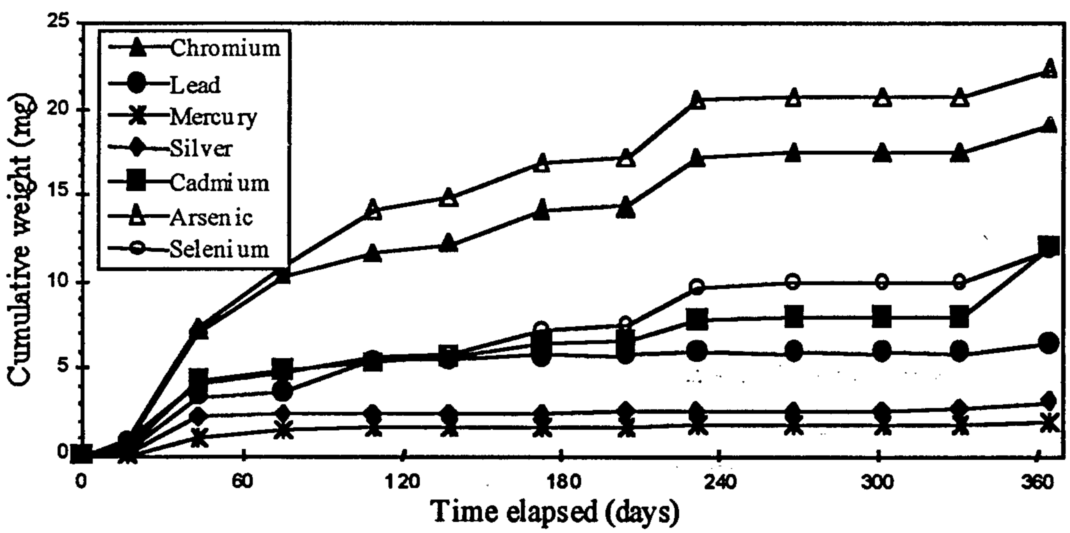


Figure 2-28 Cumulative weights of selected elements (excluding Barium) in the leachate as a function of time

	18	44	76	110	138	173
Arsenic	<0.0001	0.0002	0.0003	0.0005	0.0005	0.0005
Barium	<0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Cadmium	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Chromium	<0.0001	<0.0001	<0.0001	0.0001	0.0001	0.0001
Lead	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Mercury	0.0001	0.0014	0.0020	0.0021	0.0021	0.0021
Selenium	0.0009	0.0039	0.0047	0.0054	0.0056	0.0068
Silver	0.0001	0.0014	0.0015	0.0016	0.0016	0.0016

Table 2-8 Cumulative percent leached for selected elements. The number at the head of each column represents the days elapsed since construction of the embankment

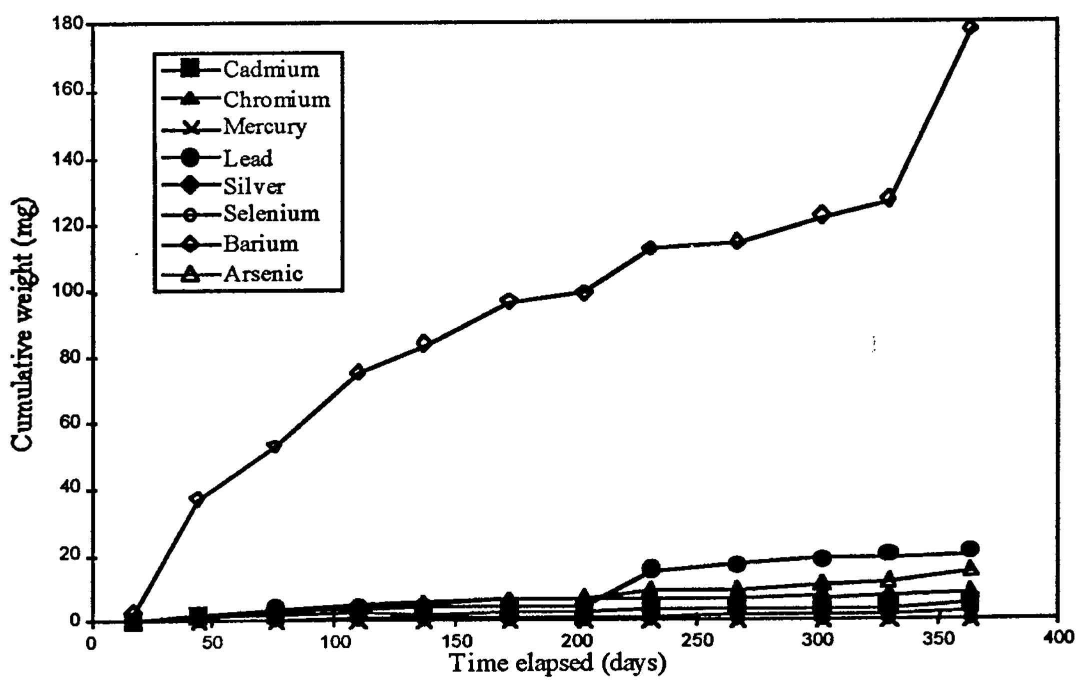


Figure 2-29 Cumulative weights of selected elements in the runoff as a function of time

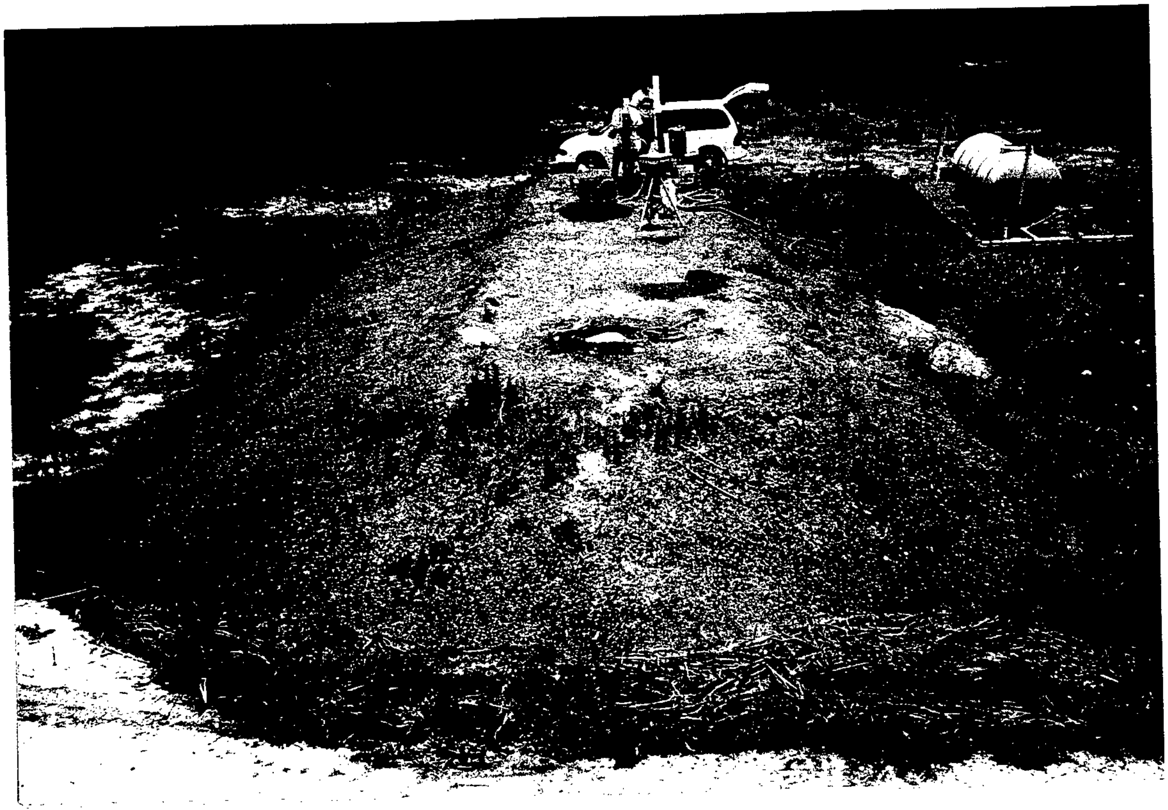


Figure 2-30 View of the combined ash embankment approximately one year after

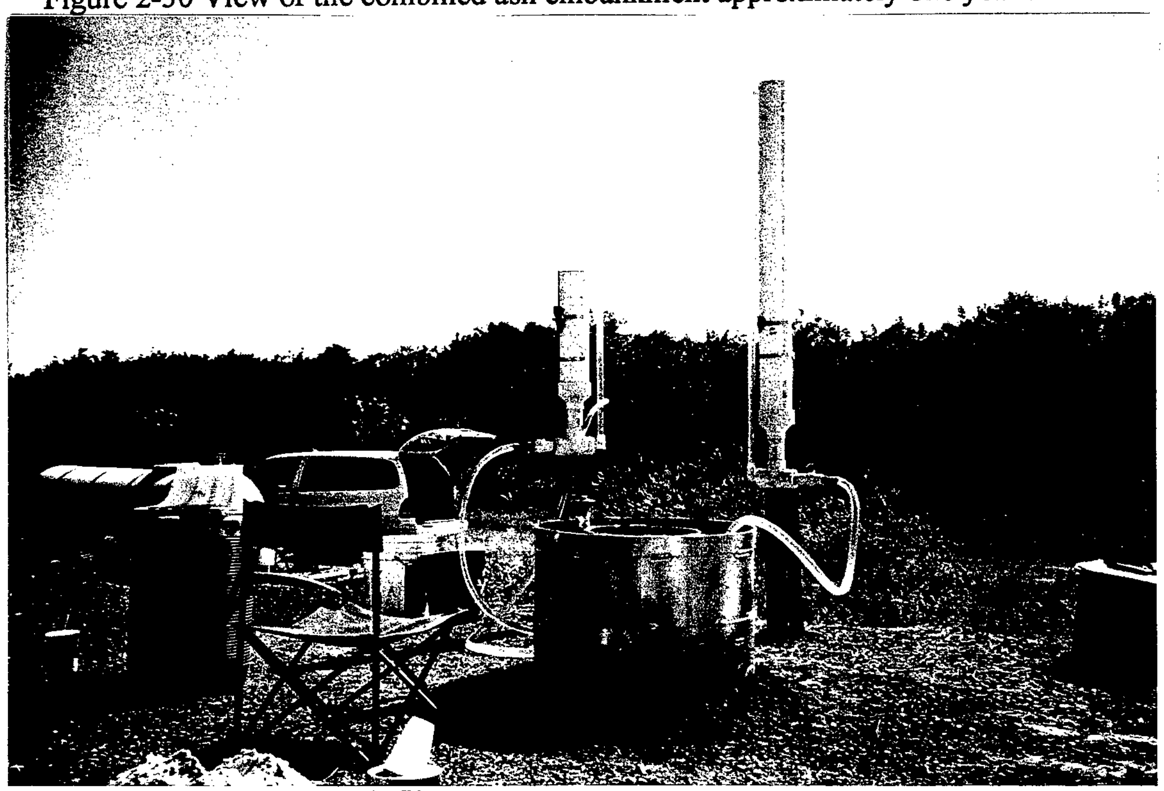


Figure 2-31 Double ring infiltrometer test set-up

Cone Penetrometer Test Results 24 feet from the south end

Depth (feet)	Qc* (tsf)	N values
0.5	116	31
1	285	49
1.5	367	65
2	571	87
2.5	390	72
3	552	82
3.5	448	71
4	228	43

Qc*- an average over a 6 inch interval

Field CBR Test Results at surface

Location	CBR @ 0.2 inch
13 feet south of north end	86
22 feet south of north end	51
39 feet south of north end	55

Pressuremeter Test Results

	Rebound Modulus	Limit Pressure
Average of all tests at a depth of 21 inches	E_r = 32198 psi	Exceeded pressure gage limit, estimated at over 300 psi (22 tsf)

Table 2-9 Field test results conducted May 1997 for the combined ash embankment

Waste-to-energy Facility Abbreviation	Location City	Location County	Design capacity (TPD)	Startup Year	Technology Type	Energy Generation	Megawatts	Air Pollution Controls	Owner	Operator
A	Hudson	Pasco	1000	1991	Mass Burn	Electricity	31.2	DSCR/FF	Pasco County	Ogden Martin
B	Miami	Dade	3000	1982	RDF	Electricity	78.5	ESP	Dade County	Montenay
C	Okahumpka	Lake	528	1991	Mass Burn	Electricity	12.5	DSCR/FF	Ogden Martin	Ogden Martin
D	Pompano Beach	Broward	2250	1991	Mass Burn	Electricity	66.5	DSCR/FF	Wheelabrator	Wheelabrator
E	Ft. Lauderdale	Broward	2250	1991	Mass Burn	Electricity	64	DSCR/FF	Wheelabrator	Wheelabrator
F	Brandon	Hillsborough	1200	1987	Mass Burn	Electricity	29	ESP	Hillsborough Co.	Ogden Martin
G	West Palm Beach	Palm Beach	2000	1989	RDF	Electricity	61.3	DSCR/ESP	SW Authority of Palm Beach County	Babcox & Wilcox
H	Ft. Myers	Lee	1200	1994	Mass Burn	Electricity	30	DSCR/FF/ NOX/A/C	Lee County	Ogden Martin
I	St. Petersburg	Pinellas	3000	1983	Mass Burn	Electricity	75	ESP	Pinellas County	Wheelabrator
J	Tampa	Hillsborough	1000	1985	Mass Burn	Electricity	22	ESP	City of Tampa	Wheelabrator
K	Panama City	Bay	510	1987	Mass Burn	Electricity	12	ESP	Ford Motor Credit	Westinghouse Energy Systems
L	Key West	Monroe	150	1986	Mass Burn	Electricity	4	ESP	City of Key West	City of Key West
Total			18088				486			

LEGEND:

A = Carbon Absorption; RDF = Refuse Derived Fuel; FF = Fabric Filter

C= Cyclone Separator; ESP = Electrostatic Precipitator; NOX = Thermal Denox; DSCR = Dry Acid Gas Scrubber

Table 3-1 Florida WTE facilities that provided the MWC combined ash for this investigation (Hinkley, 1996)

Composition	Facility abbreviation												Mean	Standard deviation
	A	B	C	D	E	F	G	H	I	J	K	L		
Metal	35.0	7.6	29.5	8.6	15.6	14.4	21.0	12.3	16.4	8.7	6.0	5.2	15.0	9.4
Glass	6.9	8.6	8.9	22.6	8.6	8.6	2.1	12.7	5.8	4.3	5.6	9.0	8.6	5.2
PWP	0.0	2.5	0.2	0.2	4.4	0.3	2.5	0.7	0.1	0.2	2.3	0.8	1.2	1.4
Ceramic	2.8	0.8	5.8	2.0	6.2	3.6	0.5	0.4	1.4	0.0	1.1	0.8	2.1	2.1
Clinker	19.7	1.7	25.9	10.8	4.9	9.5	10.9	17.6	10.9	7.0	3.8	8.7	10.9	7.0
Unclassified > # 8 sieve	28.7	27.0	14.6	14.5	15.5	11.1	32.1	17.1	19.5	23.5	25.0	20.3	20.7	6.5
Unclassified < # 8 sieve	6.9	51.9	15.1	41.2	44.9	52.6	30.9	39.2	45.9	56.4	56.2	55.2	41.4	16.2

Table 3-2 The percent of metal, glass, PWP (paper, wood, and plastic), ceramic, clinker, unclassified >#8 sieve, and unclassified <#8 sieve of combined ash from the 12 Florida WTE facilities

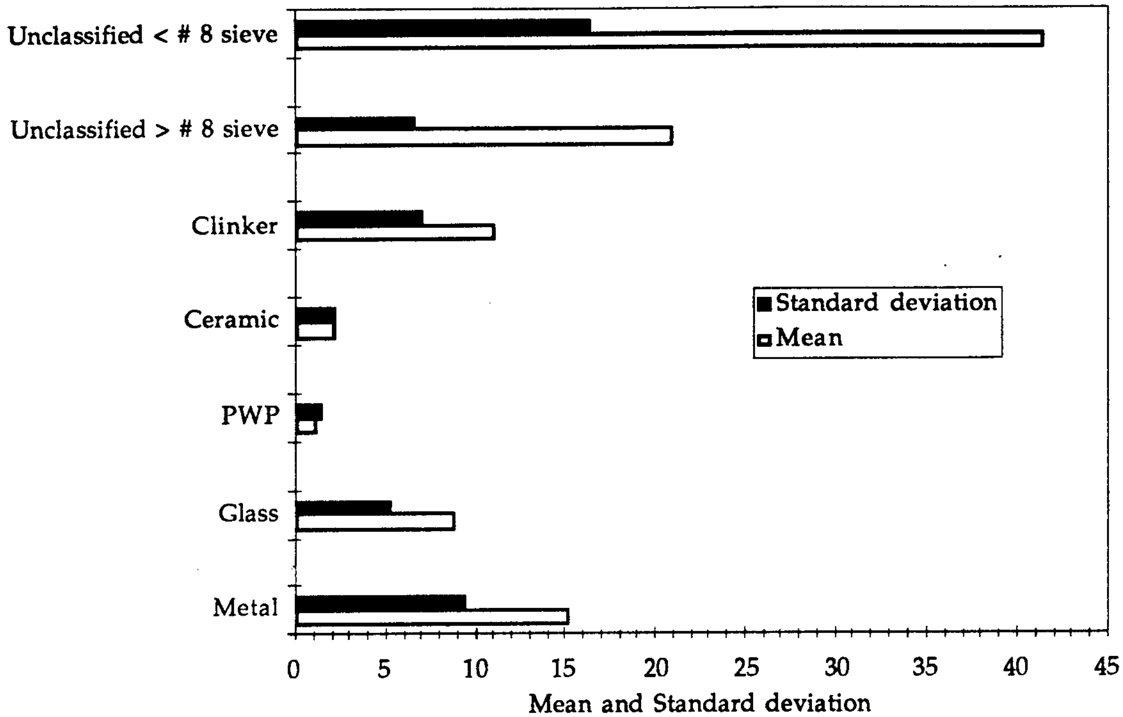


Figure 3-1 Mean value and standard deviation of physical properties of combined ash from the 12 Florida WTE facilities

Facility name	Date of testing	Sample Lot no.	Moisture content
Pasco County Solid Waste Resource Recovery Facility	9/23/96	A	8
Dade County Resources Recovery Facility	9/23/96	B	7
Lake County Resource Recovery Facility	9/23/96	C	16
North Broward County Resource Recovery Facility	10/10/96	D	18
South Broward County Resource Recovery Facility	10/10/96	E	31
Hillsborough County Solid Waste Energy Recovery Facility	10/10/96	F	11
North County Regional Resource Recovery Facility	10/10/96	G	21
Lee County Solid Waste Resource Recovery Facility	10/26/96	H	40
Pinellas County Solid Waste Resource Recovery Facility	3/20/96	I	12
McKay Bay Refuse to Energy Project	10/26/96	J	75
Bay County Resource Recovery Facility	11/9/96	K	40
Southernmost Waste-to-Energy Facility	11/22/96	L	38
Mean			26
Standard deviation			20

Table 3-3 Moisture content, dry unit weight, and CBR/LBR values for combined ash from the 12 Florida WTE facilities

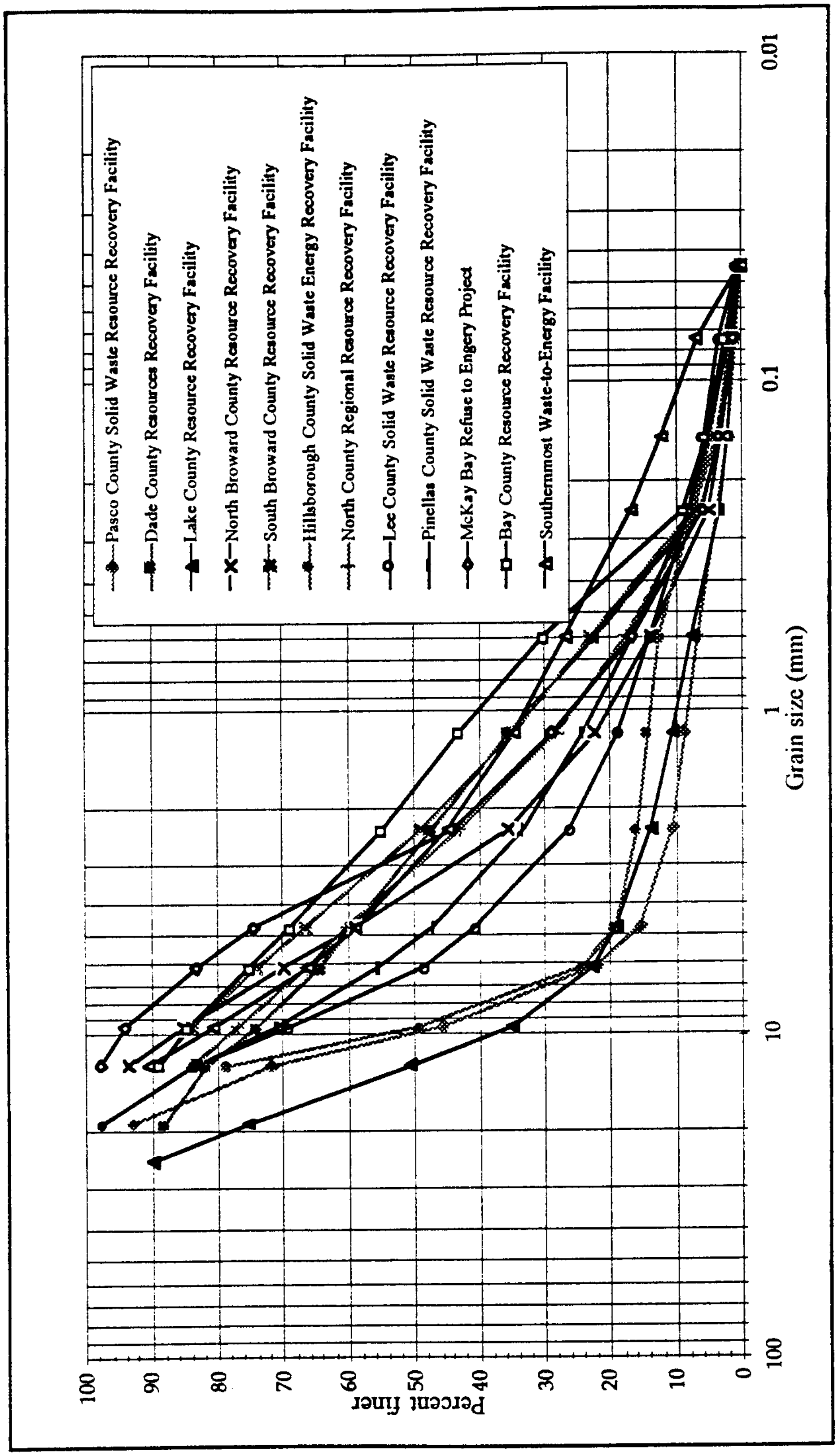


Figure 3-2 Grain size distribution of the MWC combined ash from the 12 Florida WTE facilities

Facility name	Index property			Classification	
	C_U	C_C	F. M.	USCS	AASHTO
Pasco County Solid Waste Resource Recovery Facility	7.1	2.5	6.1	SW	A-1-a (0)
Dade County Resources Recovery Facility	16.1	0.5	4.6	SP	A-1-a (0)
Lake County Resource Recovery Facility	15	4.3	6.3	SP	A-1-a (0)
North Broward County Resource Recovery Facility	12.3	1.7	4.7	SW	A-1-a (0)
South Broward County Resource Recovery Facility	13.1	0.7	4.3	SP	A-1-a (0)
Hillsborough County Solid Waste Energy Recovery Facility	28.2	11.4	5.7	SP	A-1-a (0)
North County Regional Resource Recovery Facility	15.5	1.3	4.6	SW	A-1-a (0)
Lee County Solid Waste Resource Recovery Facility	24.2	3.2	5.2	SW	A-1-a (0)
Pinellas County Solid Waste Resource Recovery Facility	23.3	1.7	4.9	SW	A-1-a (0)
McKay Bay Refuse to Energy Project	10	1.6	4.3	SW	A-1-a (0)
Bay County Resource Recovery Facility	11.1	0.4	4.0	SP	A-1-a (0)
Southernmost Waste-to-Energy Facility	44.4	1.16	4.2	SW	A-1-a (0)
Mean	18.4	2.5	4.9		
Standard deviation	10.3	3.0	0.8		

Table 3-4 Index properties and soil classification of the combined ash from the 12 Florida WTE facilities.

Facility Name	Moisture Density		Bearing Ratio			
	OMC (%)	γ_{dry} (kN/m³)	CBR @ OMC	CBR @ MAX	LBR @ OMC	LBR @ MAX
Pasco County Solid Waste Resource Recovery Facility	15.2	15.9	39	44	44	49
Dade County Resources Recovery Facility	14.7	13.3	35	37	39	42
Lake County Resource Recovery Facility	13.7	17.5	48	64	49	69
North Broward County Resource Recovery Facility	17.1	16.0	46	47	44	52
South Broward County Resource Recovery Facility	17.8	14.3	38	38	45	47
Hillsborough County Solid Waste Energy Recovery Facility	15	15.8	37	45	35	50
North County Regional Resource Recovery Facility	17	13.8	36	39	42	47
Lee County Solid Waste Resource Recovery Facility	14.6	15.6	42	42	49	49
Pinellas County Solid Waste Resource Recovery Facility	15.5	17.3	64	64	62	66
McKay Bay Refuse to Energy Project	14.3	12.3	32	32	37	37
Bay County Resource Recovery Facility	16	11.6	35	35	42	42
Southernmost Waste-to-Energy Facility	13.9	13.3	41	41	51	51
Mean	15.4	14.7	41.1	44.0	44.9	50.1
Standard deviation	1.3	1.9	8.6	10.3	7.2	9.2

Table 3-5 Moisture content, dry unit weight, and CBR/LBR values for combined ash from the 12 Florida facilities

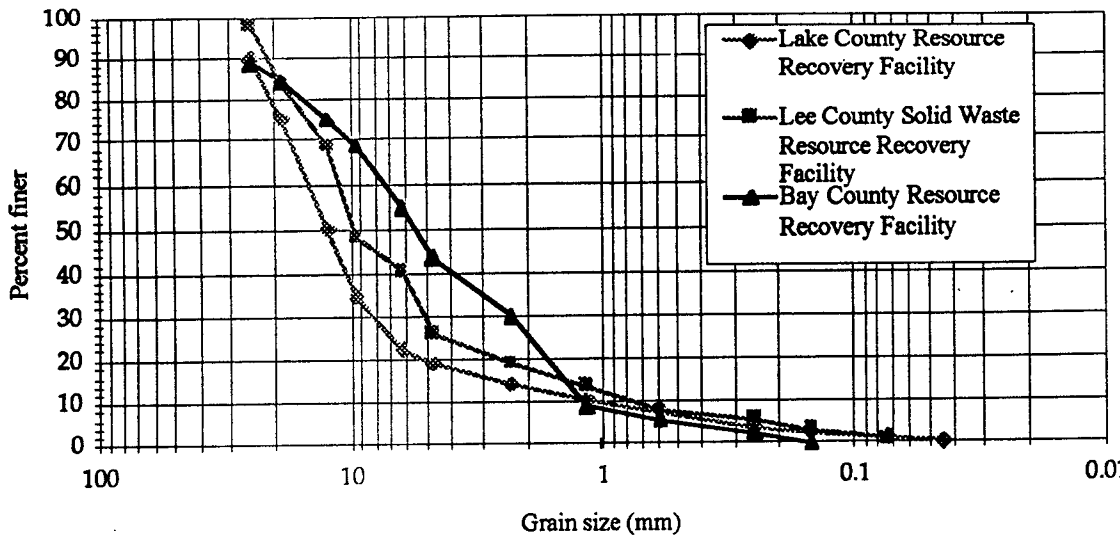


Figure 3-3 Grain size distribution of combined ash from selected Florida WTE facilities

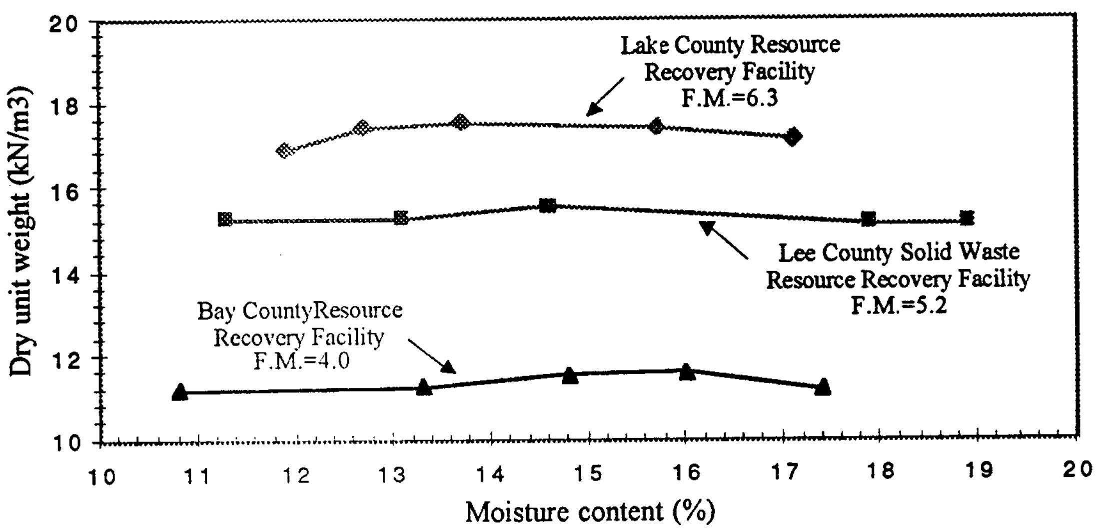


Figure 3-4 Maximum, medium, and minimum dry unit weight of combined ash from selected Florida WTE facilities

Physical parameter X axis	Engineering parameter Y axis	r	Relation	Slope of trendline
% finer than # 4 sieve	Max. dry unit weight	0.80	Strong	Negative
% finer than # 8 sieve	Max. dry unit weight	0.80	Strong	Negative
% of metal plus clinker	Max. dry unit weight	0.70	Moderate	Positive
Fineness modulus	Max. dry unit weight	0.80	Strong	Positive
% of material retained on # 200 sieve	Max. dry unit weight	0.60	Moderate	Negative
Effective diameter (D_{10})	Max. dry unit weight	0.50	Moderate	Positive
D_{15}	Max. dry unit weight	0.70	Moderate	Positive
D_{30}	Max. dry unit weight	0.70	Moderate	Positive
D_{60}	Max. dry unit weight	0.80	Strong	Positive
Coefficient of curvature (C_C)	Max. dry unit weight	0.50	Weak	Positive
Uniformity coefficient (C_U)	Max. dry unit weight	0.05	Weak	Positive
Optimum moisture content	Max. dry unit weight	0.08	Weak	Negative
% finer than # 100 sieve	Max. dry unit weight	0.34	Weak	Negative
% finer than # 200 sieve	Max. dry unit weight	0.27	Weak	Negative
% finer than # 4 sieve	Max. dry density	0.75	Strong	Negative
% finer than # 8 sieve	Max. dry density	0.75	Strong	Negative
Fineness modulus	Max. dry density	0.75	Strong	Positive
% of metal plus clinker	CBR @ OMC	0.20	Weak	Negative
Fineness modulus	CBR @ OMC	0.28	Weak	Positive
% of material retained on # 200 sieve	CBR @ OMC	0.25	Weak	Negative
Effective diameter (D_{10})	CBR @ OMC	0.04	Weak	Negative
D_{15}	CBR @ OMC	0.03	Weak	Positive
D_{30}	CBR @ OMC	0.13	Weak	Positive
D_{60}	CBR @ OMC	0.30	Weak	Positive
Coefficient of curvature (C_C)	CBR @ OMC	0.01	Weak	Negative
Uniformity coefficient (C_U)	CBR @ OMC	0.21	Weak	Positive
Optimum moisture content	CBR @ OMC	0.04	Weak	Negative
% finer than # 100 sieve	CBR @ OMC	0.01	Weak	Negative
% finer than # 200 sieve	CBR @ OMC	0.03	Weak	Negative
% finer than # 4 sieve	LBR @ OMC	0.03	Weak	Negative
% finer than # 8 sieve	LBR @ OMC	0.09	Weak	Negative
% of metal plus clinker	LBR @ OMC	0.26	Weak	Negative
Fineness modulus	LBR @ OMC	0.06	Weak	Positive
% of material retained on # 200 sieve	LBR @ OMC	0.06	Weak	Positive
Effective diameter (D_{10})	LBR @ OMC	0.02	Weak	Negative
D_{15}	LBR @ OMC	0.06	Weak	Negative
D_{30}	LBR @ OMC	0.08	Weak	Negative
D_{60}	LBR @ OMC	0.12	Weak	Positive
Coefficient of curvature (C_C)	LBR @ OMC	0.30	Weak	Negative
Uniformity coefficient (C_U)	LBR @ OMC	0.34	Weak	Positive
Optimum moisture content	LBR @ OMC	0.08	Weak	Negative
% finer than # 100 sieve	LBR @ OMC	0.30	Weak	Positive
% finer than # 200 sieve	LBR @ OMC	0.25	Weak	Positive
Physical parameter X axis	**Physical parameter Y axis**	**r**	**Relation**	**Slope of trendline**
% finer than # 200 sieve	Optimum moisture content	0.28	Weak	Negative
Fineness modulus	Optimum moisture content	0.14	Weak	Negative
Optimum moisture content	% unclassified > # 8 sieve	0.02	Weak	Positive
Optimum moisture content	% unclassified < # 8 sieve	0.00	Weak	Positive
Engineering parameter X axis	**Engineering parameter Y axis**	**r**	**Relation**	**Slope of trendline**
Max. dry unit weight	CBR @ OMC	0.74	Moderate	Positive
Max. dry unit weight	LBR @ OMC	0.71	Moderate	Positive
Dry unit weight (all values)	CBR (all values)	0.74	Moderate	Positive

Table 3-6 Physical and geotechnical parameter relationships

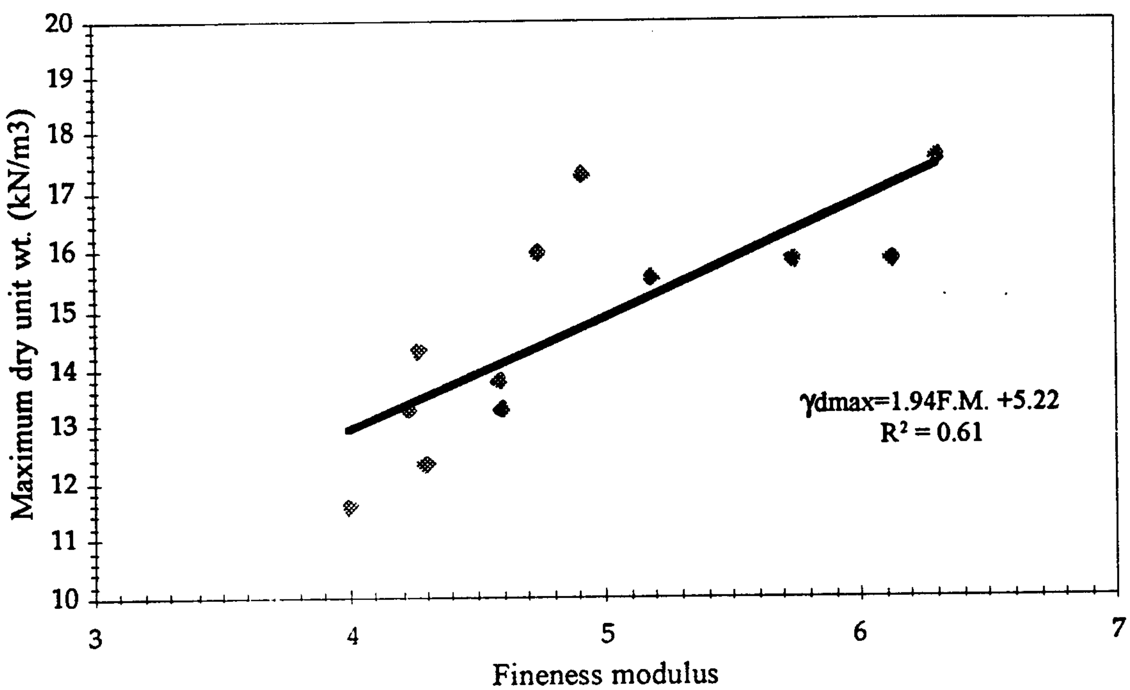


Figure 3-5 Fineness modulus versus maximum dry unit weights of combined ash from the 12 Florida WTE facilities

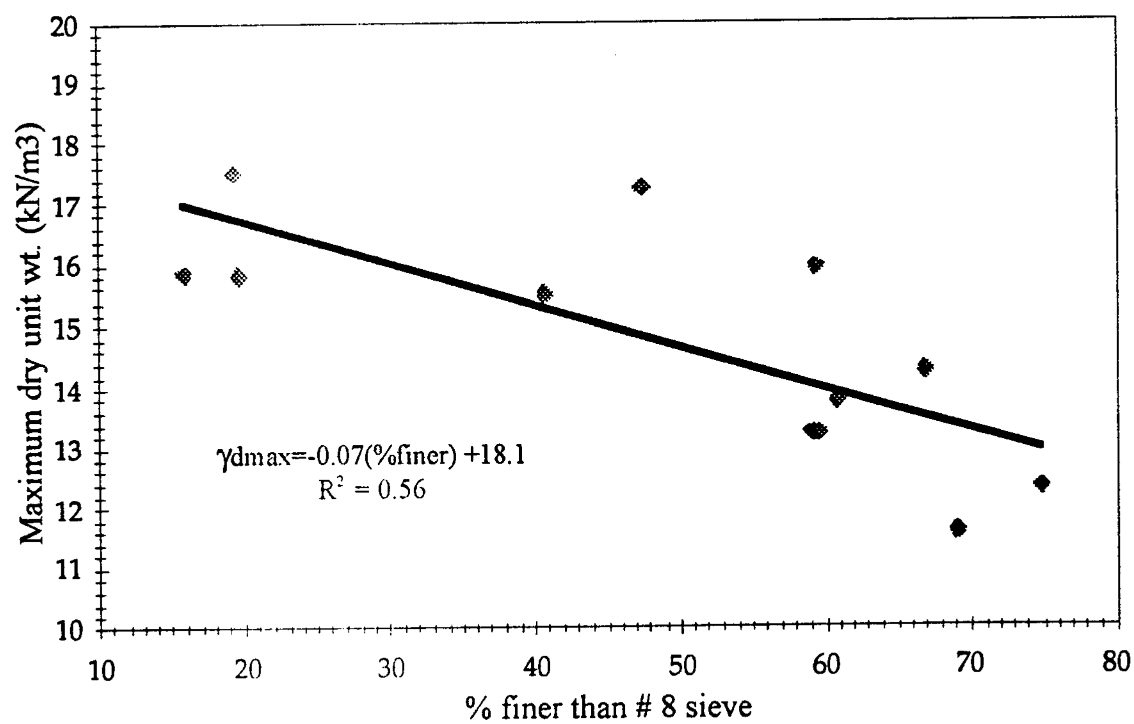


Figure 3-6 The percent (%) finer than #8 sieve versus maximum dry unit weights for combined ash from the 12 Florida WTE facilities

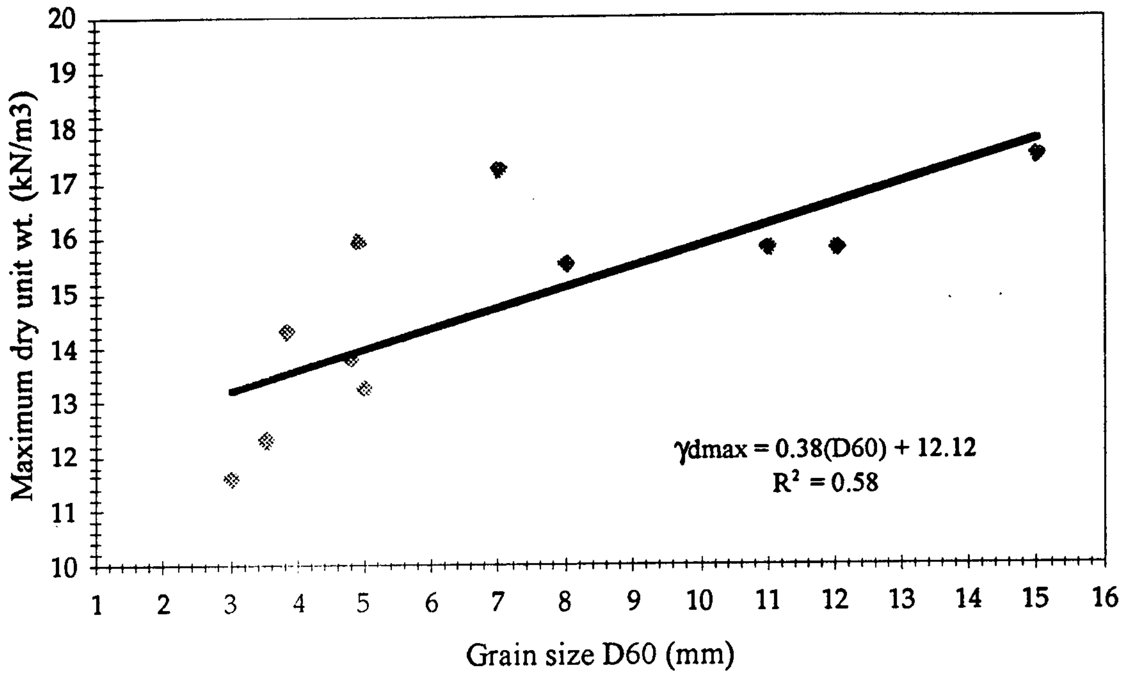


Figure 3-7 Grain size D_{60} versus maximum unit weights of combined ash from the 12 Florida WTE facilities

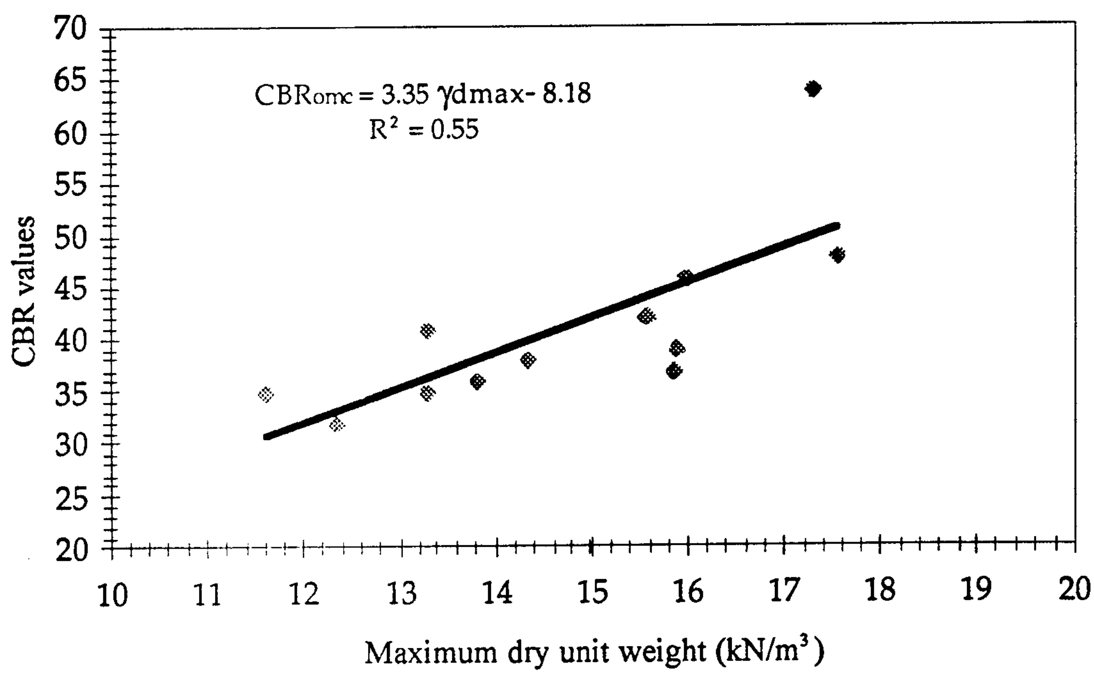


Figure 3-8 Maximum dry unit weights versus the corresponding CBR values of combined ash from the 12 Florida WTE facilities

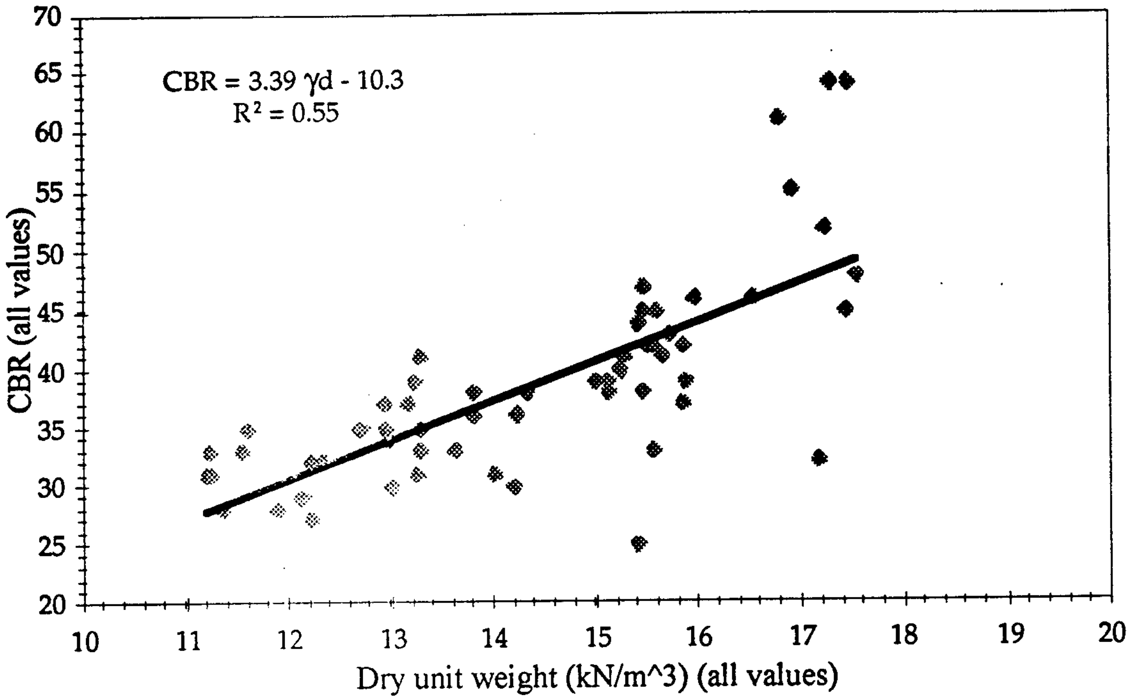


Figure 3-9 All dry unit weights versus all CBR values of combined ash from the 12 Florida WTE facilities

Appendix A

Tables of

Physical composition of combined ash from twelve Florida waste-to-energy facilities.

Operational Waste-to-Energy Plants names	Locatio City	County	Sample lot no.	Weight retained on	Total Weigh (g)	Meta (g)	Glass (g)	Plastic (g)	Wood (g)	Paper (g)	Ceramic (g)	Clinker (g)	Unclassified soil (g)	Unclassified fines (g)
Pasco County Solid Waste Resource Recovery Facility	Hudson	Pasco	A	# 1/2	356	129	18.9				22.6	79.6	105.8	
				# 3/8	256.3	101	23.7				2.2	57.2	72.5	
				# 1/4	226.8	84.4	18.4				3	47.5	73.5	
				# 4	54.7	19.6	3.5					10.1	21.5	
				# 8	36.9	16.4	4					2.4	14.1	
				passing # 8	69.3									69.3
		Total weight of sample		=	1000	350	68.5	0	0	0	27.8	196.8	287.4	69.3
Dade County Resources Recovery Facility	Miami	Dade	B	# 1/2	99.7	28	7.2	5.7	14.4		7.5		36.9	
				# 3/8	69.2		27.5		1.7			15.4	24.6	
				# 1/4	135.9	11.3	29.7			2.8		1.1	91	
				# 4	98.4	11.2	8.7						78.5	
				# 8	77.6	25.6	12.4				0.8		38.8	
				passing # 8	519.2									519.2
		Total weight of sample		=	1000	76.1	85.5	5.7	16.1	2.8	8.3	16.5	269.8	519.2
Lake County Resource Recovery Facility	Okahumpka	Lake	C	# 1/2	551.8	196	61.4			1.8	54.8	136.4	101.2	
				# 3/8	118.1	38.6	9.5					60.6	9.4	
				# 1/4	108.2	36.5	9.5			0.2	3.3	48.1	10.8	
				# 4	35.4	14.1	4.1					13.5	3.7	
				# 8	35.8	9.4	4.6					0.6	21.2	
				passing # 8	150.7									150.7
		Total weight of sample		=	1000	296	89.1	0	0	2	58.1	259.2	145.1	150.7
North Broward County Resource Recovery Facility	Pompano Beach	Broward	D	# 1/2	84.9	8.4	25.9			0.9	15	17.7	17	
				# 3/8	45.1	2.2	27.2			0.1	4.1	10.7	0.8	
				# 1/4	158	27.1	63.6			0.4		46.9	20	
				# 4	99.9	13.6	40.5	0.3	0.5		0.6	32.6	11.8	
				# 8	199.8	34.8	69.2						65.8	
				passing # 8	412.3									412.3
		Total weight of sample		=	1000	86.1	226.4	0.3	0.5	1.4	19.7	107.5	145.4	412.3

Table A-1 Physical composition of the combined ash from 12 Florida WTE facilities

Operational Waste-to-Energy Plants names	Location City	County	Sample lot no.	Weight retained on	Total Weight (g)	Metal (g)	Glass (g)	Plastic (g)	Wood (g)	Paper (g)	Ceramic (g)	Clinker (g)	Unclassified soil (g)	Unclassified fines (g)
South Broward County Resource Recovery Facility	Ft. Lauderdale	Broward	E	# 1/2	161.6	53.5	6.6			38.6	38.2	4.8	19.7	
				# 3/8	47.9	9.9	2.9		1.3	1.1	16.3	8.8	7.6	
				# 1/4	89.7	28.9	17		0.5	1	4.3	20.3	17.7	
				# 4	80.5	19.6	9.3		0.8	0.1	0.7	14.7	15.3	
				# 8	191	43.9	50.4		0.3		2.2		94.2	
				passing # 8	449.3									449.3
	Total weight of sample			=	1000	166	86.2	0	2.5	41	61.7	48.6	164.6	449.3
Hillsborough County Solid Waste Energy Recovery Facility	Brandon	Hillsborough	F	# 1/2	109.2	36.8	11.5			2.5	31.6	25.6	1.2	
				# 3/8	35.4	12.3	12.8			0.1	1.8	5.4	3	
				# 1/4	92	22.6	22.3			0.1	0.6	36.2	10.2	
				# 4	83.3	26.6	13.9			0.1	2.3	27.3	13.1	
				# 8	154.5	45.5	25.1						83.9	
				passing # 8	525.6									525.6
	Total weight of sample			=	1000	144	86.6	0	0	2.8	36.3	94.6	111.4	525.6
North County Regional Resource Recovery Facility	West Palm Beach	Palm Beach	G	# 1/2	139.3	56.2		4.8	0.7	7.3		63.1	7.2	
				# 3/8	75.1	22.5			0.5	2		21.5	28.6	
				# 1/4	154.8	37	4.5		0.6	4	1.2	18.8	88.7	
				# 4	115.6	30.6	3.7		0.6	1.3		1.3	78.1	
				# 8	206.2	63.9	12.8		1.2	2.2	3.6	4	118.5	
				passing # 8	309									309
	Total weight of sample			=	1000	210	21	4.8	3.6	16.8	4.8	108.7	321.1	309
Lee County Solid Waste Resource Recovery Facility	Ft. Myers	Lee	H	# 1/2	147.5	25.9	28.6			4.6		85.2	3.2	
				# 3/8	95.3	15.4	40.3			0.4		23.9	15.3	
				# 1/4	120.4	22.5	27.2			0.7	3.3	38.8	27.9	
				# 4	80.3	19.6	9.2			1.1	0.7	24.5	25.2	
				# 8	184.7	40	21.3			0.1		3.6	99.7	
				passing # 8	391.8									391.8
	Total weight of sample			=	1000	123	126.6	0	0	6.9	4	176	171.3	391.8

Table A-1 cont. Physical composition of the combined ash from 12 Florida WTE facilities

Operational Waste-to-Energy Plants names	Location City	County	Sample lot no	Weight retained on	Total Weight (g)	Metal (g)	Glass (g)	Plastic (g)	Wood (g)	Paper (g)	Ceramic (g)	Clinker (g)	Unclassified soil (g)	Unclassified fines (g)
Pinellas County Solid Waste Resource Recovery Facility	St. Petersburg	Pinellas	I	# 1/2	86.7	28.5					7.2	22.9	29.1	
				# 3/8	85.5	20.4	9.1				2.9	27.5	25.6	
				# 1/4	137.7	40.8	23.1		1		1	38.8	33	
				# 4	82.1	28.1	7.5		0.2	0.1	1.2	18.1	28.9	
				# 8	148.6	47.9	16.2				1.5	1	60	
				passing # 8	459.4									459.4
	Total weight of sample =				1000	164	55.9	0	1.2	0.1	13.8	108.3	184.6	459.4
McKay Bay Refuse to Energy Project	Tampa	Hillsborough	J	# 1/2	21.8	4.5	2			0.2		15.1		
				# 3/8	19.7	1.4	3.4			0.6		3.9	10.4	
				# 1/4	67.8	19.7	10.8		0.1	0.4		20.4	16.4	
				# 4	69.4	16.5	4.3		0.3	0.4		29.8	18.1	
				# 8	257.6	44.8	22			0.1		1	189.7	
				passing # 8	563.7									563.7
	Total weight of sample =				1000	86.9	42.5	0	0.4	1.7	0	70.2	234.6	563.7
Bay County Resource Recovery Facility	Panama City	Bay	K	# 1/2	53.4	9.3	2.9				9.5	6.2	25.5	
				# 3/8	35.8	7.6	2.4					8.8	16.8	
				# 1/4	79.7	12.8	13.8		2.8		1.3	13.5	35.5	
				# 4	78	12.6	9.2		3.3			9.8	41.1	
				# 8	193	17.6	28		16.8				130.6	
				passing # 8	562.3									562.3
	Total weight of sample =				1000	59.9	56.3	0	22.9	0	10.8	38.3	249.5	562.3
Southernmost Waste-to-Energy Facility	Key West	Monroe	L	# 1/2	91.1	3.1	27.9		0.4	4.4	2.1	20.8	32.4	
				# 3/8	48.3	8.2	6.2			0.7		16.2	17	
				# 1/4	108.6	14	24.5		0.1	0.7	2.1	34.7	30.5	
				# 4	67.5	11.1	11.7		0.7	0.8	1.7	14.9	26.5	
				# 8	134.3	15.8	20			0.2	2.1		96.2	
				passing # 8	552.2									552.2
	Total weight of sample =				1000	52.2	90.3	0	1.2	6.9	8	86.6	202.6	552.2

Table A-1 cont. Physical composition of the combined ash from 12 Florida WTE facilities

Appendix B

Plots of

Twelve Florida waste-to-energy facilities versus percent of metal, glass, PWP, clinker, unclassified > # 8 sieve size, and unclassified < # 8 sieve size.

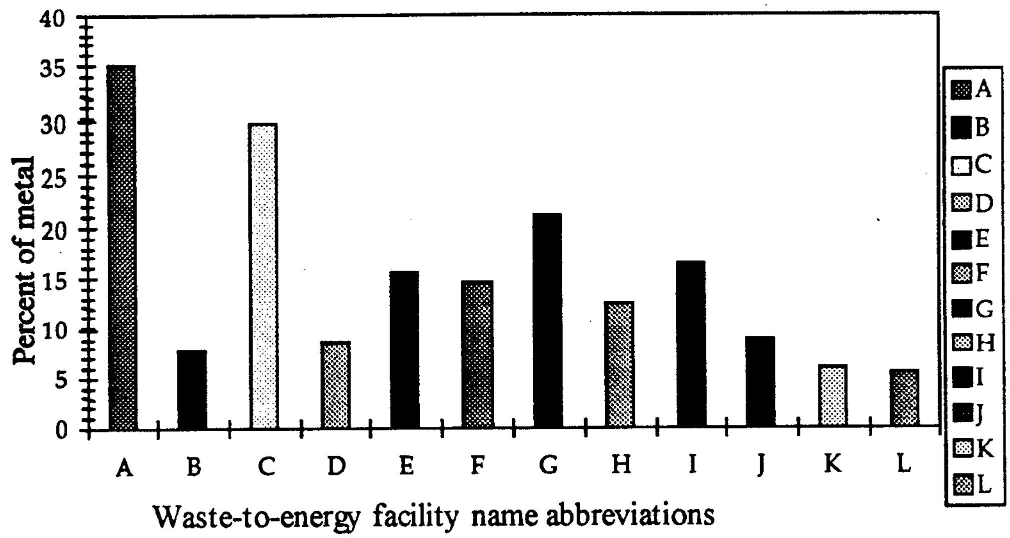


Figure B-1 Twelve waste-to-energy facilities versus percent of metals of combined ashes passing #3/4 in sieve and retained on # 8 sieve

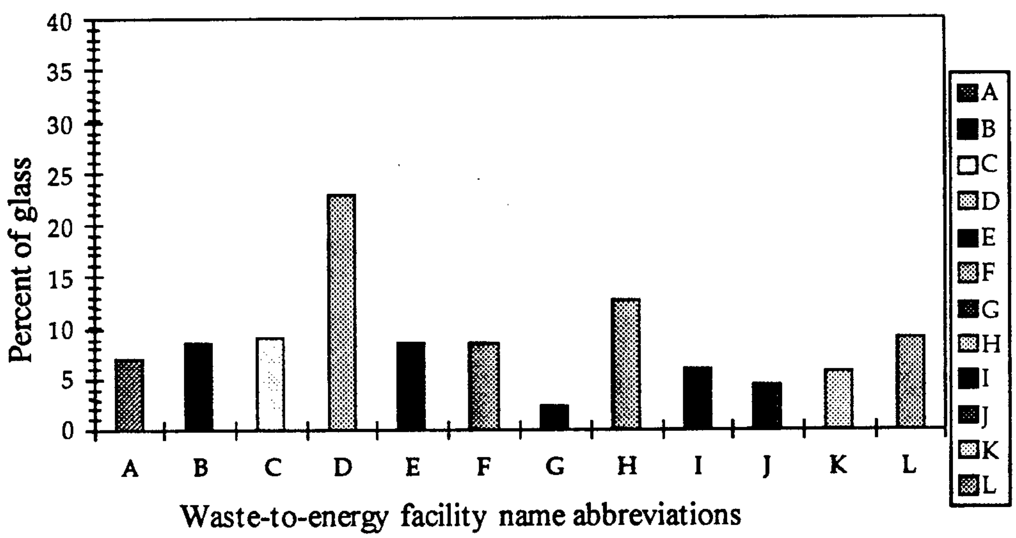


Figure B-2 Twelve waste-to-energy facilities versus percent of glass of combined ashes passing #3/4 in sieve and retained on #8 sieve

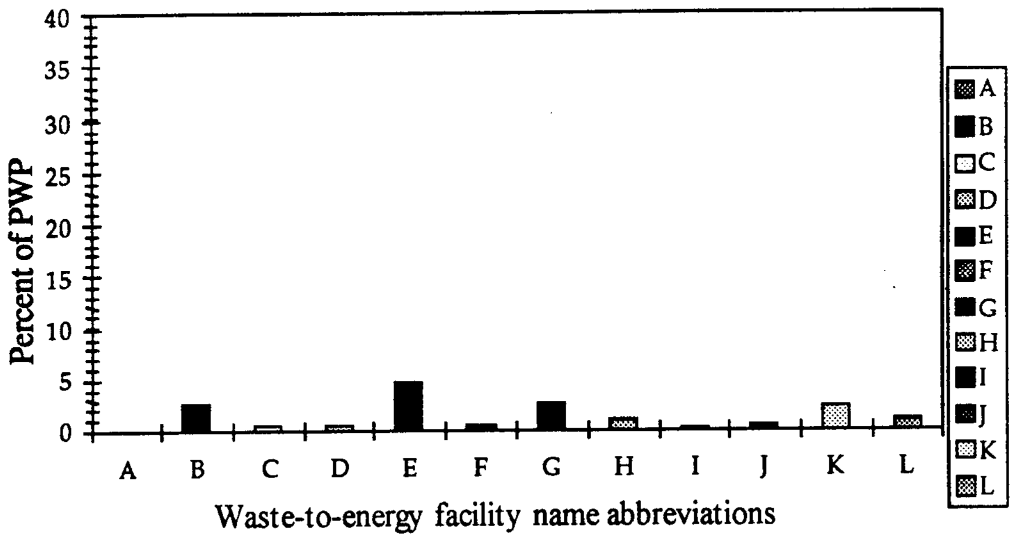


Figure B-3 Twelve waste-to-energy facilities versus percent of PWP (paper, wood, and plastic) of combined ashes passing #3/4 in sieve and retained on #8 sieve

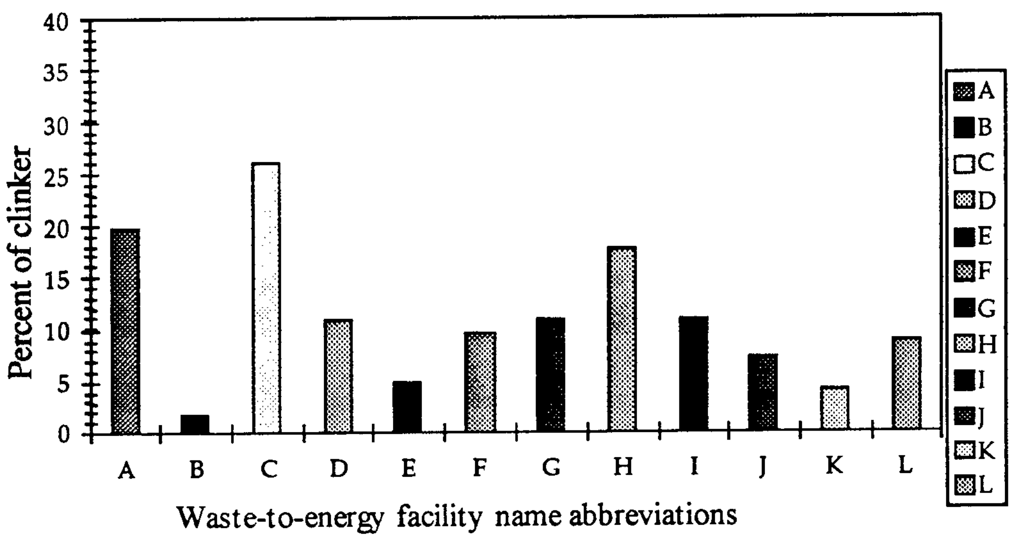


Figure B-4 Twelve waste-to-energy facilities versus percent of clinker of combined ashes passing #3/4 in sieve and retained on #8 sieve

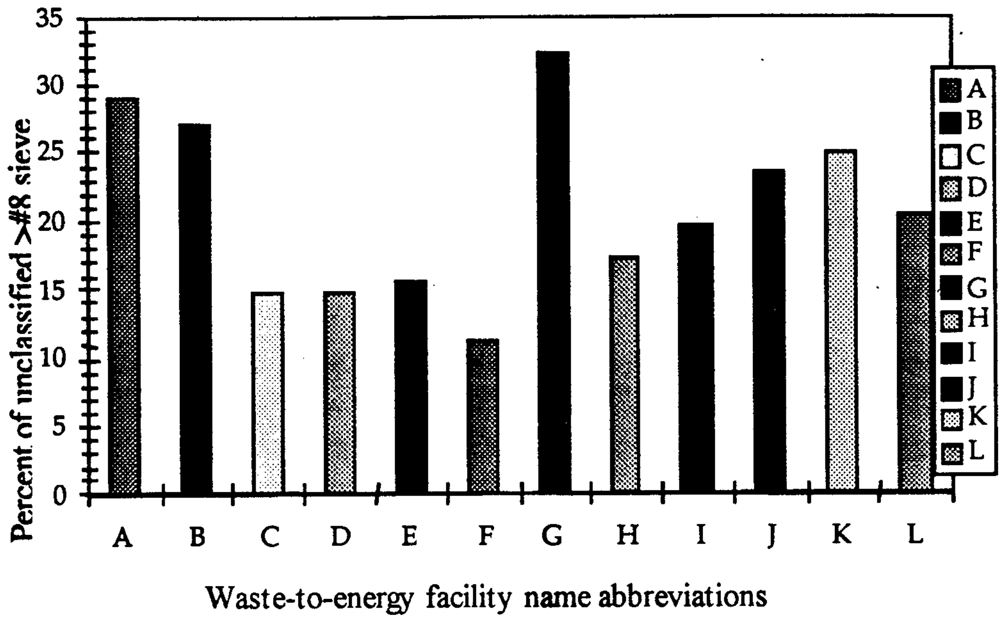


Figure B-5 Twelve waste-to-energy facilities versus percent of unclassified > # 8 sieve of combined ashes passing # 3/4 in sieve and retained on # 8 sieve

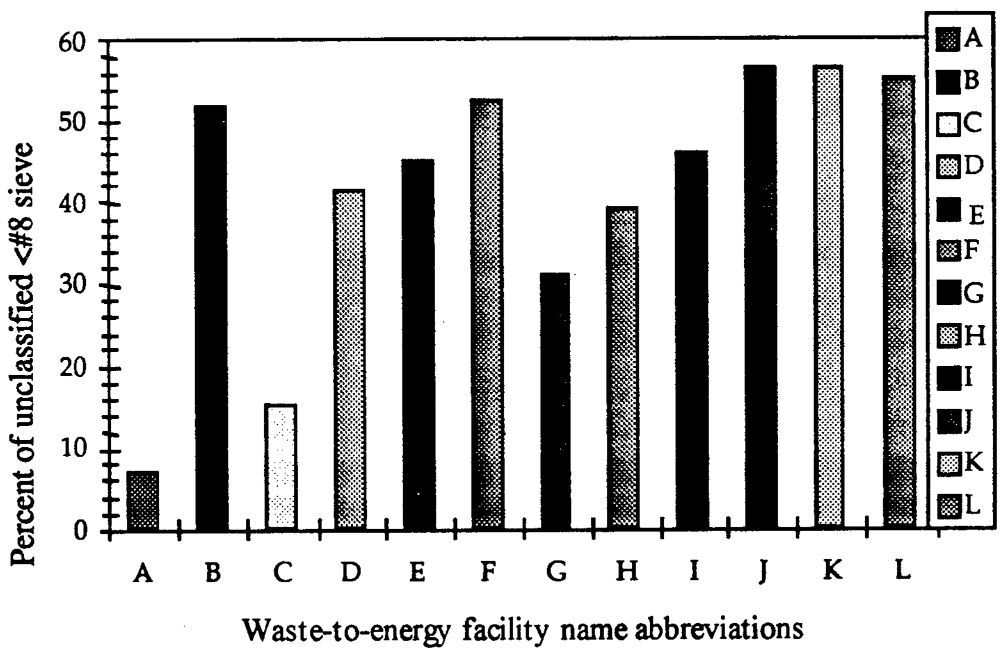


Figure B-6 Twelve waste-to-energy facilities versus percent of unclassified < # 8 sieve of combined ashes

Appendix C

Plots of

Grain size distribution curves of the combined ash from 12

Florida waste-to-energy facilities.

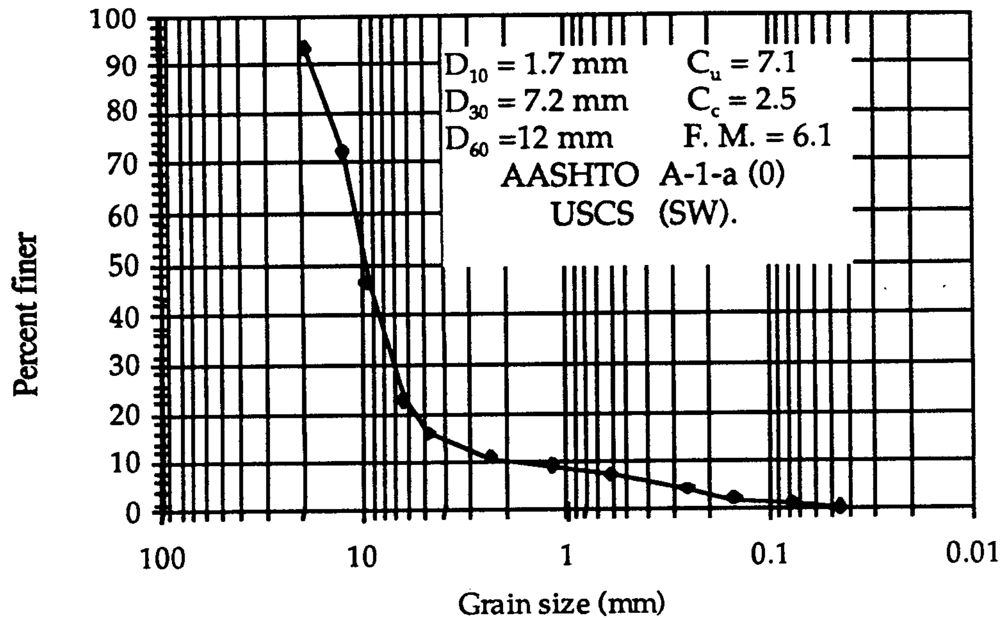


Figure C-1 Grain size distribution of the combined ash from Pasco County Solid Waste Resource Recovery Facility

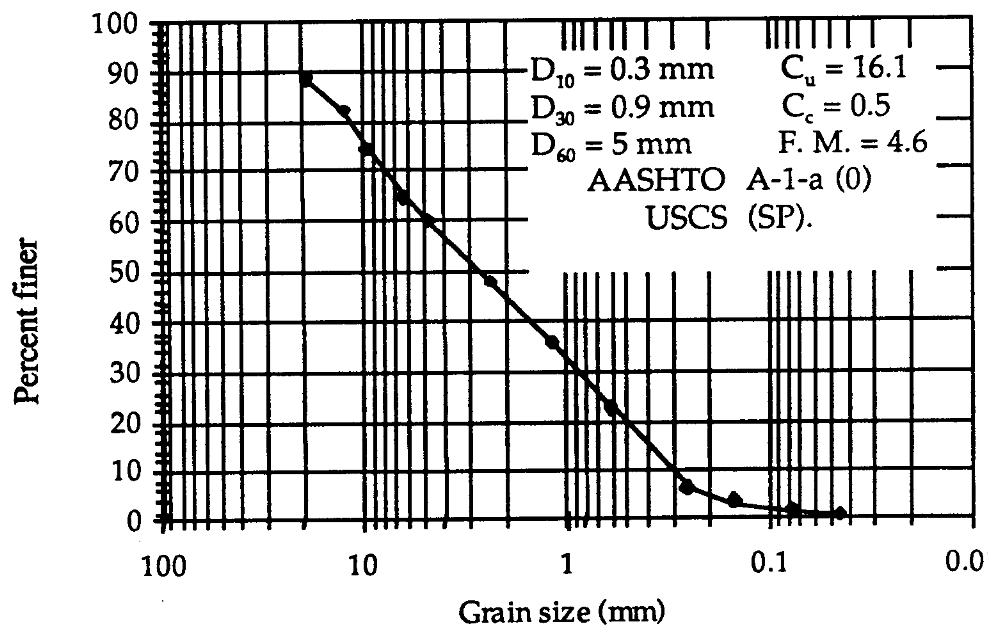


Figure C-2 Grain size distribution of the combined ash from Dade County Resources Recovery Facility

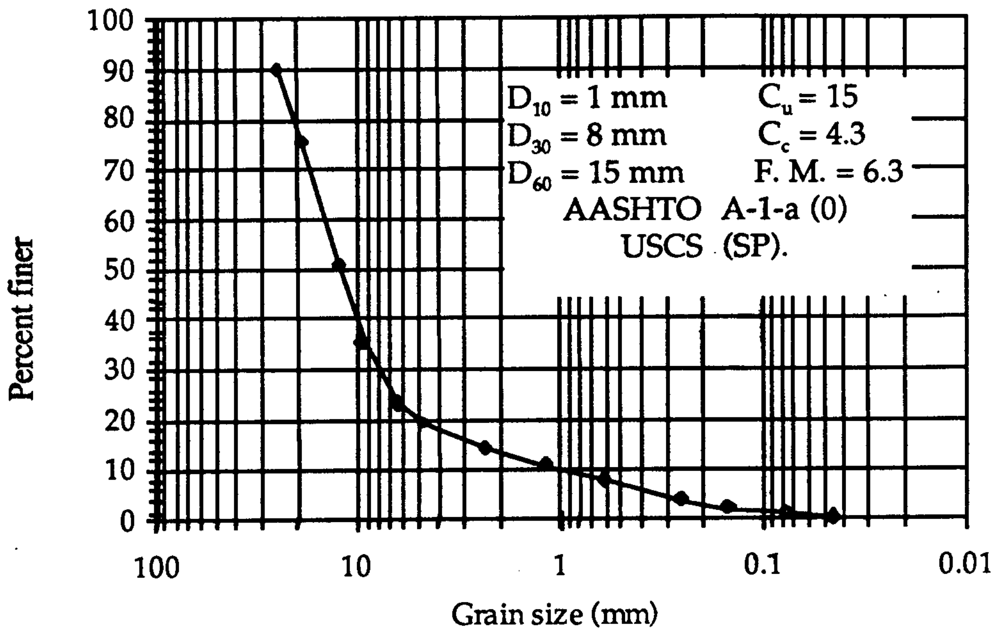


Figure C-3 Grain size distribution of the combined ash from Lake County Resource Recovery Facility

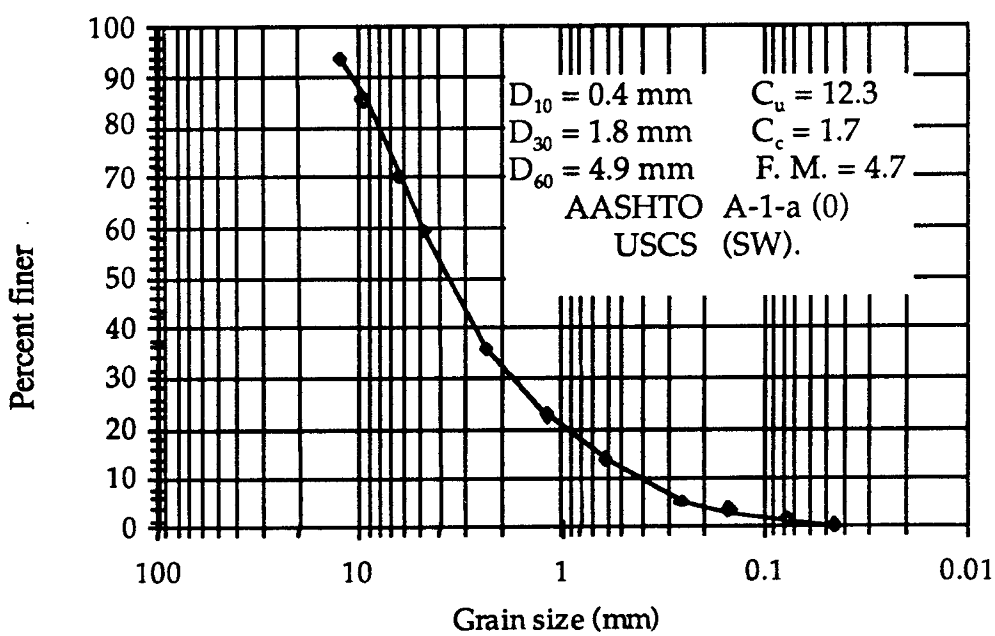


Figure C-4 Grain size distribution of the combined ash from North Broward County Resource Recovery Facility

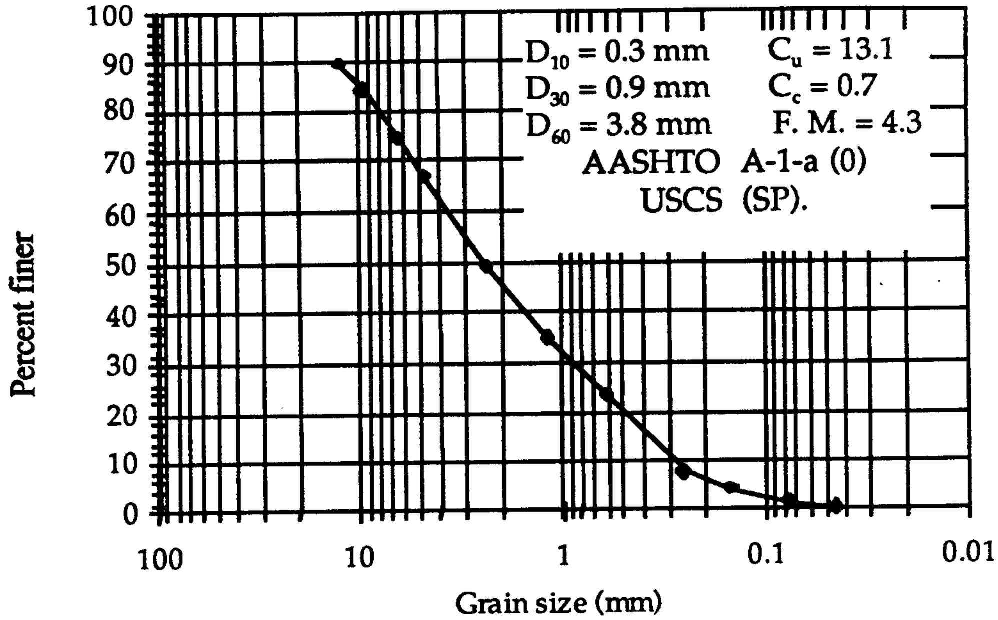


Figure C-5 Grain size distribution of the combined ash from South Broward County Resource Recovery Facility

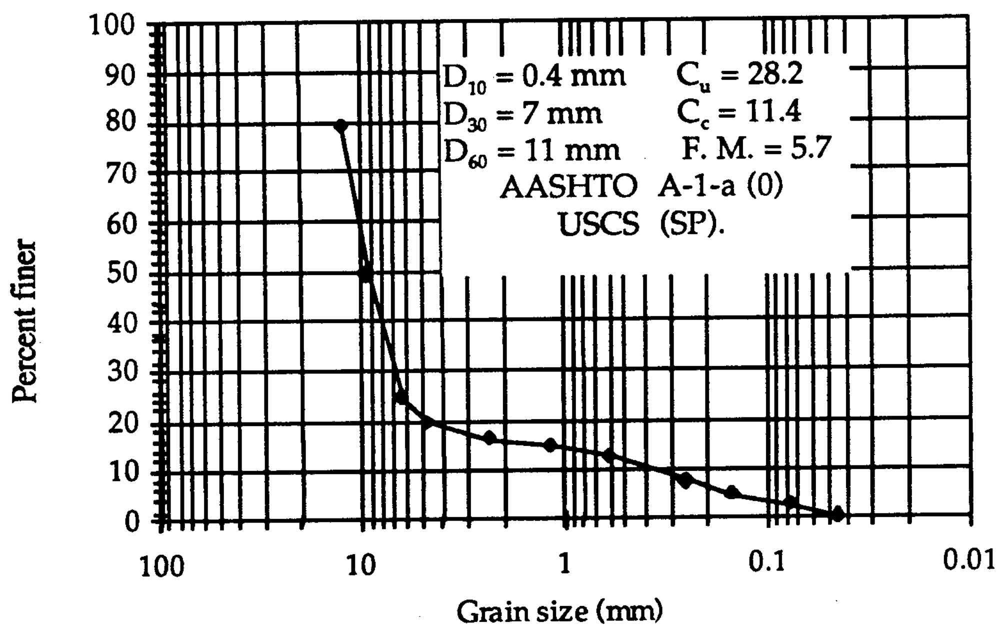


Figure C-6 Grain size distribution of the combined ash from Hillsborough County Solid Waste Energy Recovery Facility

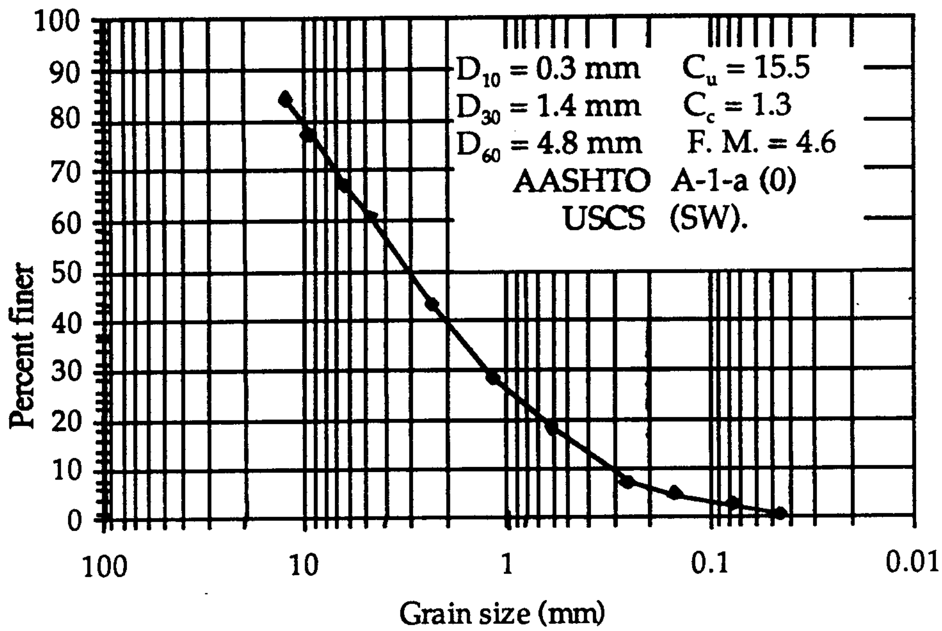


Figure C-7 Grain size distribution of the combined ash from North County Regional Resource Recovery Facility

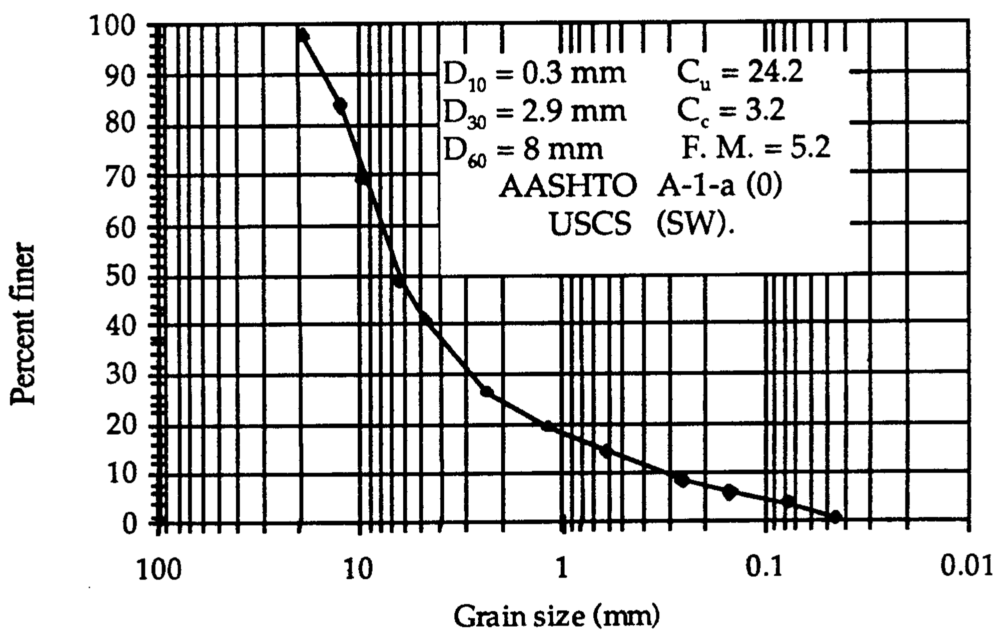


Figure C-8 Grain size distribution of the combined ash from Lee County Solid Waste Resource Recovery Facility

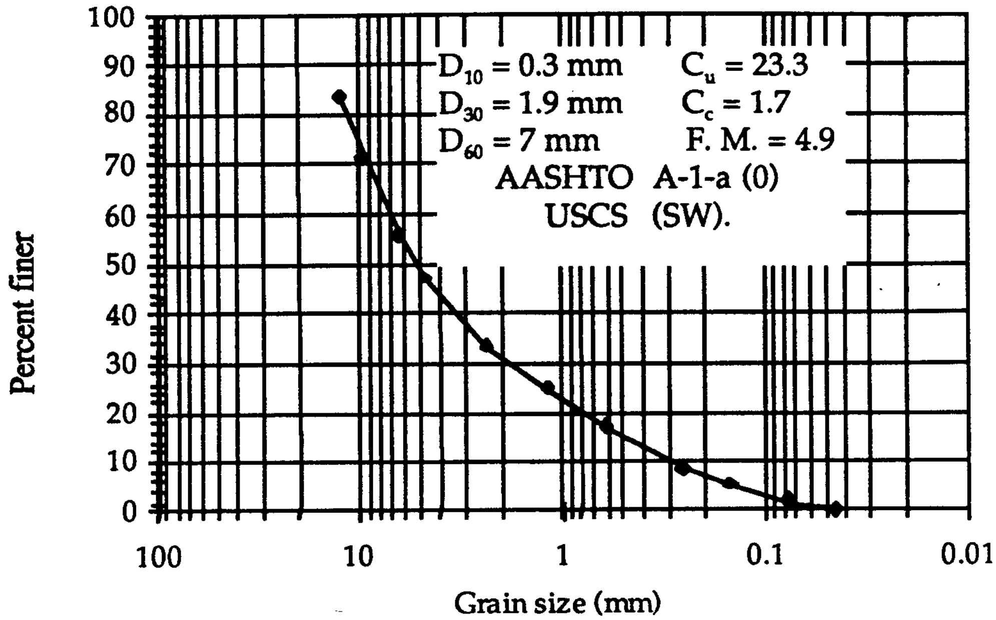


Figure C-9 Grain size distribution of the combined ash from Pinellas County Solid Waste Resource Recovery Facility

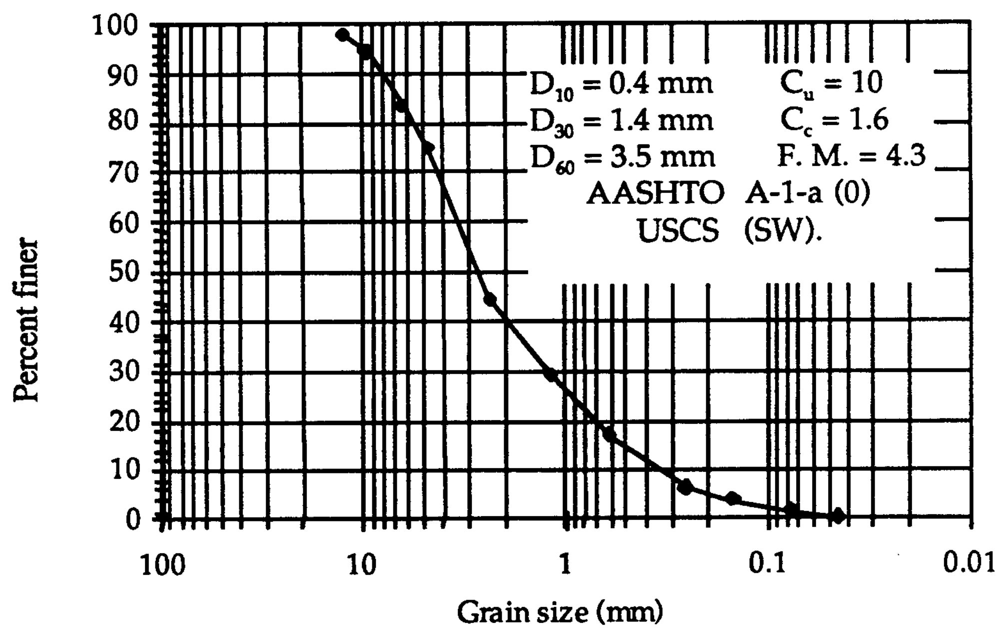


Figure C-10 Grain size distribution of the combined ash from McKay Bay Refuse to Energy Project

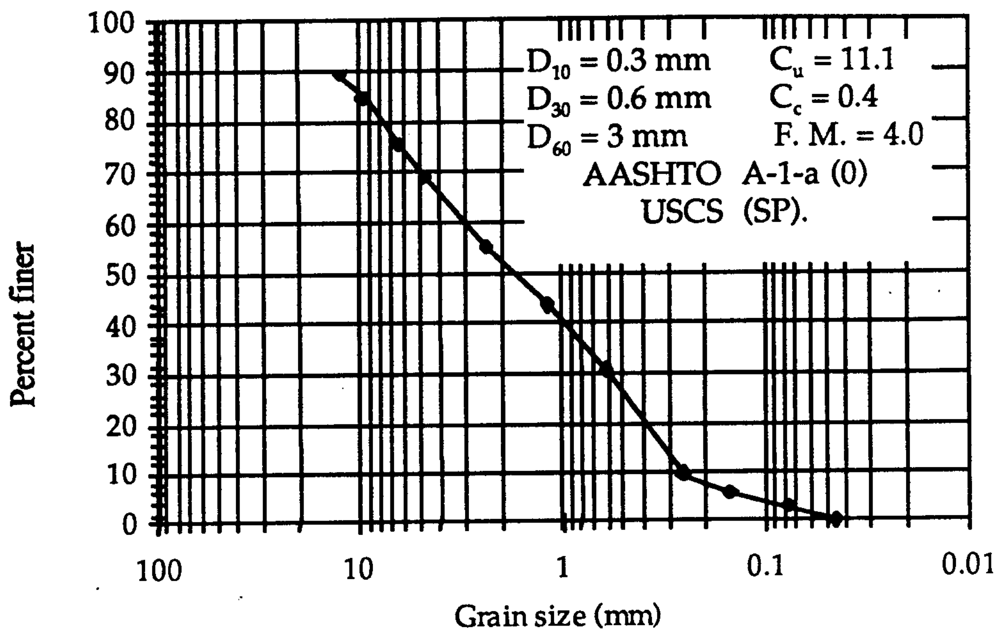


Figure C-11 Grain size distribution of the combined ash from Bay County Resource Recovery Facility

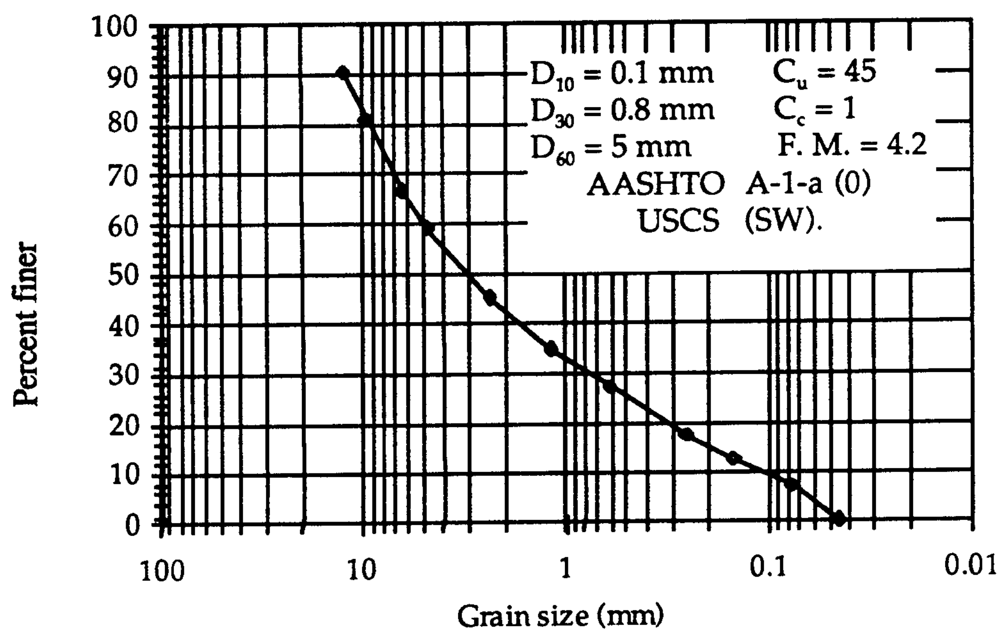
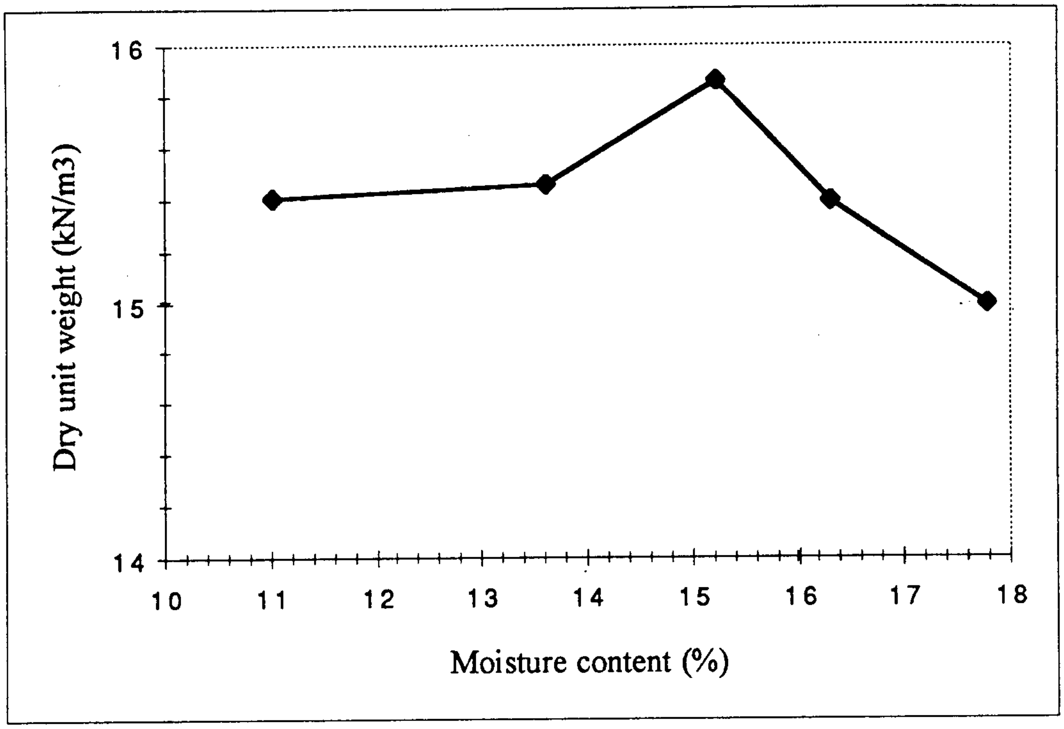


Figure C-12 Grain size distribution of the combined ash from Southernmost Waste-to-Energy Facility

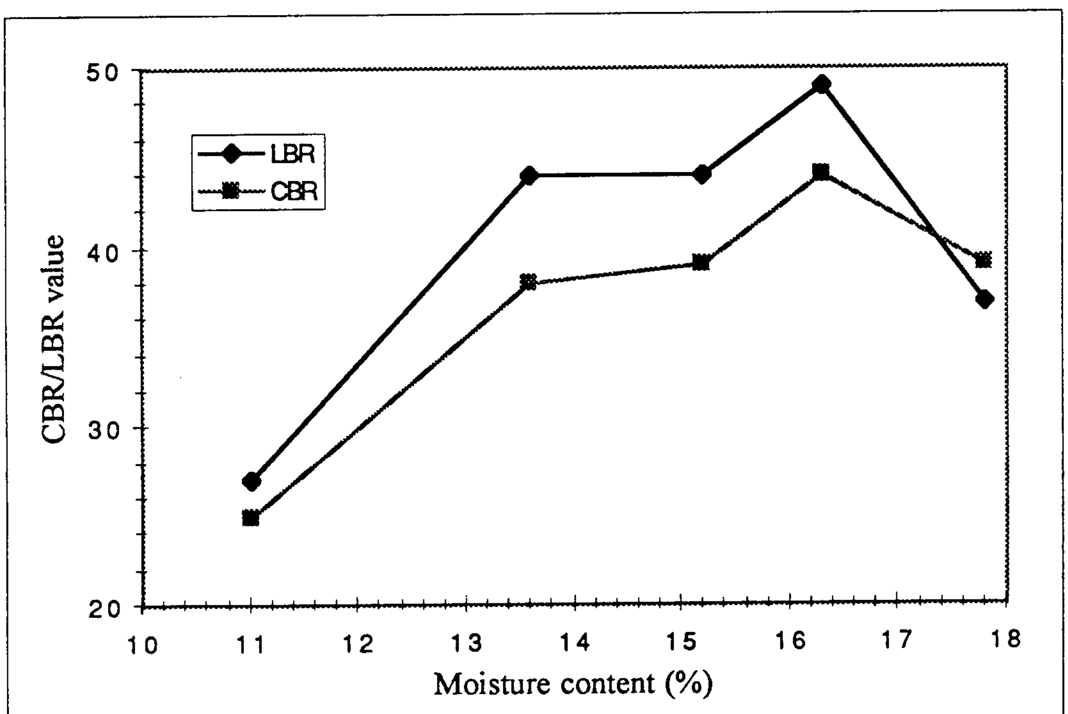
Appendix D

Plots of

Dry unit weight and CBR/LBR values with respect to moisture content from twelve Florida waste-to-energy facilities.

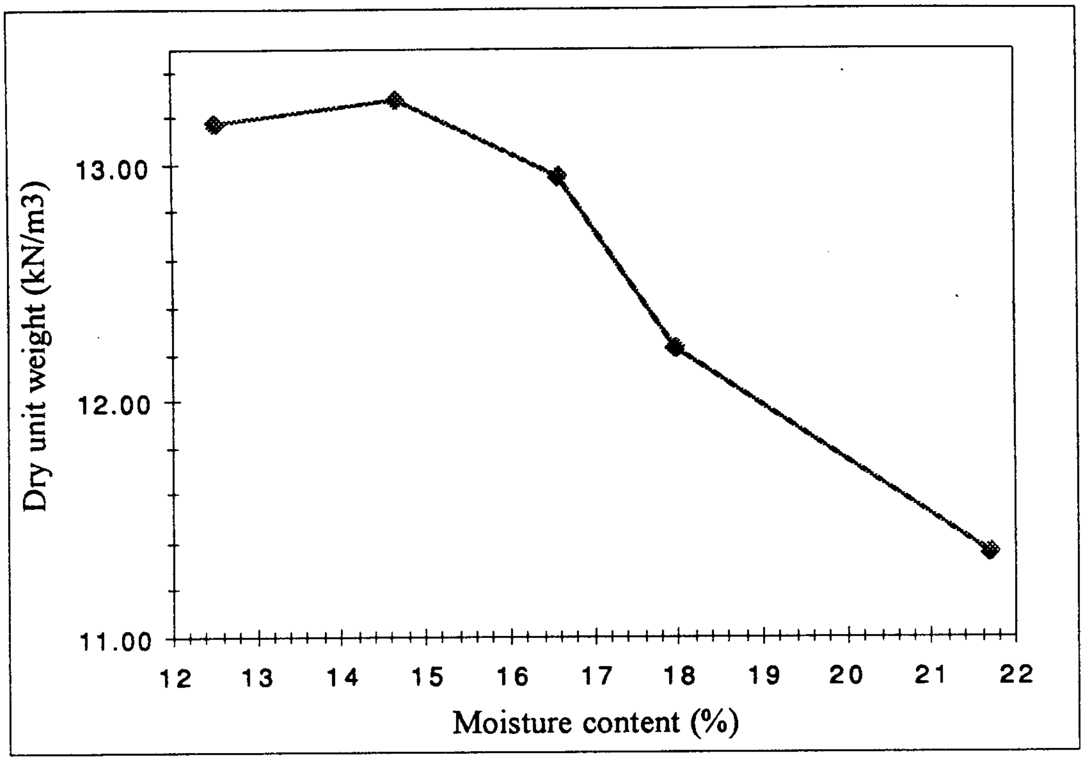


(a)

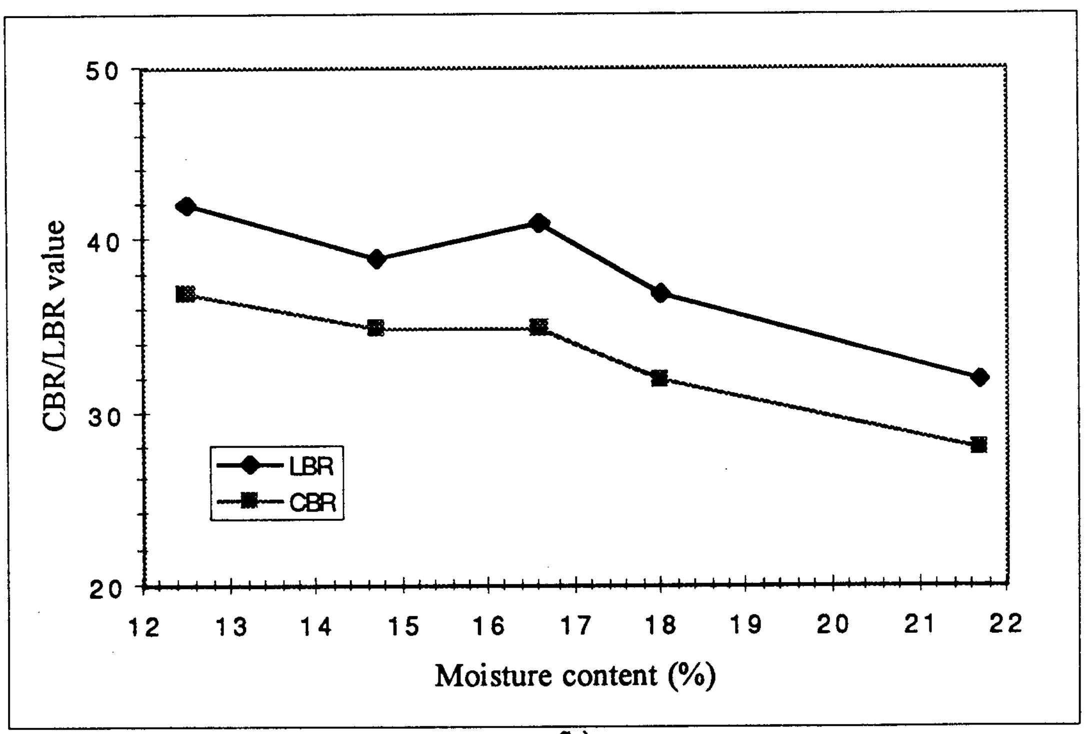


(b)

Figure D-1 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Pasco County Solid Waste Resources Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

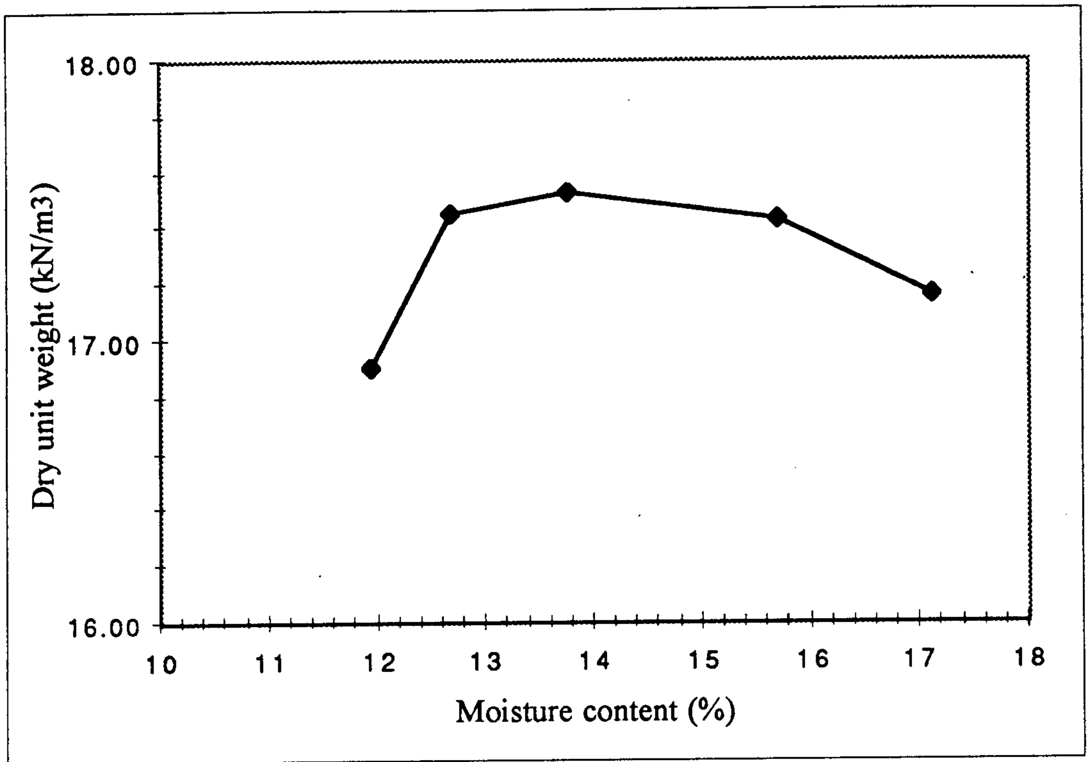


(a)

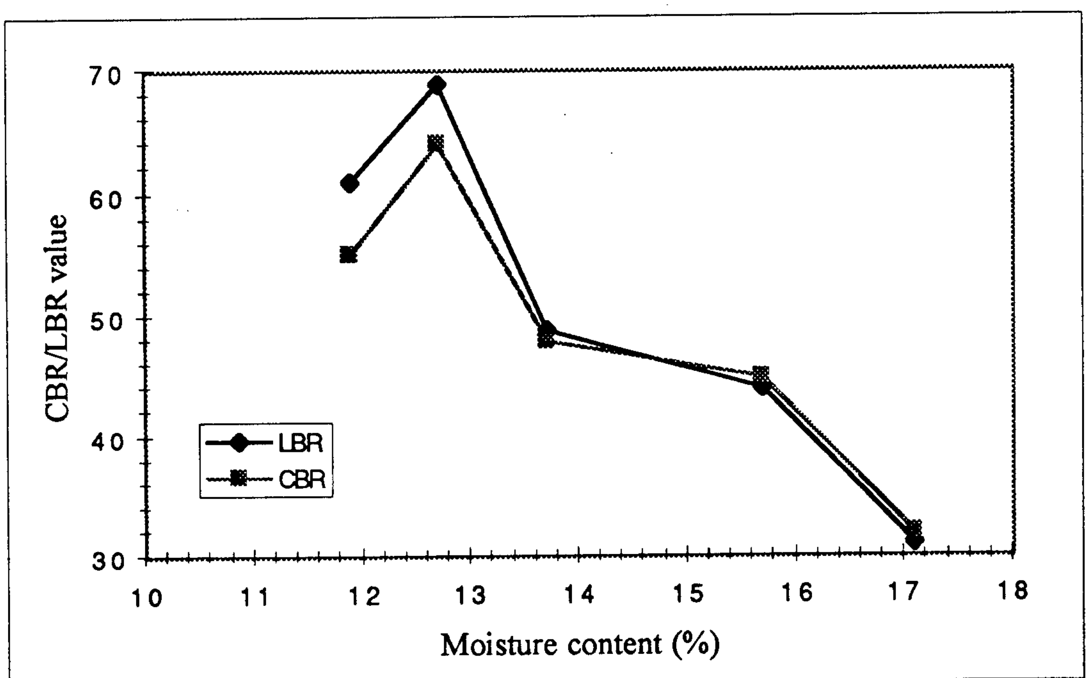


(b)

Figure D-2 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Dade County Resources Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

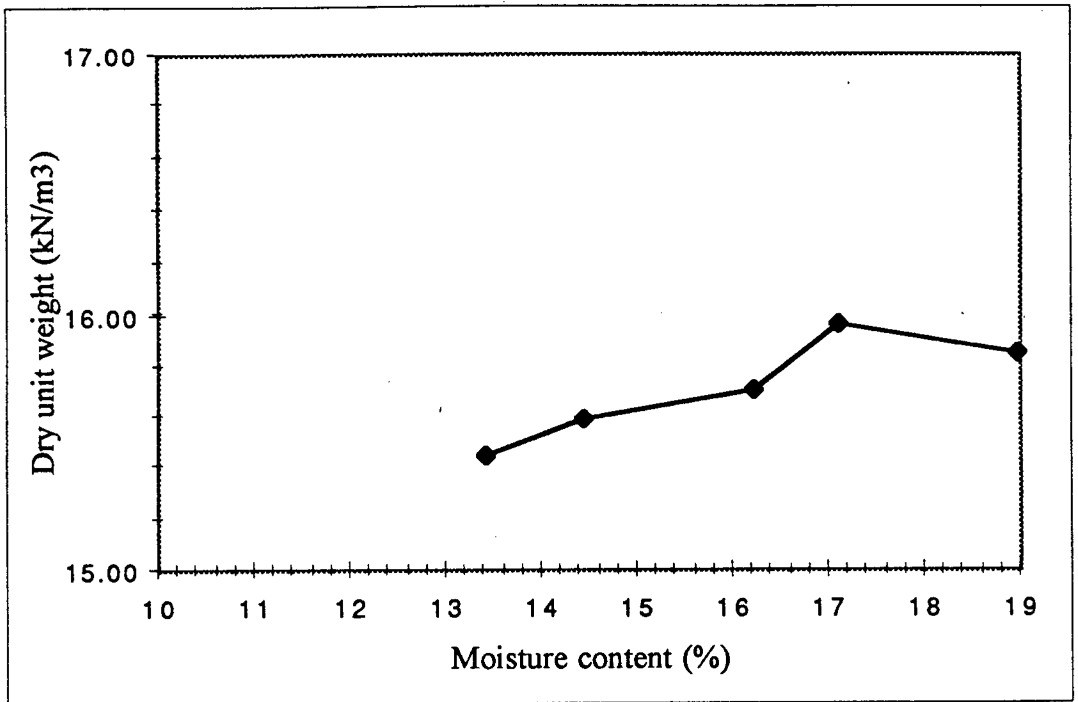


(a)

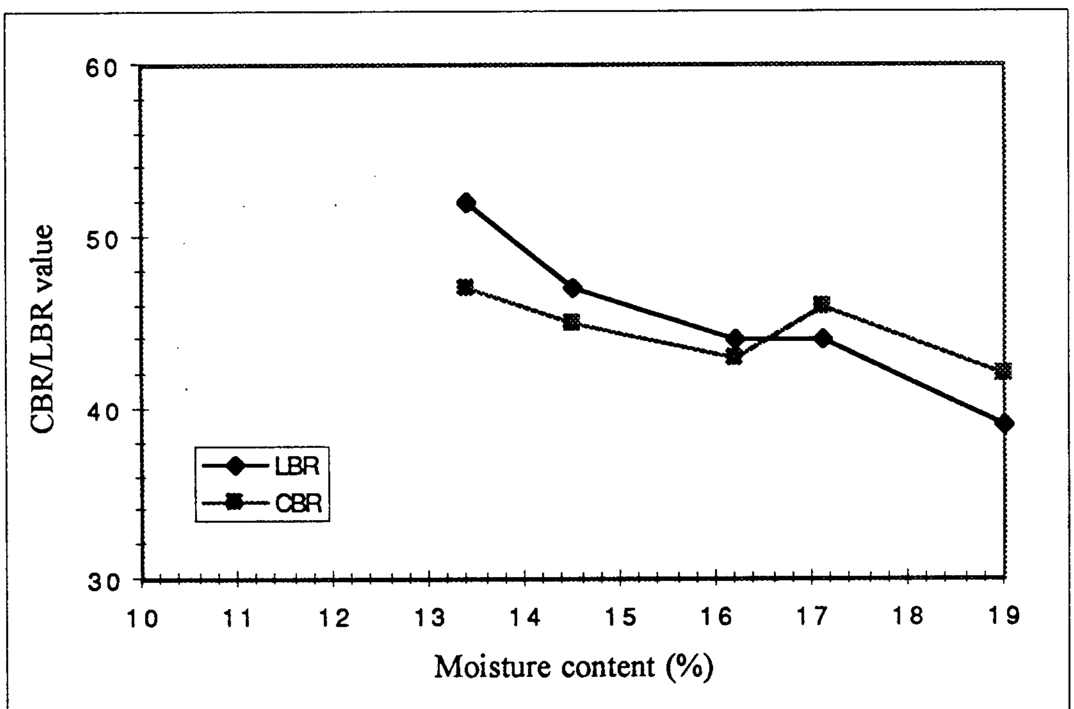


(b)

Figure D-3 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Lake County Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

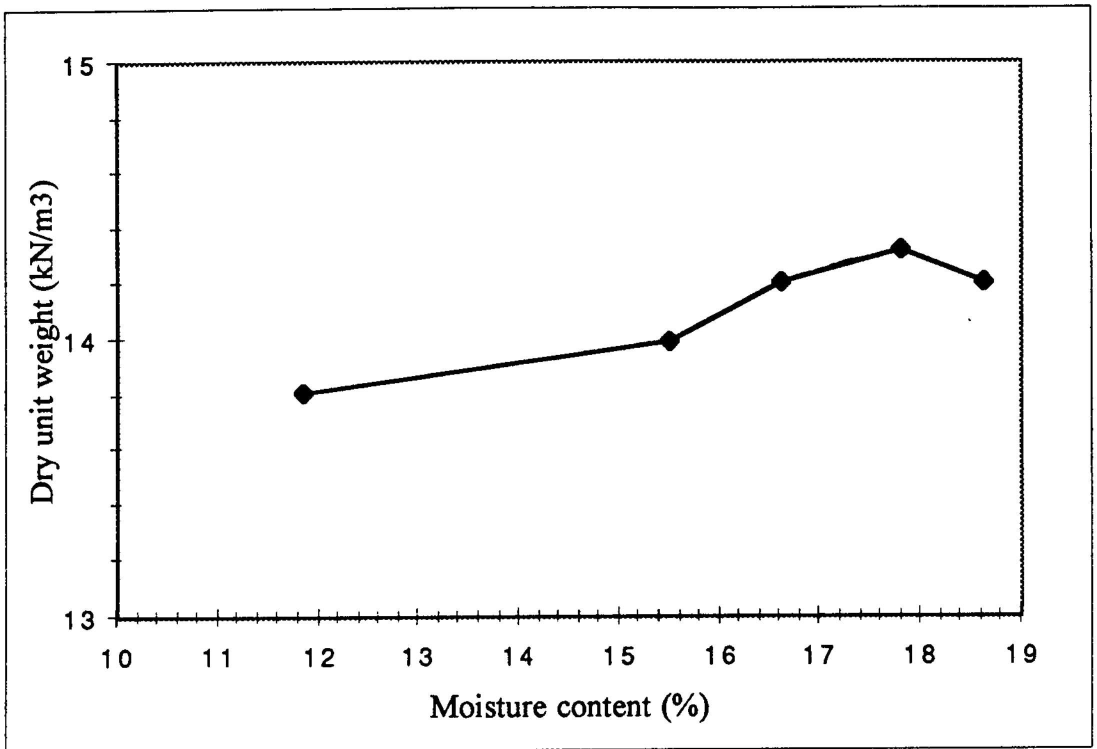


(a)

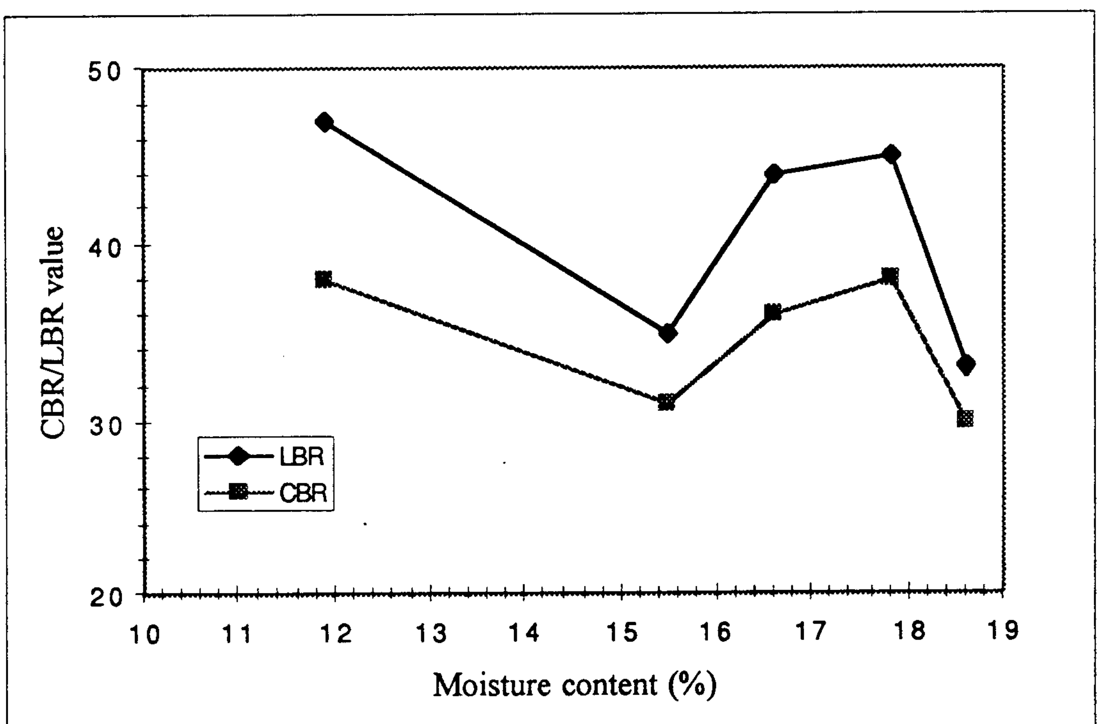


(b)

Figure D-4 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for North Broward County Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

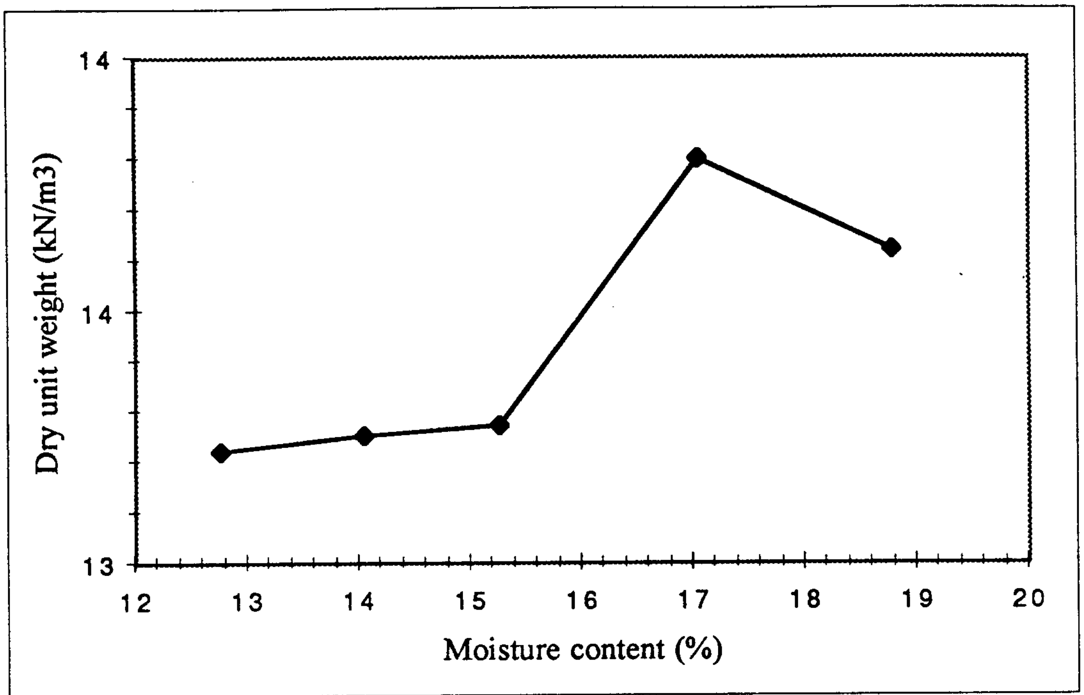


(a)

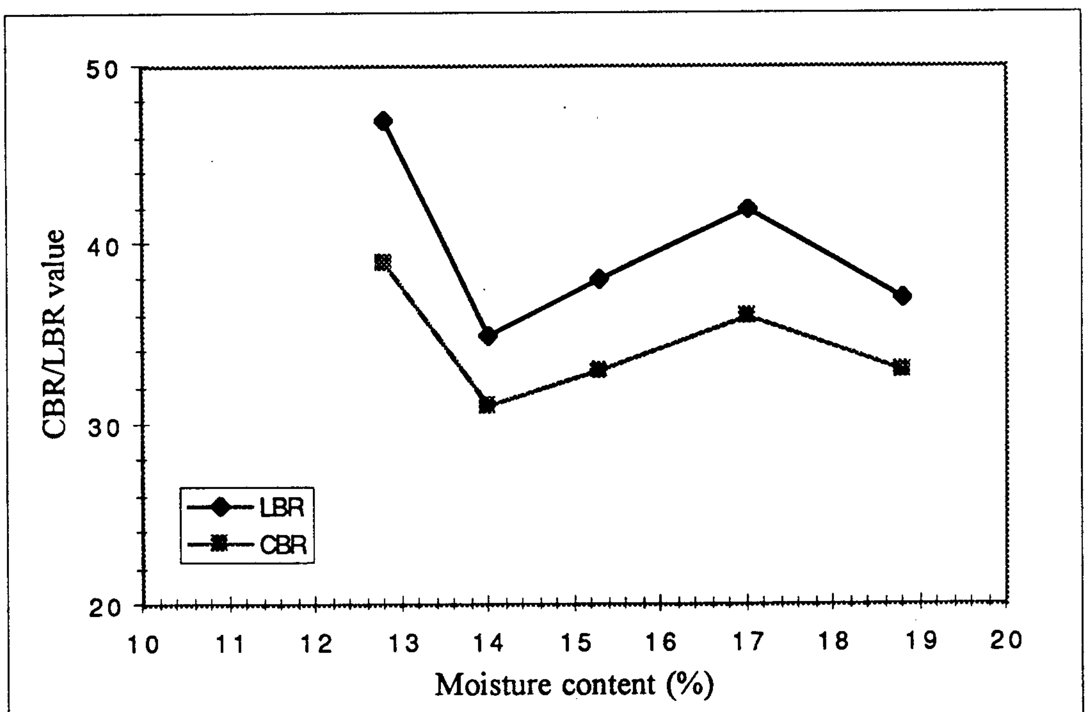


(b)

Figure D-5 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for South Broward County Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)



(a)



(b)

Figure D-6 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for North County Regional Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

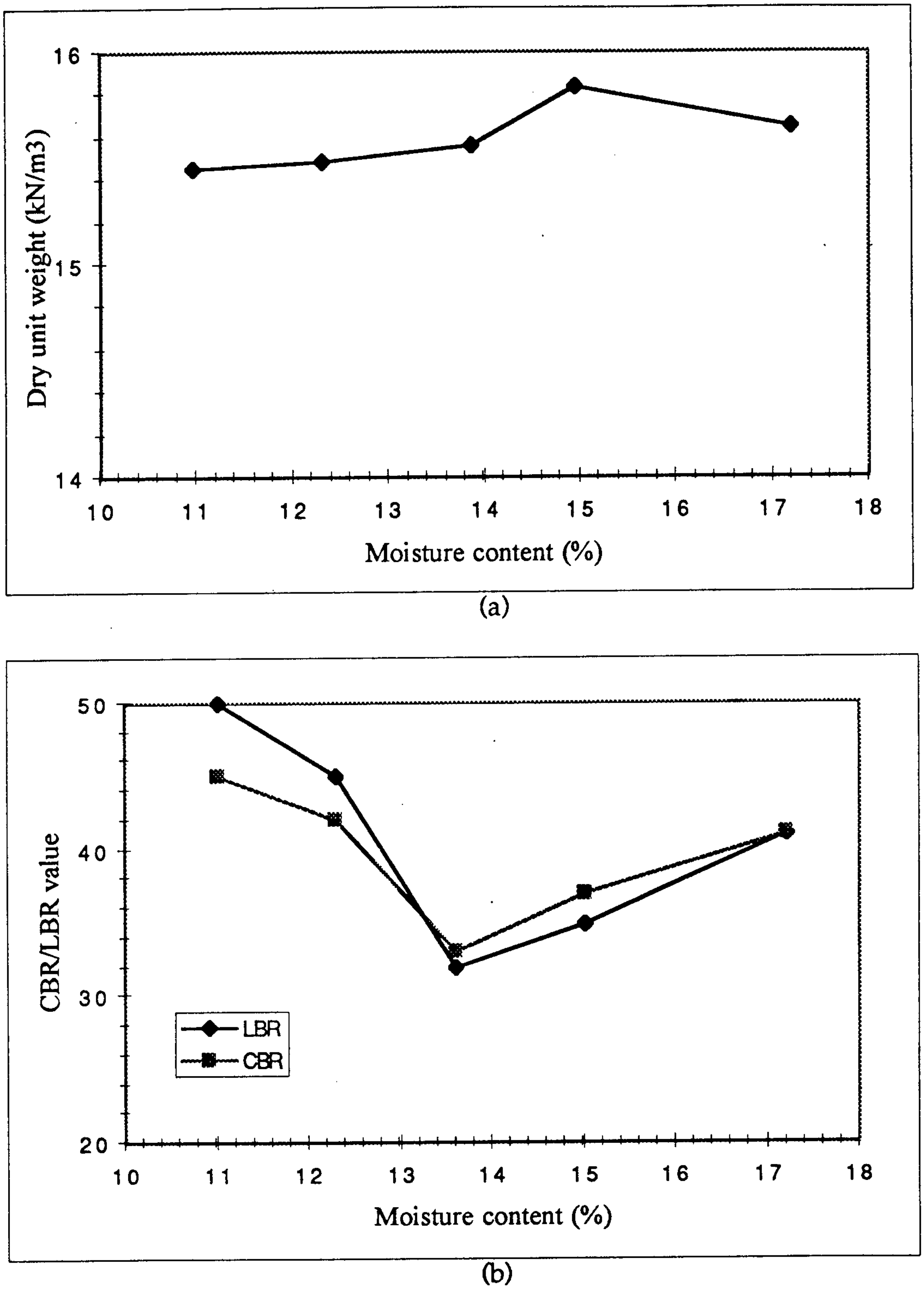


Figure D-7 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Hillsborough County Solid Waste Energy Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

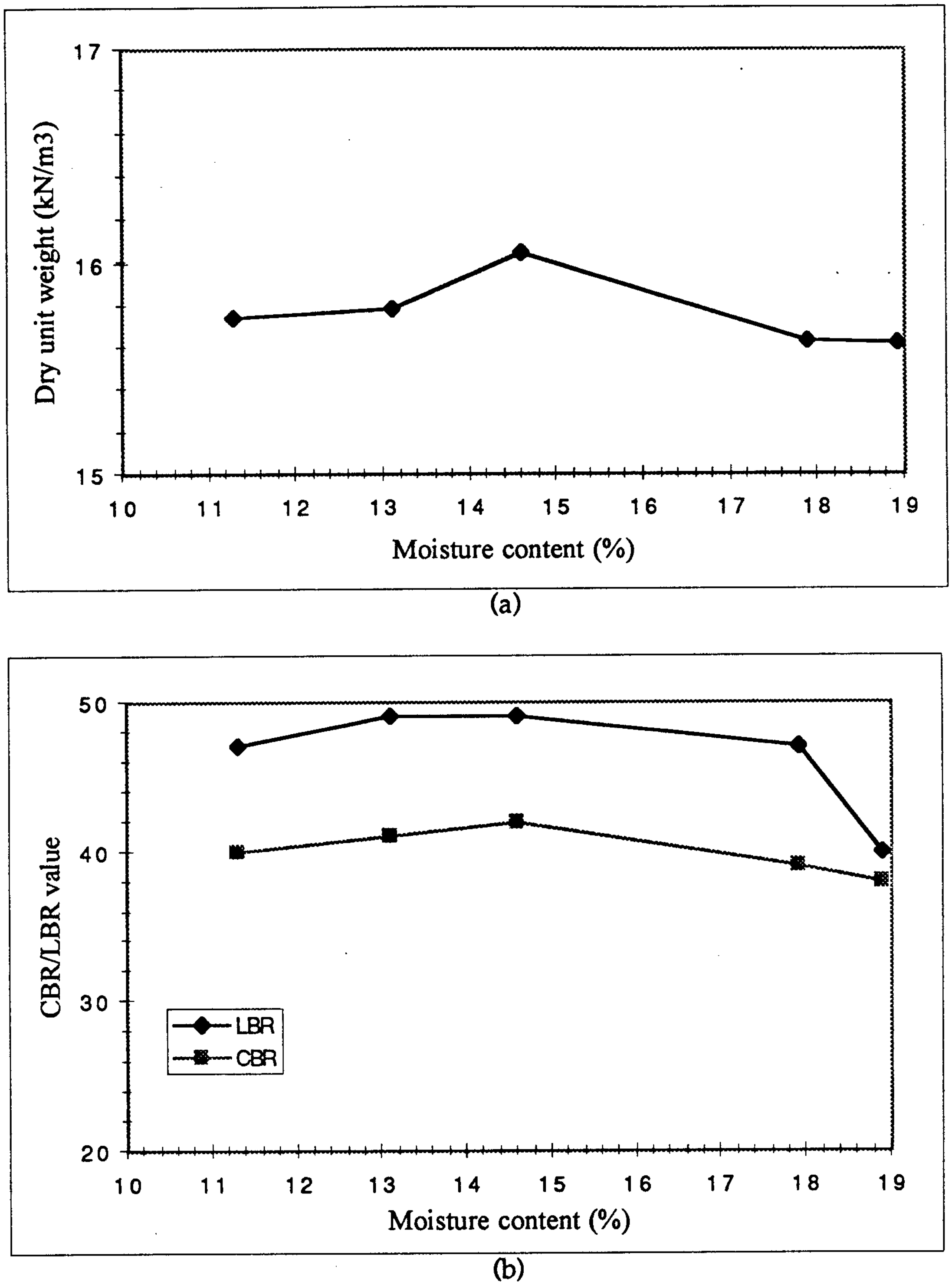
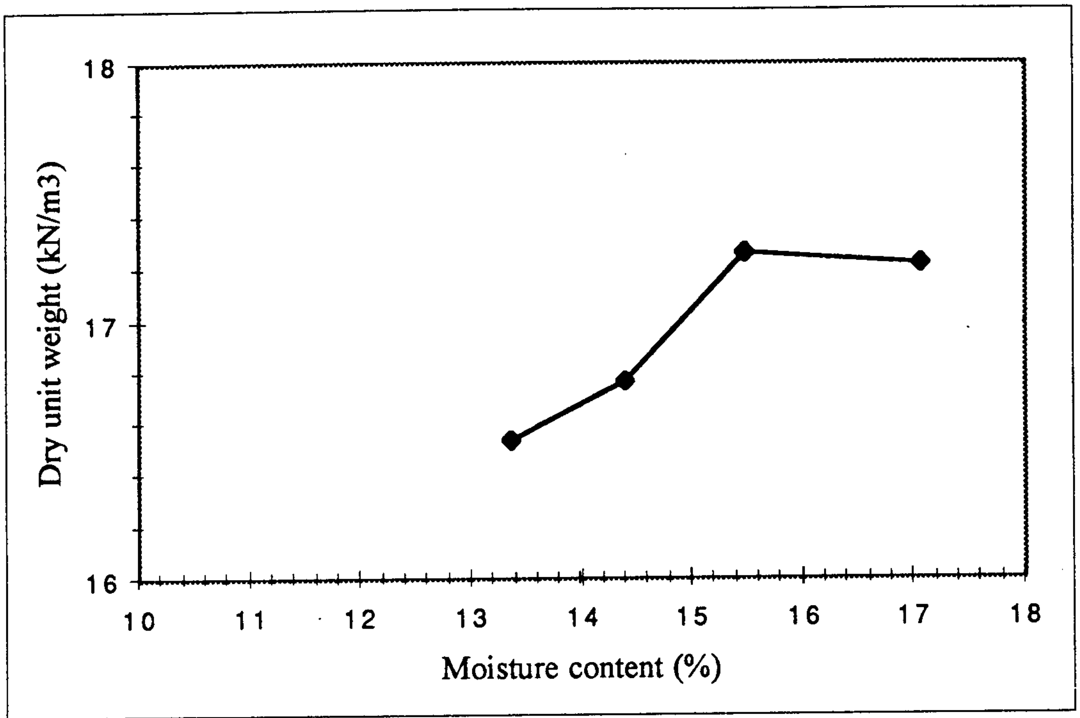
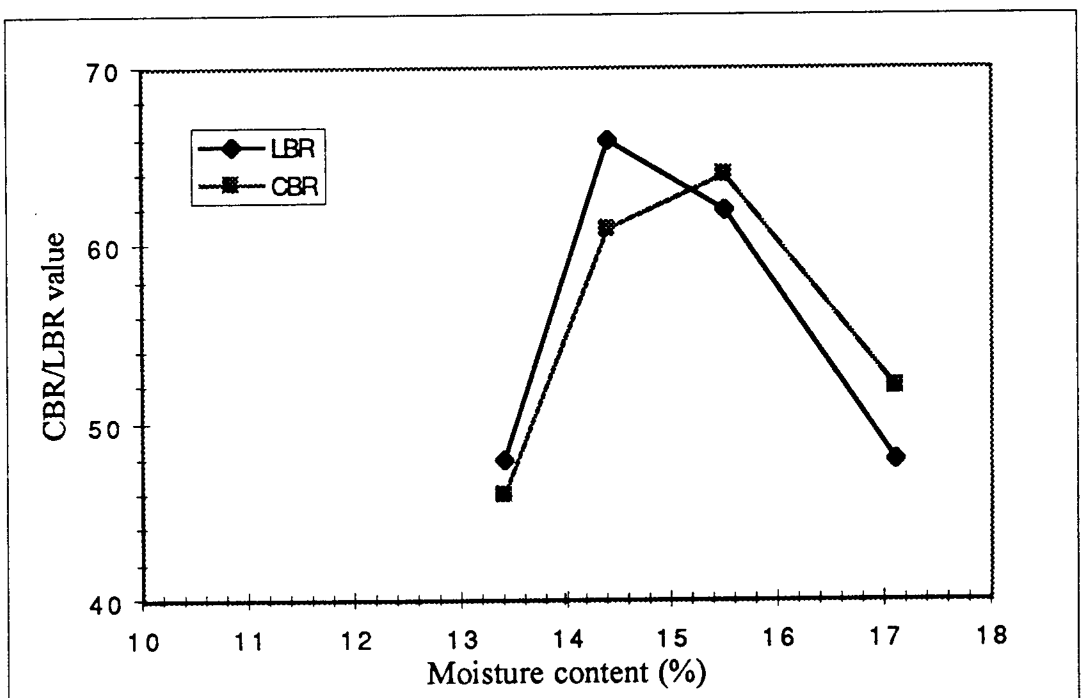


Figure D-8 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Lee County Solid Waste Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

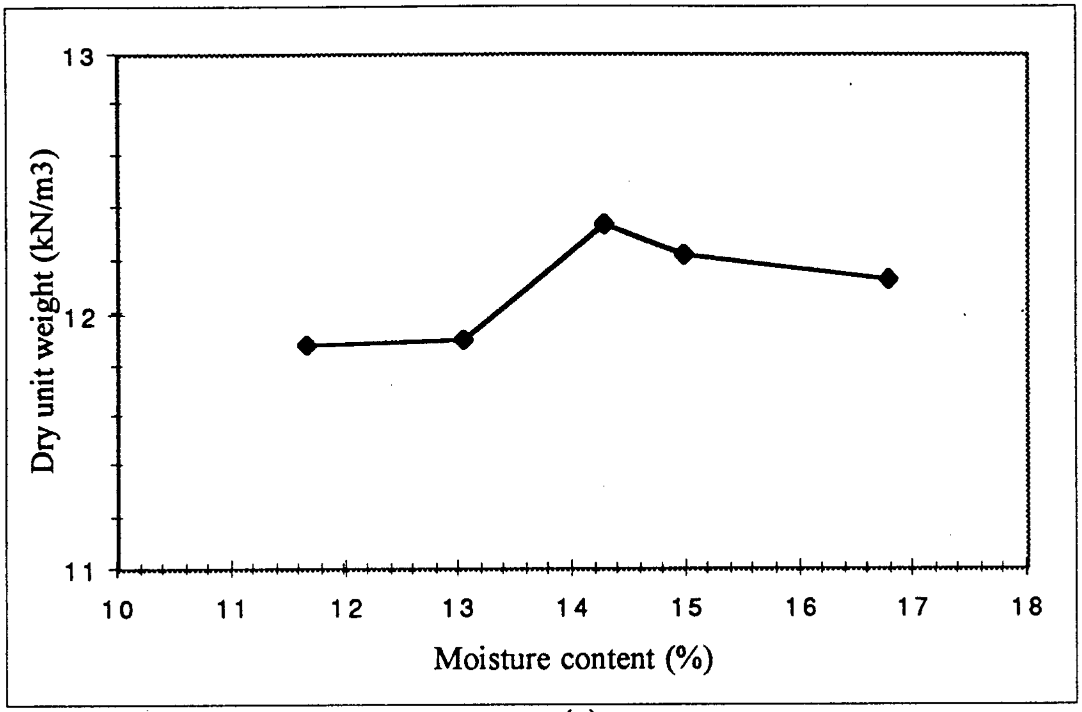


(a)

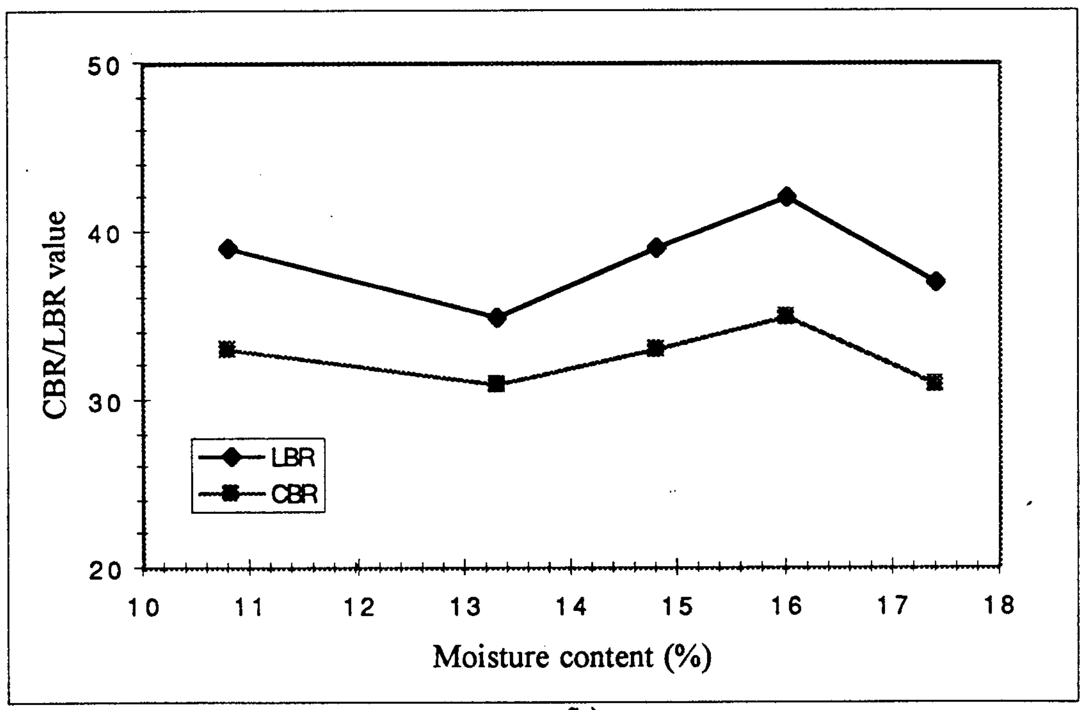


(b)

Figure D-9 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Pinellas County Solid Waste Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)



(a)



(b)

Figure D-10 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for McKay Bay Refuse to Energy Project combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

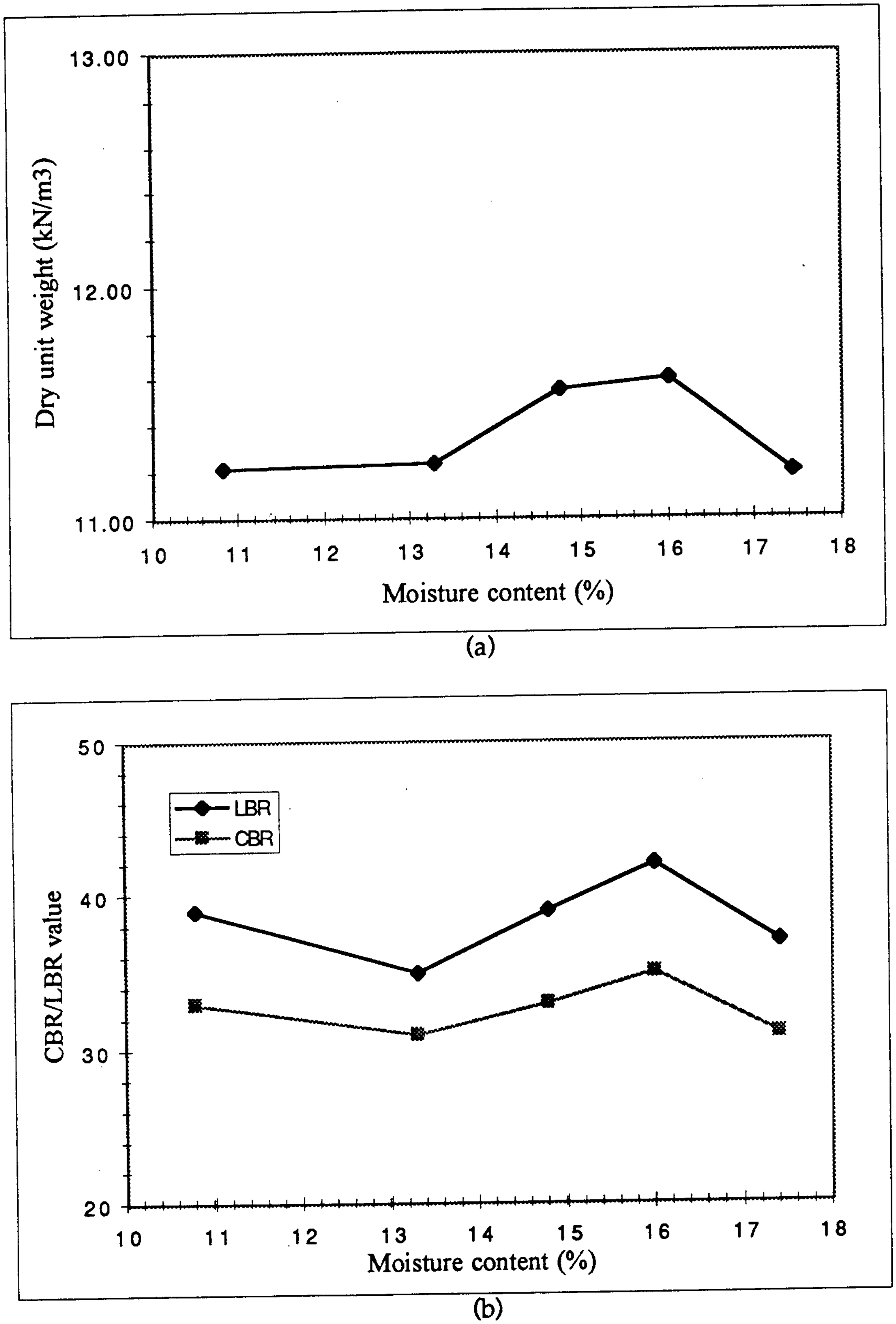
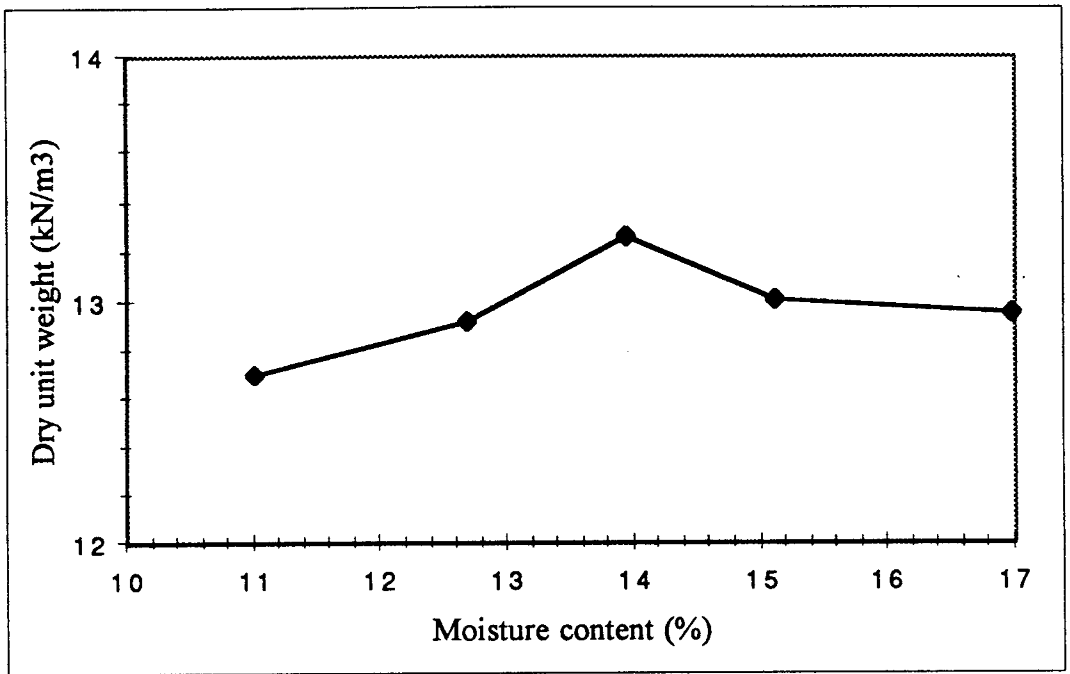
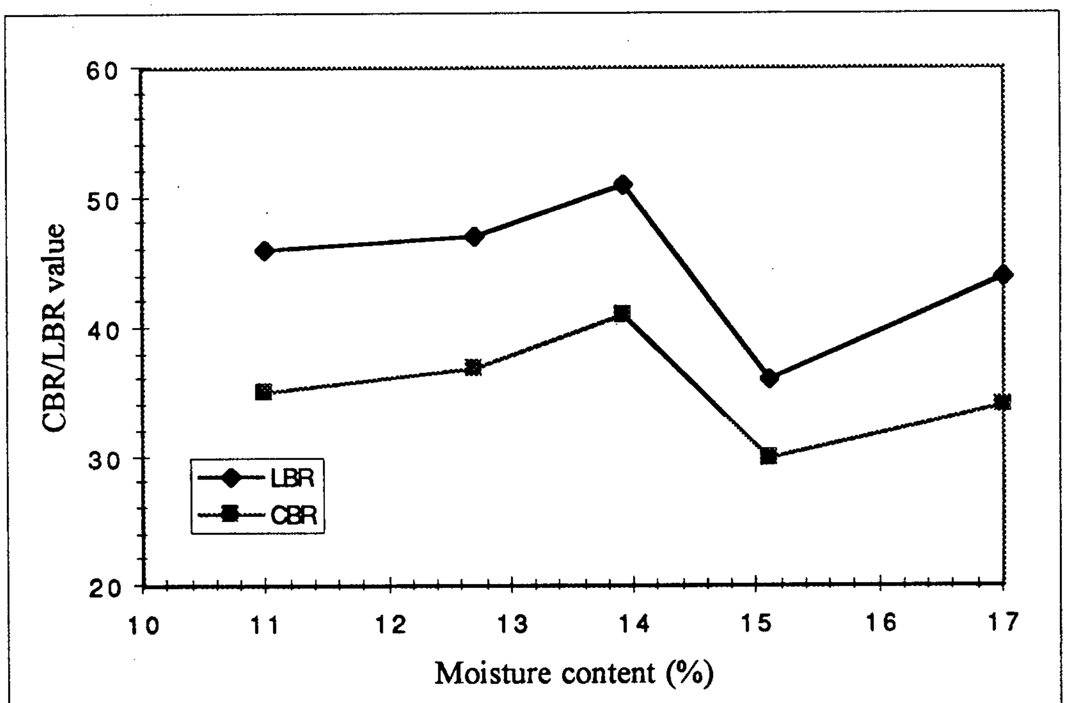


Figure D-11 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Bay County Resource Recovery Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)



(a)



(b)

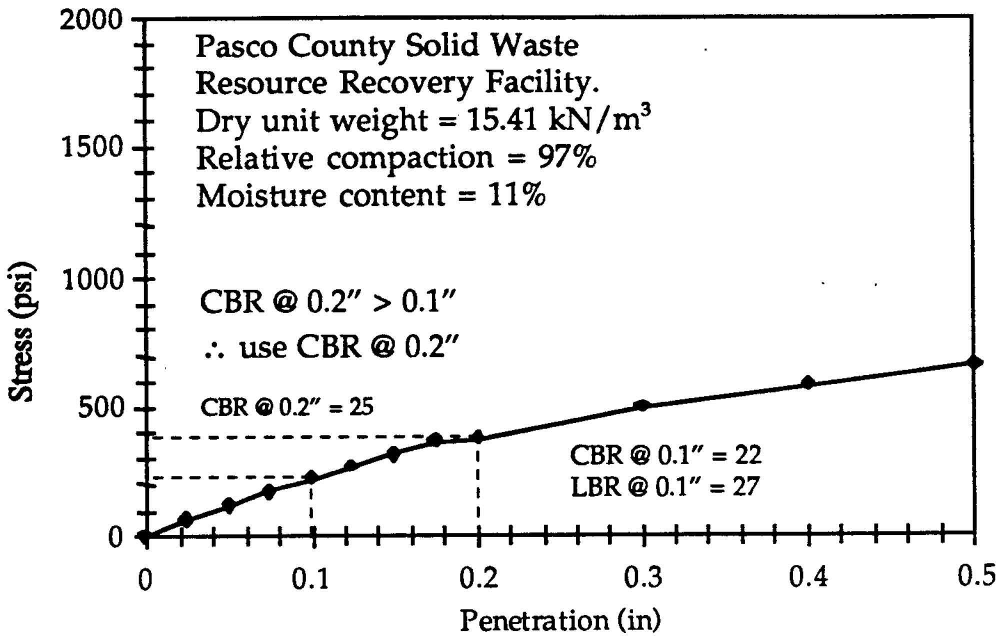
Figure D-12 Moisture content versus (a) dry unit weight and (b) CBR @ 0.2 inch deflection and LBR @ 0.1 inch deflection values for Southernmost Waste-to-Energy Facility combined ash passing #3/4 inch sieve (1 pcf= 0.157 kN/m^3)

Appendix E

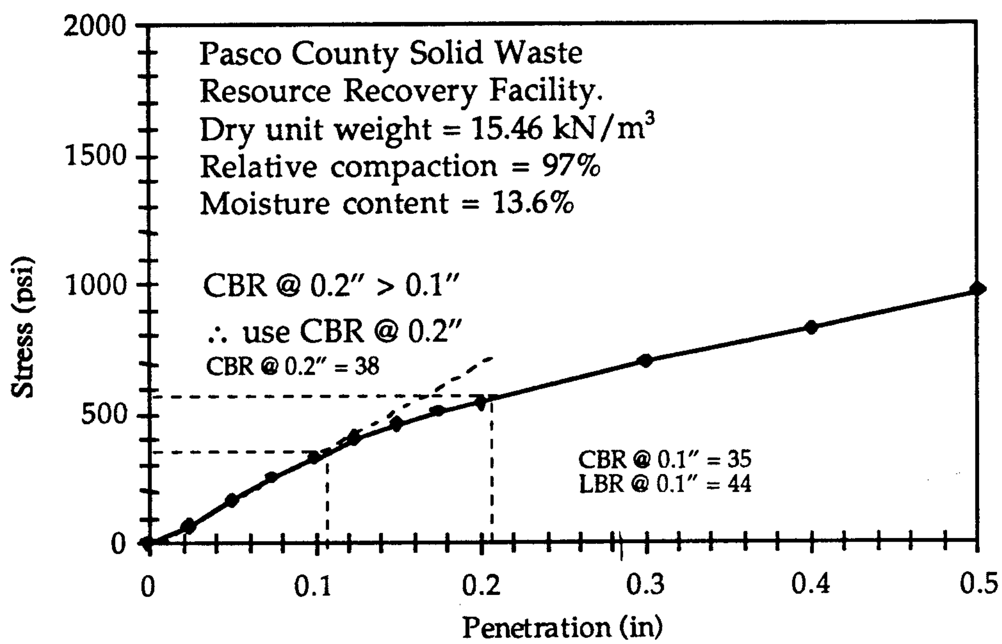
Plots of

Stress versus penetration curves of combined ash from twelve

Florida waste-to-energy facilities.

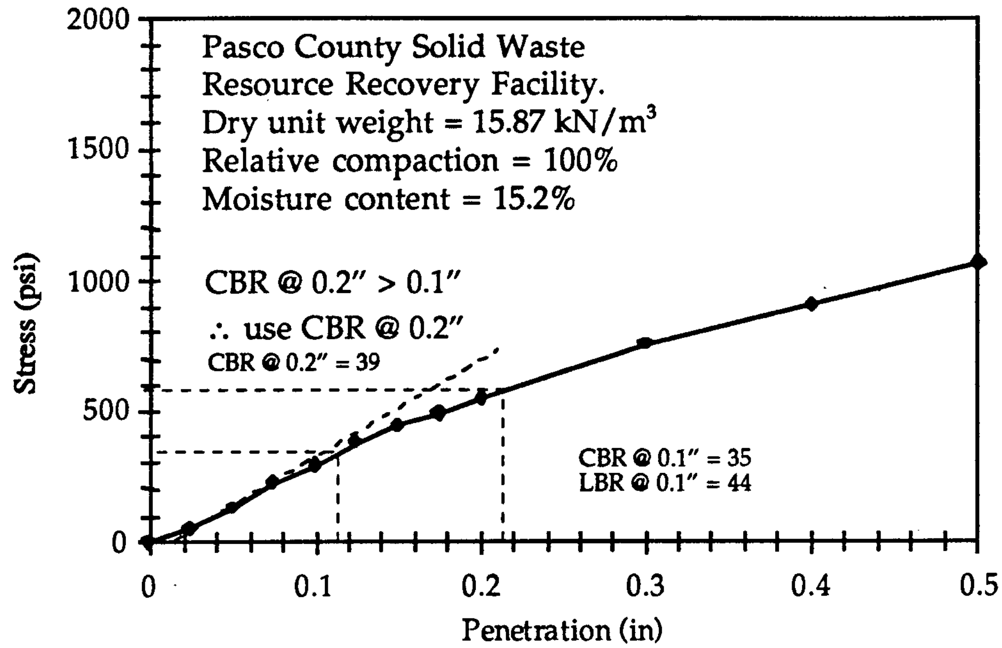


(a)

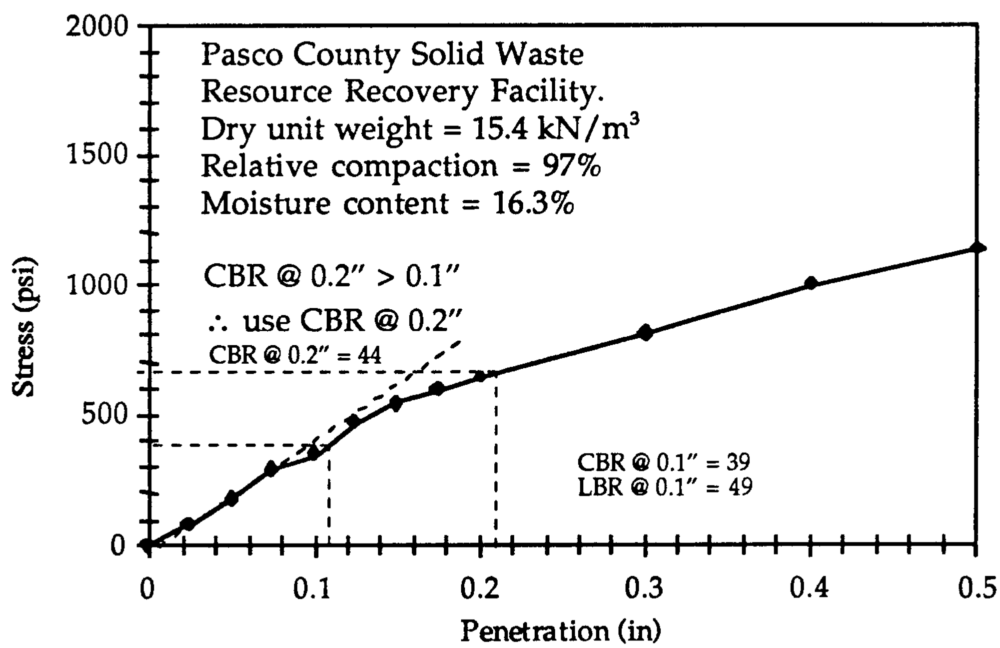


(b)

Figure E-1 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11% (b) 13.6%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

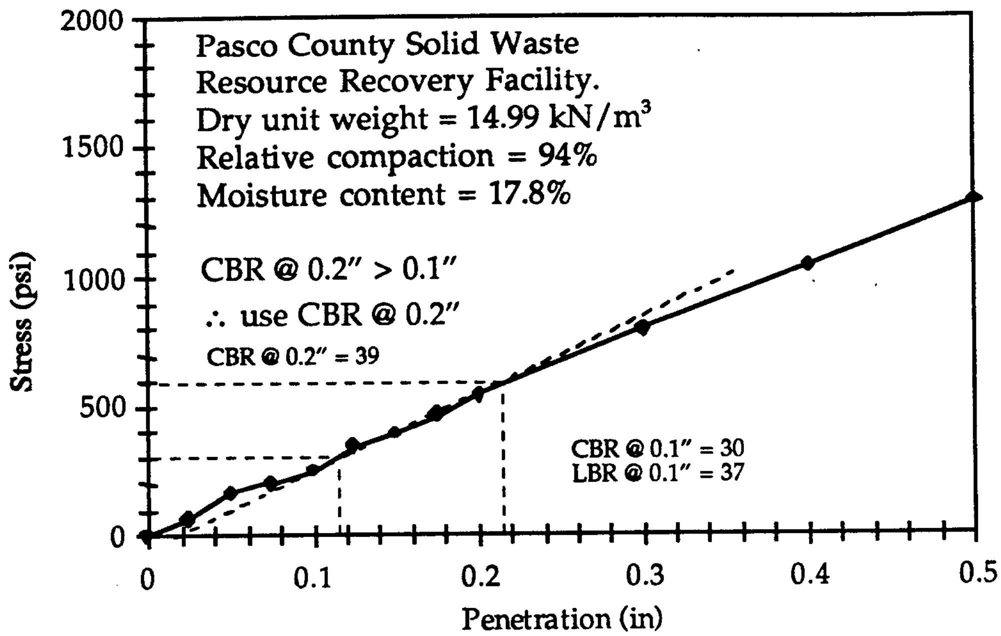


(c)



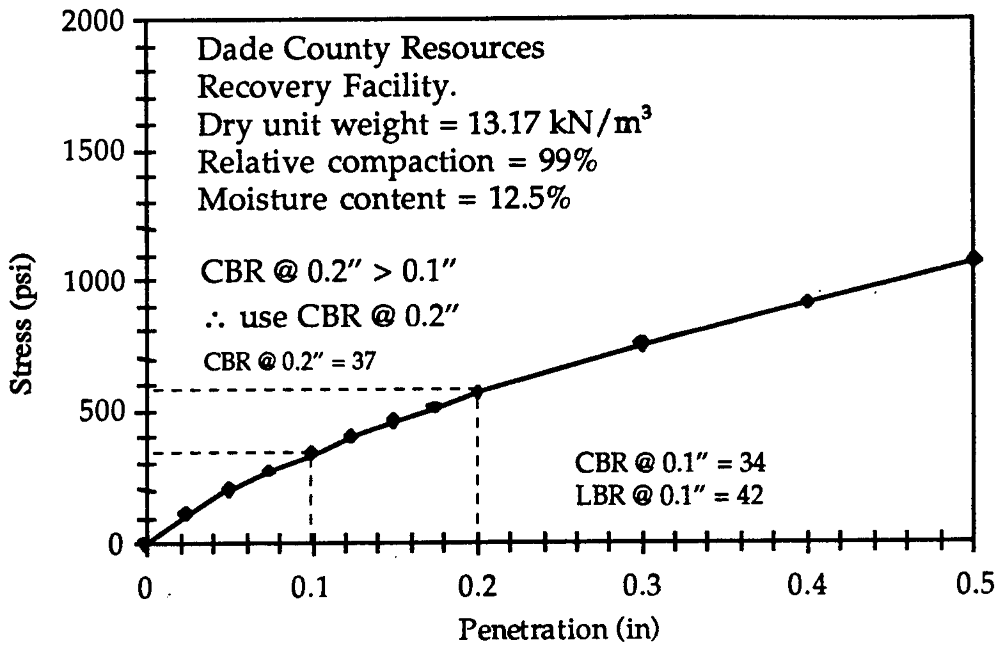
(d)

Figure E-2 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 15.2% (d) 16.3%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

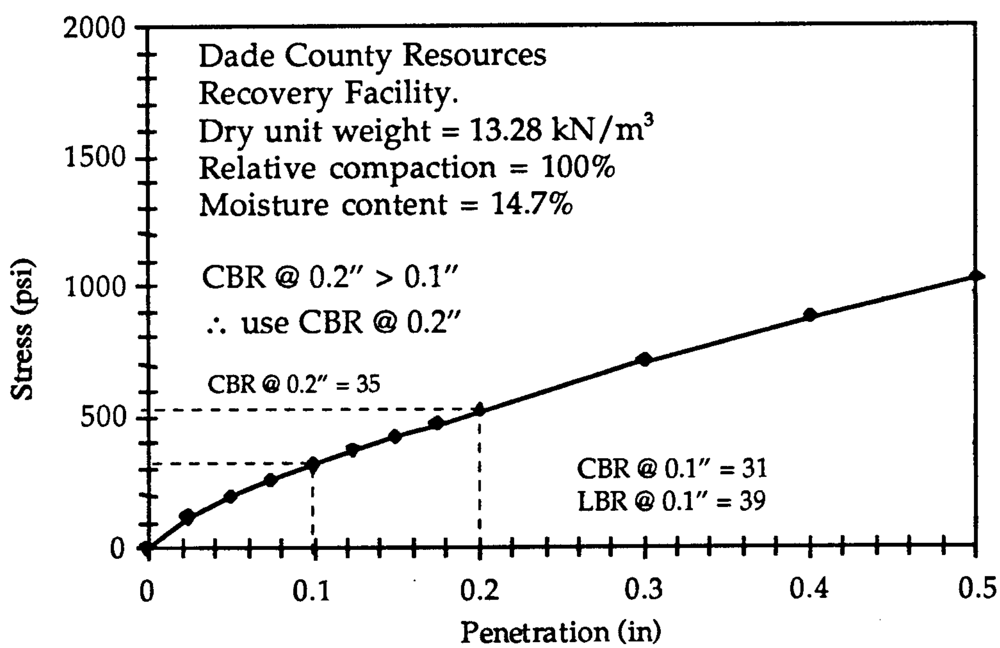


(e)

Figure E-3 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 17.8%
(1 pcf = 0.157 kN/m³, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

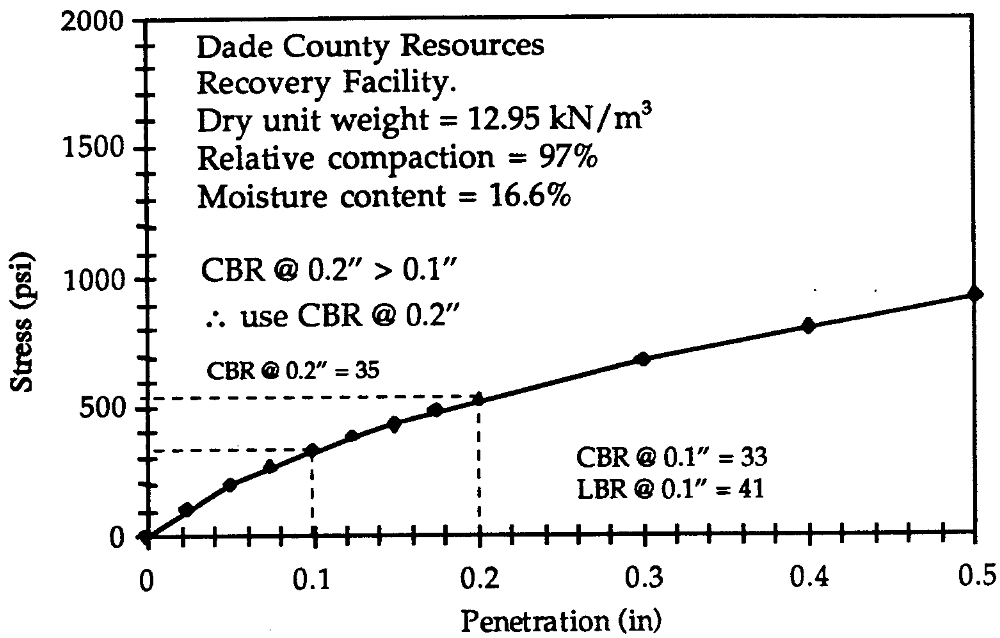


(a)

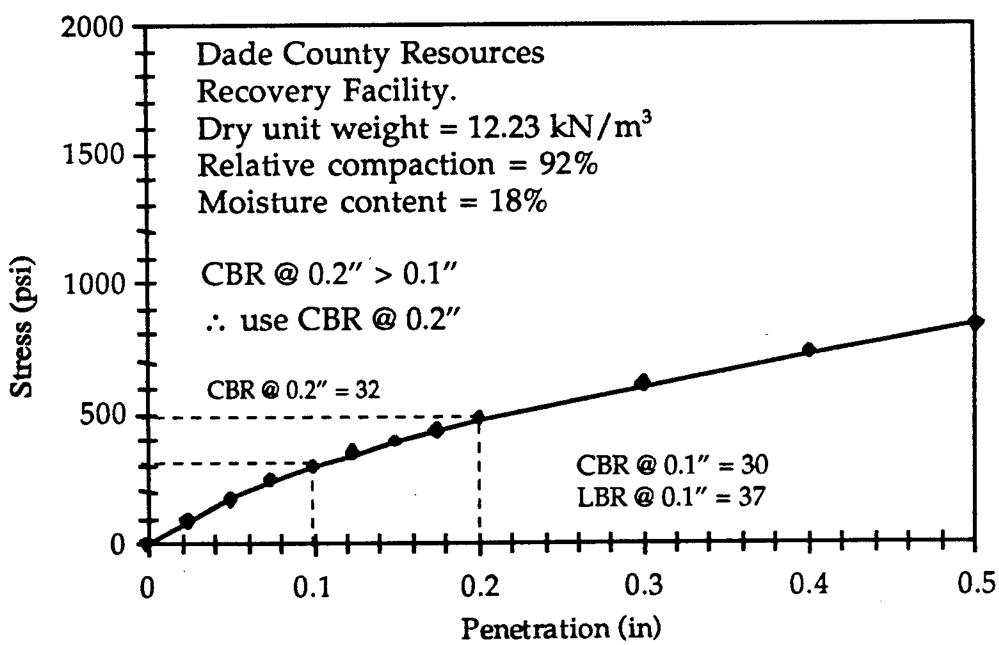


(b)

Figure E-4 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 12.5% (b) 14.7%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

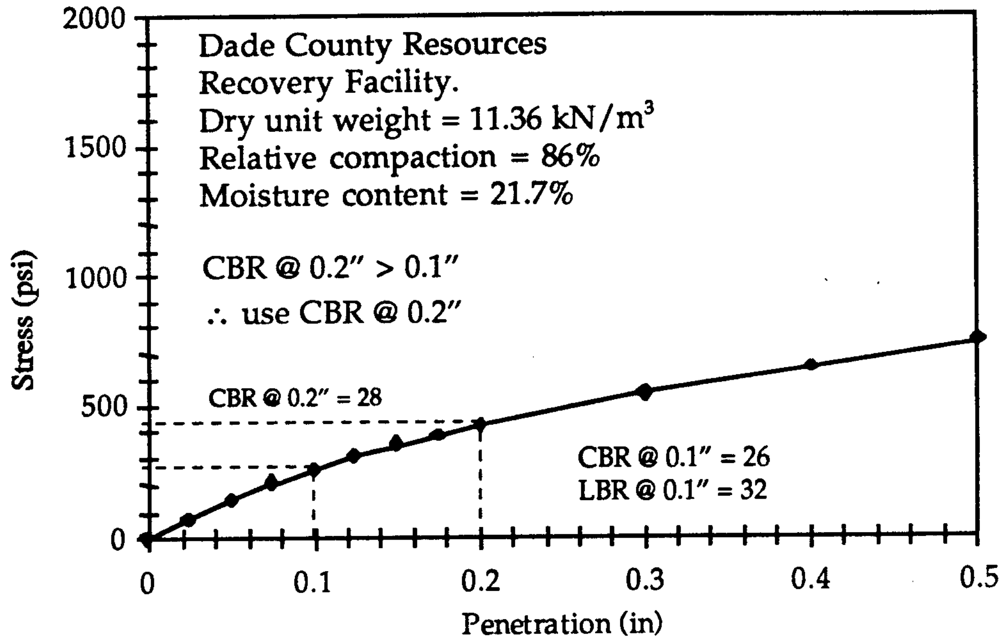


(c)



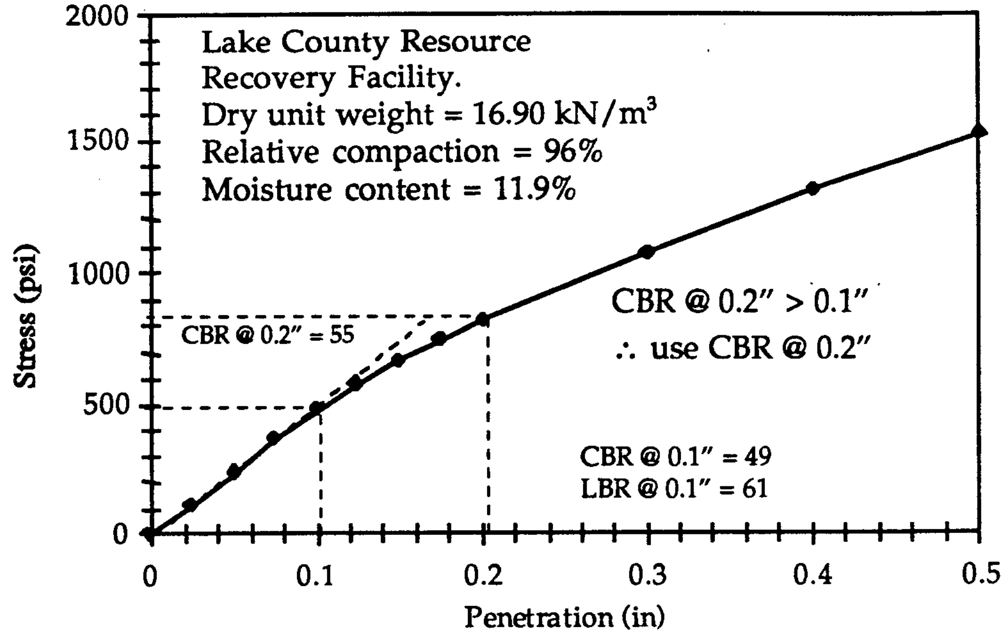
(d)

Figure E-5 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 16.6% (d) 18%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

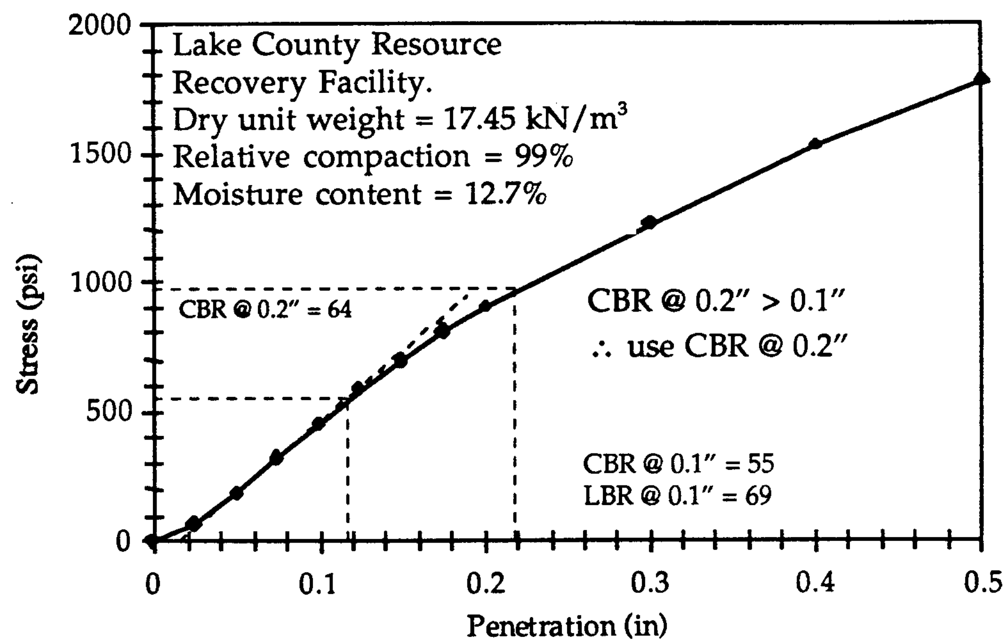


(e)

Figure E-6 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 21.7%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

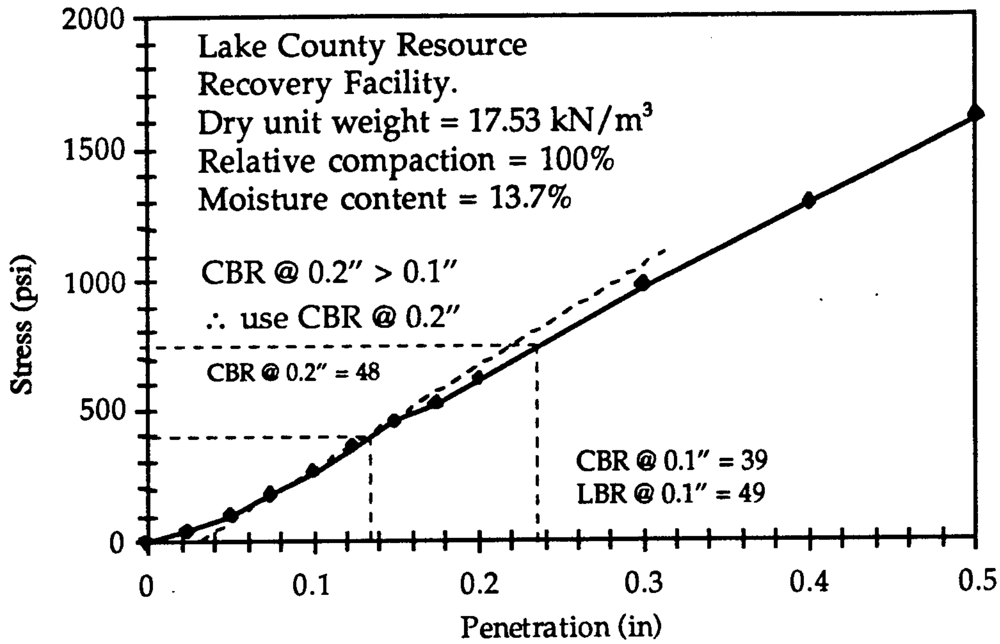


(a)



(b)

Figure E-7 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11.9% (b) 12.7%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)



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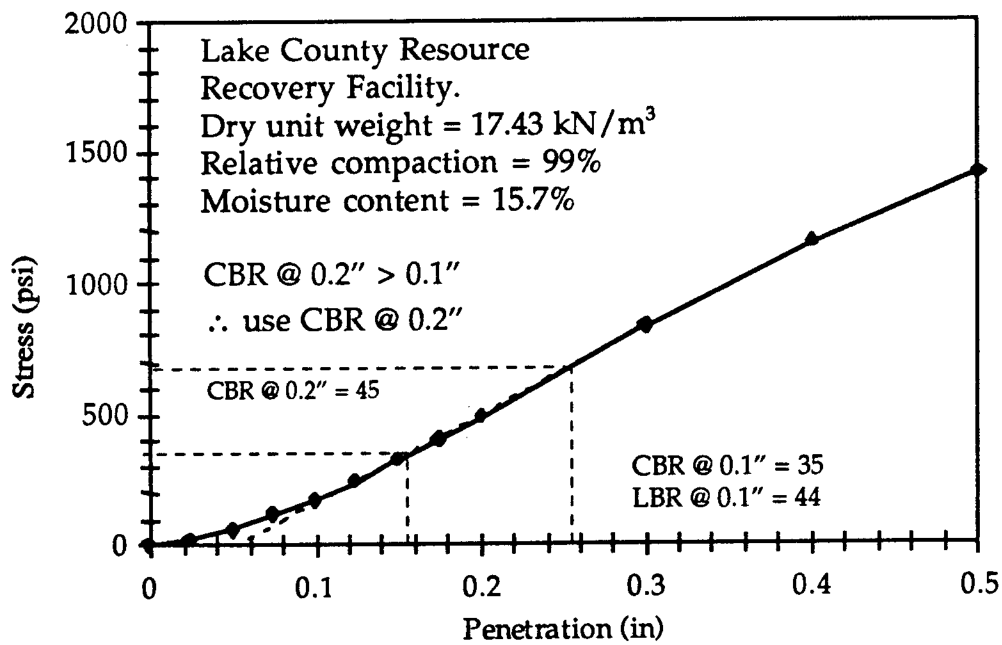
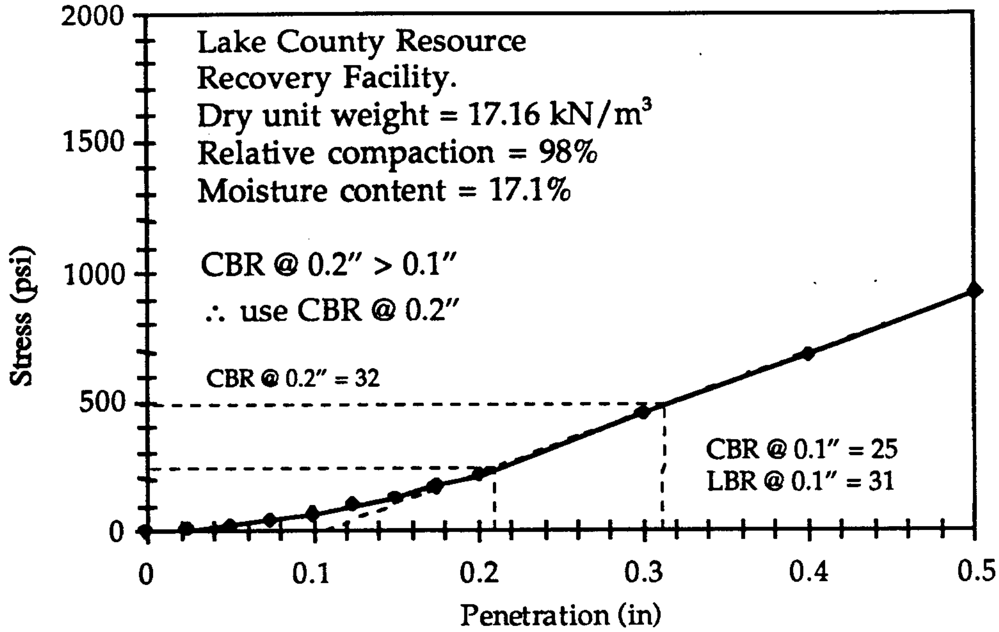


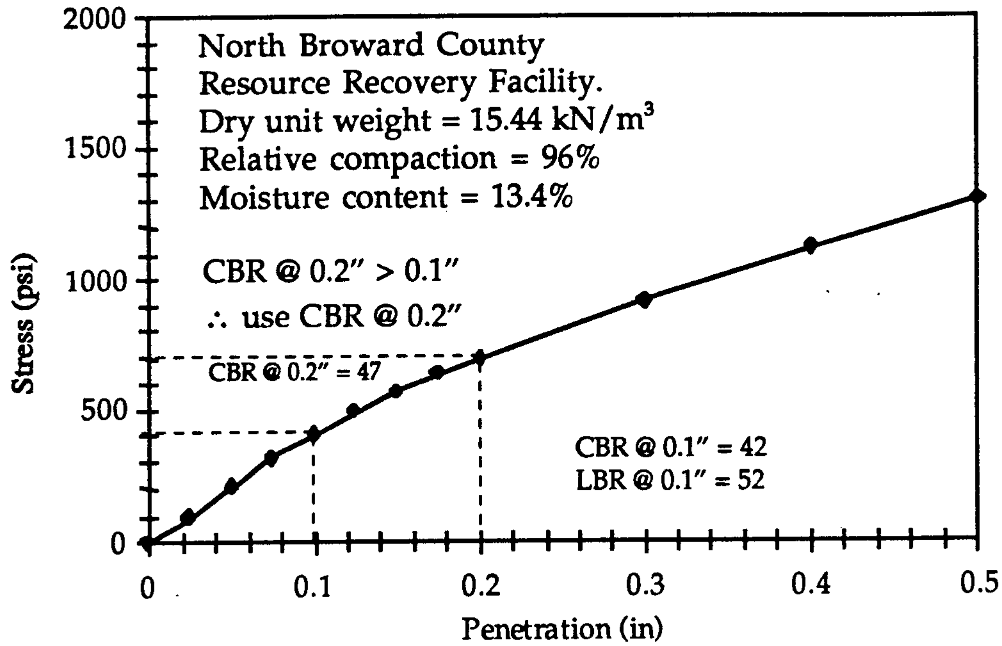
(d)

Figure E-8 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 13.7% (d) 15.7%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

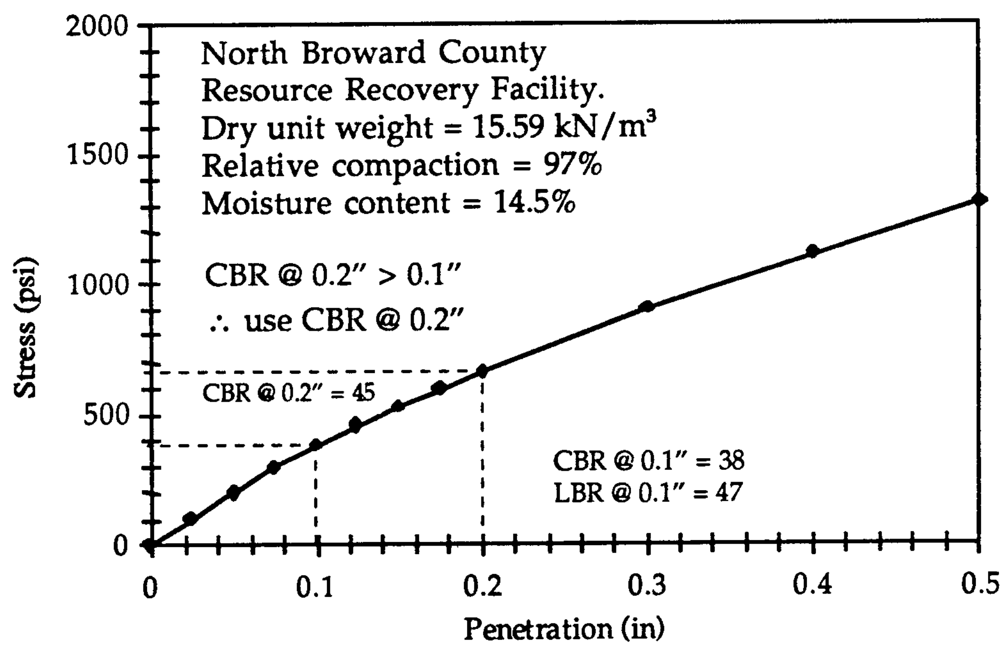


(e)

Figure E-9 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 17.1%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

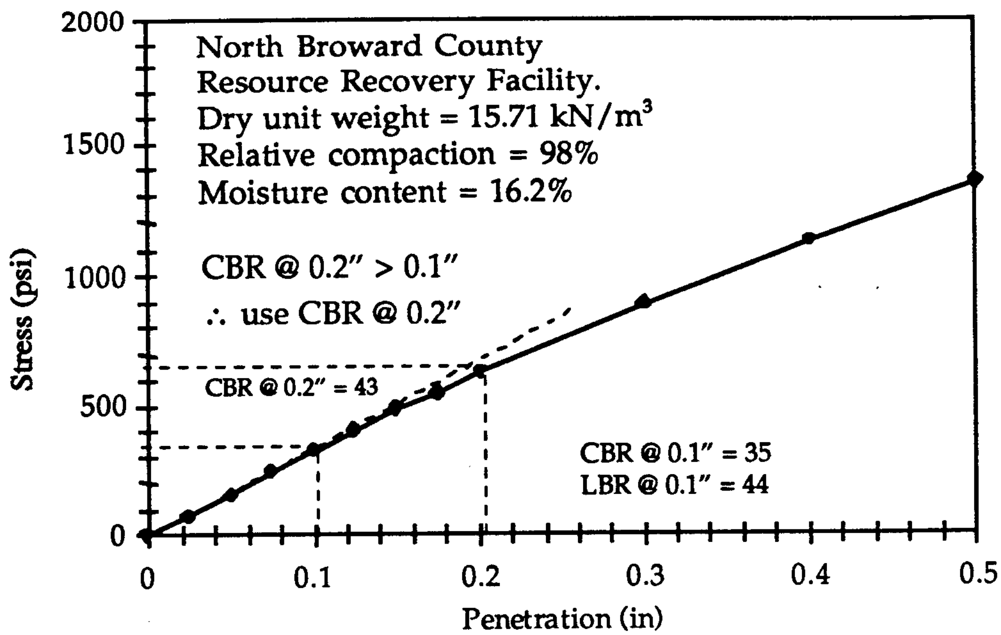


(a)



(b)

Figure E-10 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 13.4% (b) 14.5%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)



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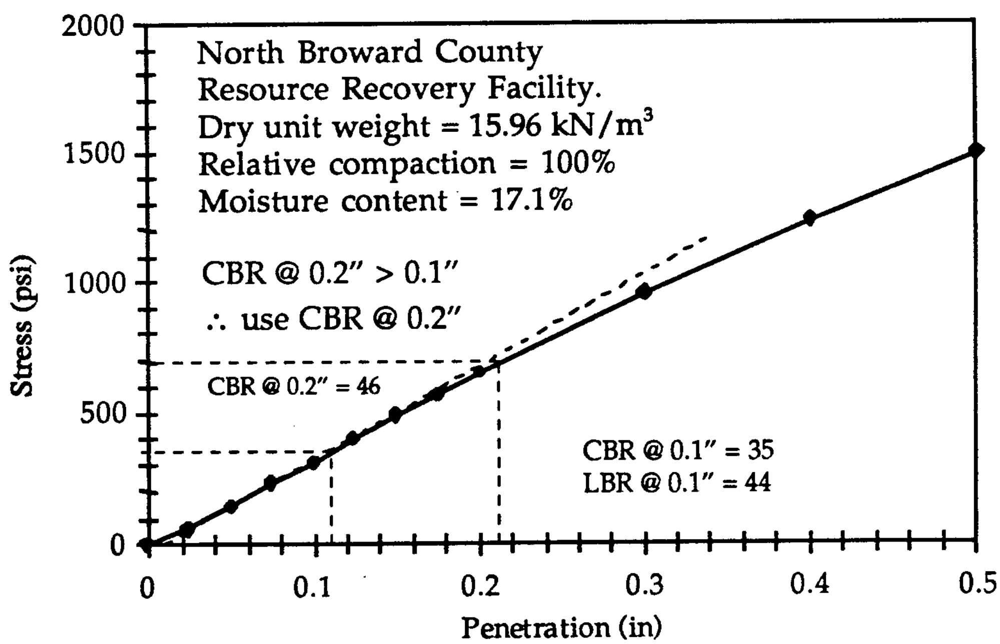
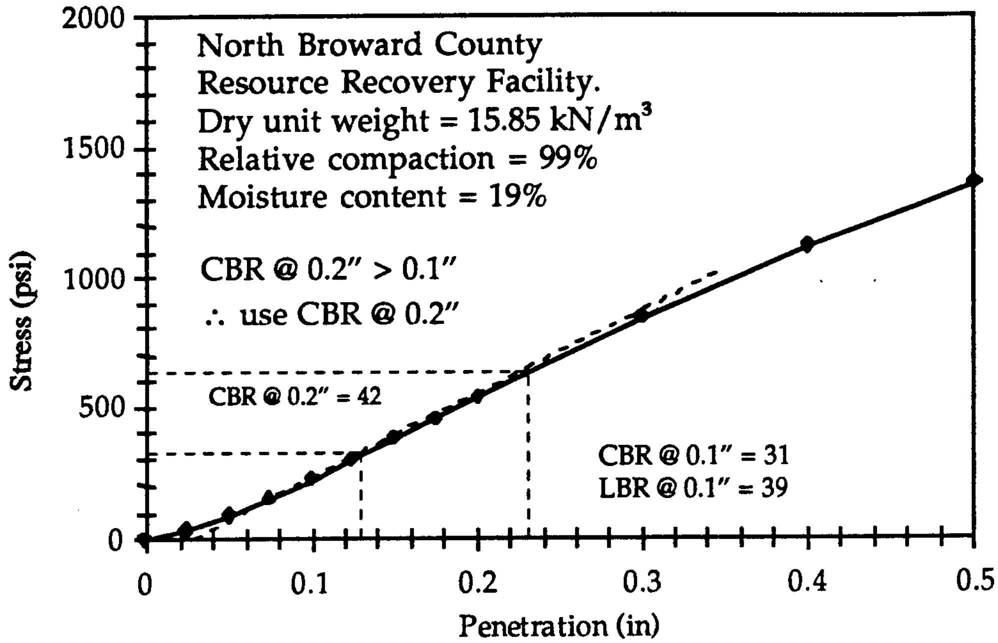


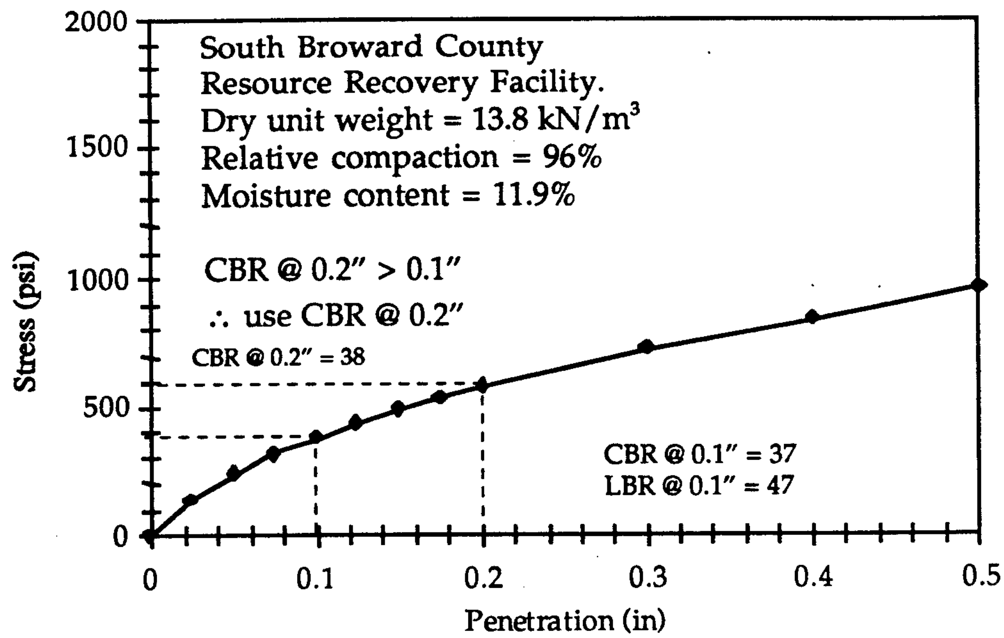
(d)

Figure E-11 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 16.2% (d) 17.1%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

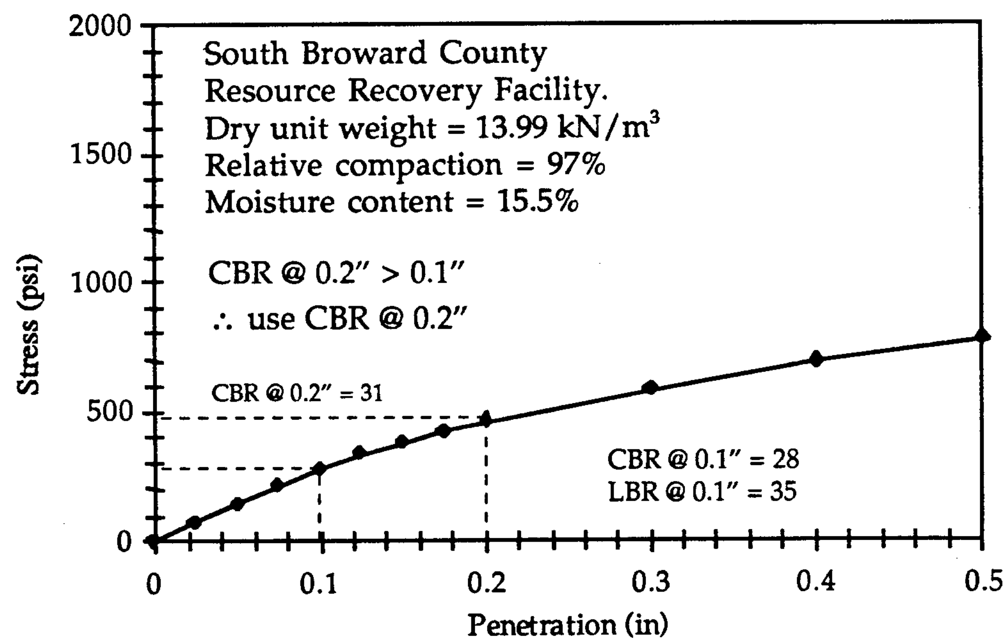


(e)

Figure E-12 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 19%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

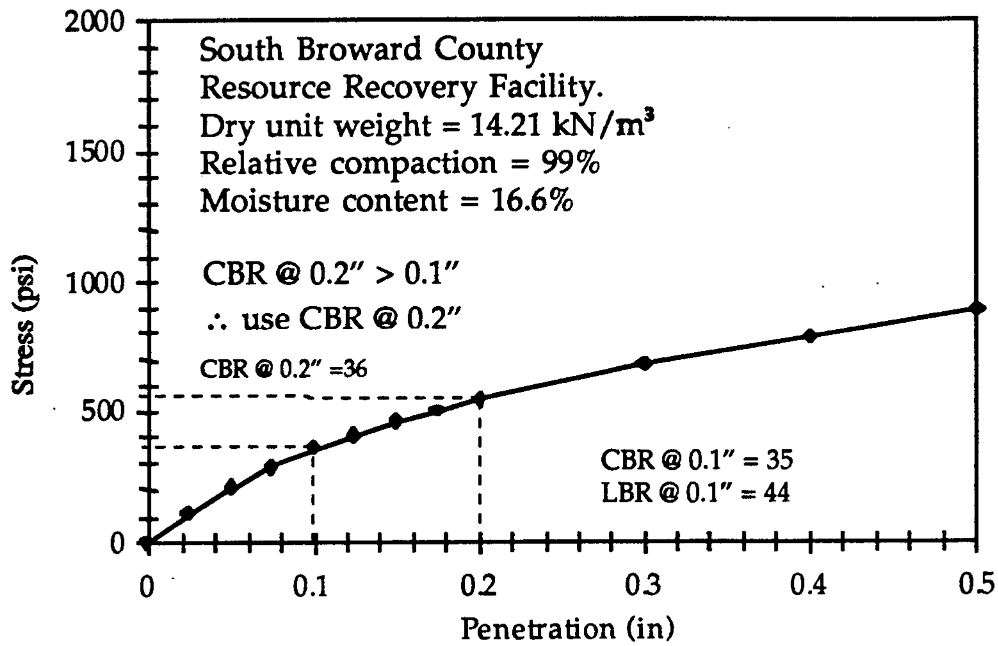


(a)



(b)

Figure E-13 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11.9% (b) 15.5%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)



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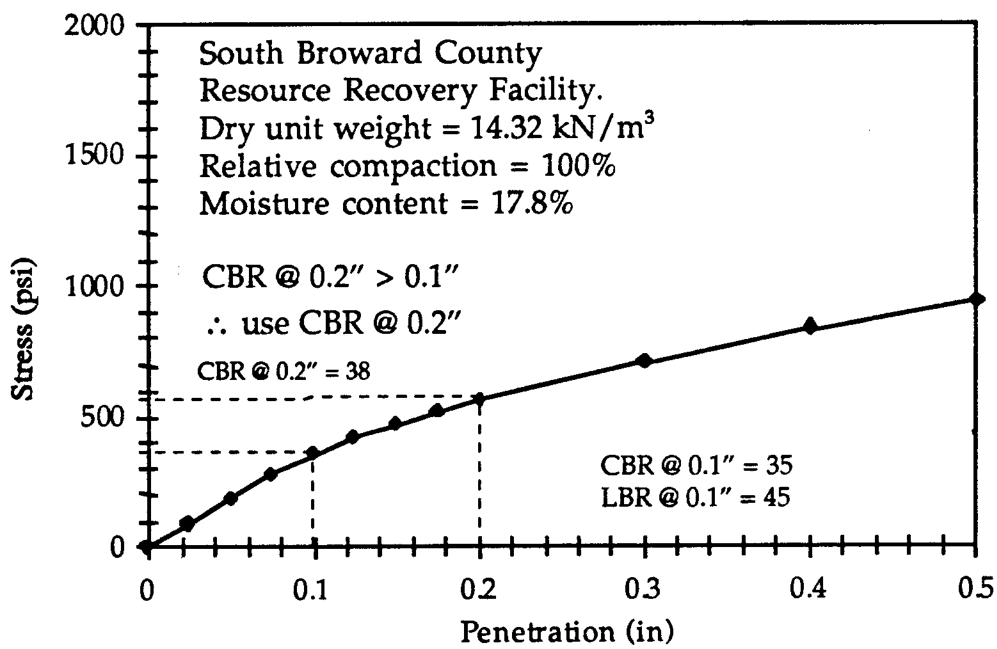
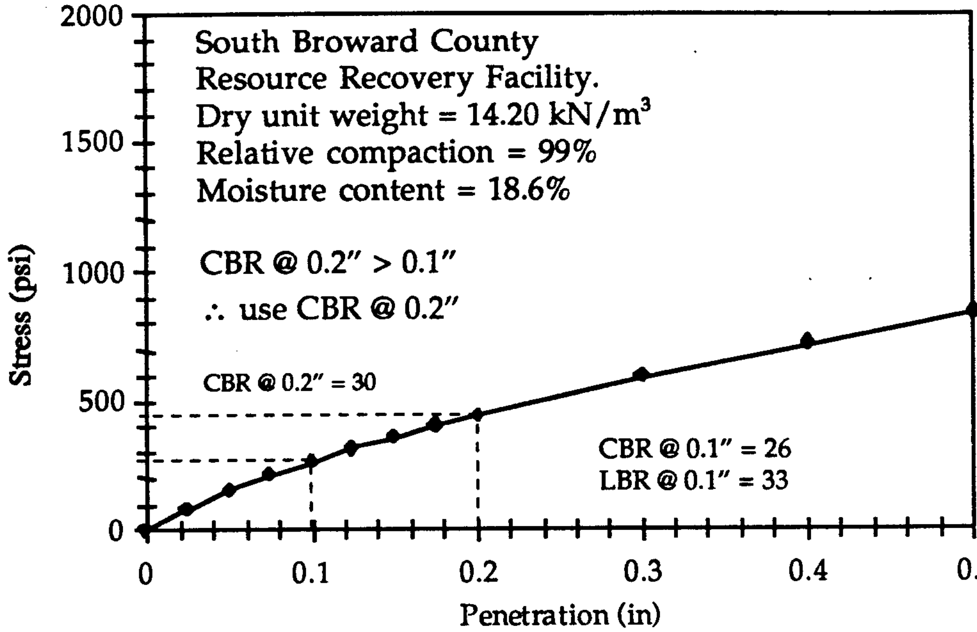


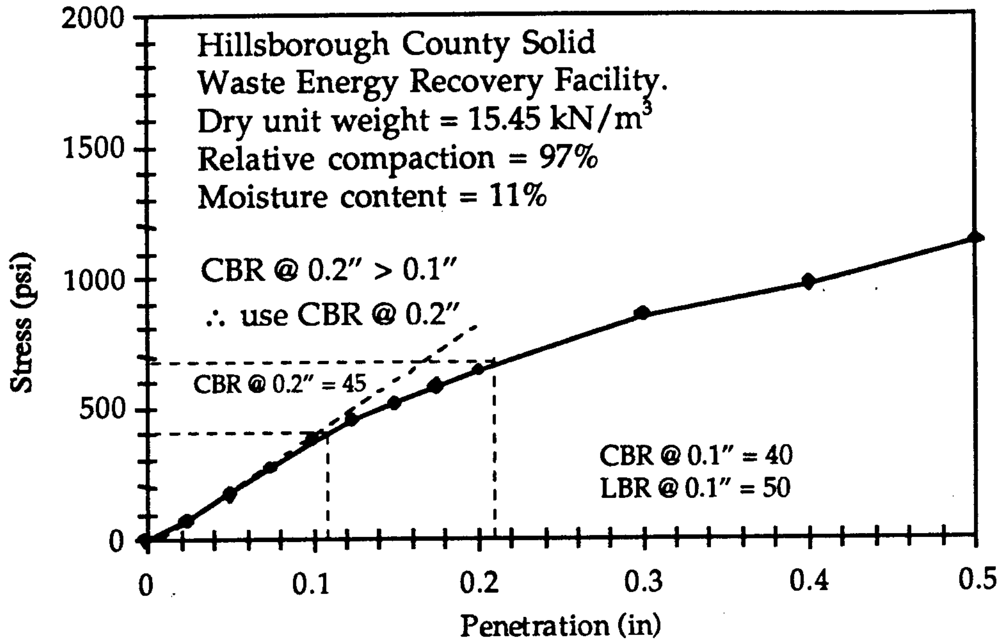
(d)

Figure E-14 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 16.6% (d) 17.8%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

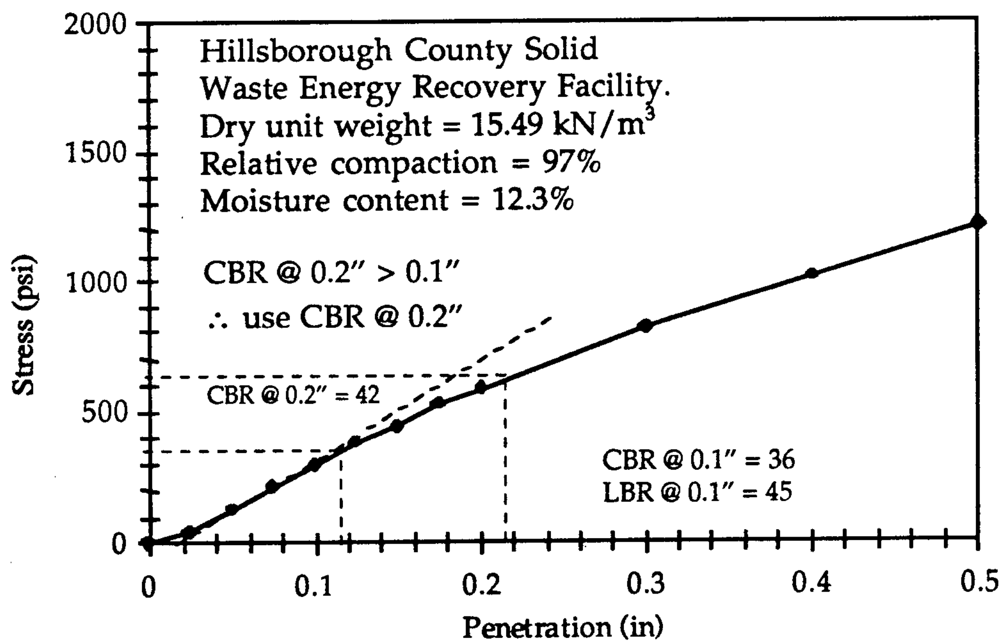


(e)

Figure E-15 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 18.6%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

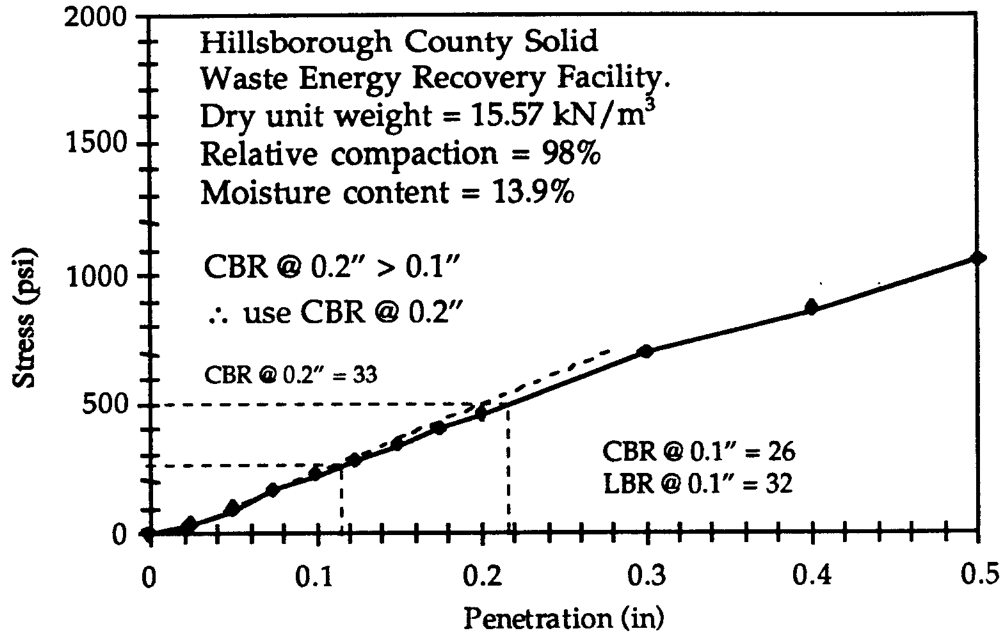


(a)

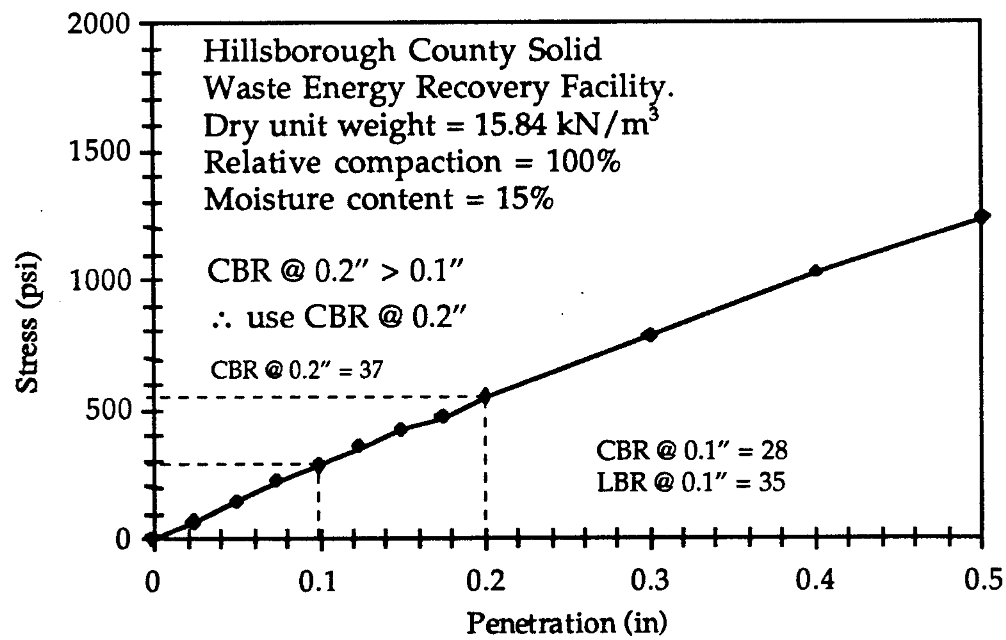


(b)

Figure E-16 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11% (b) 12.3%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

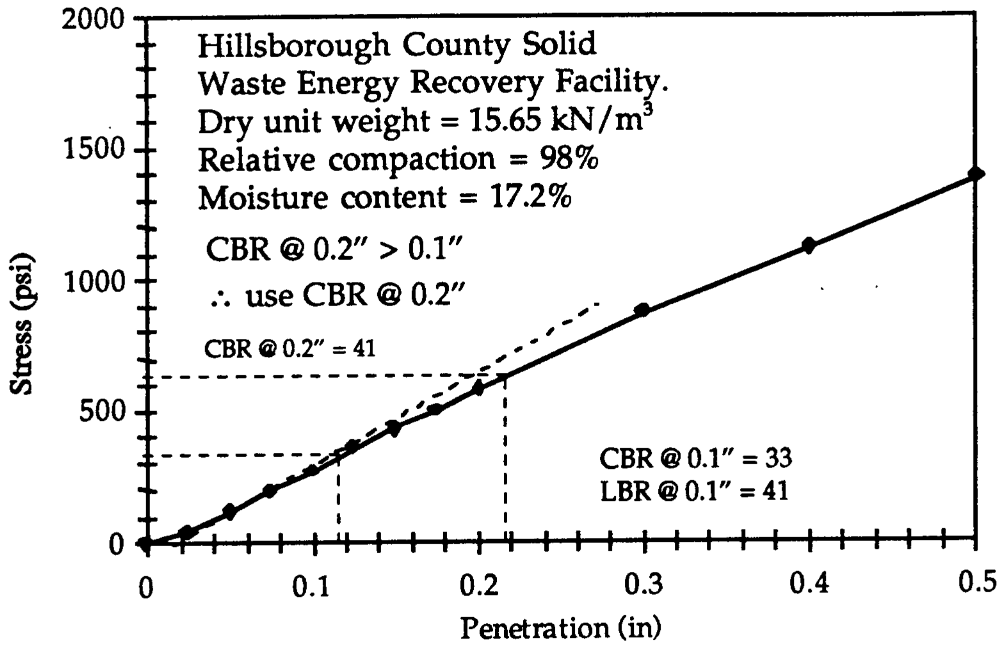


(c)



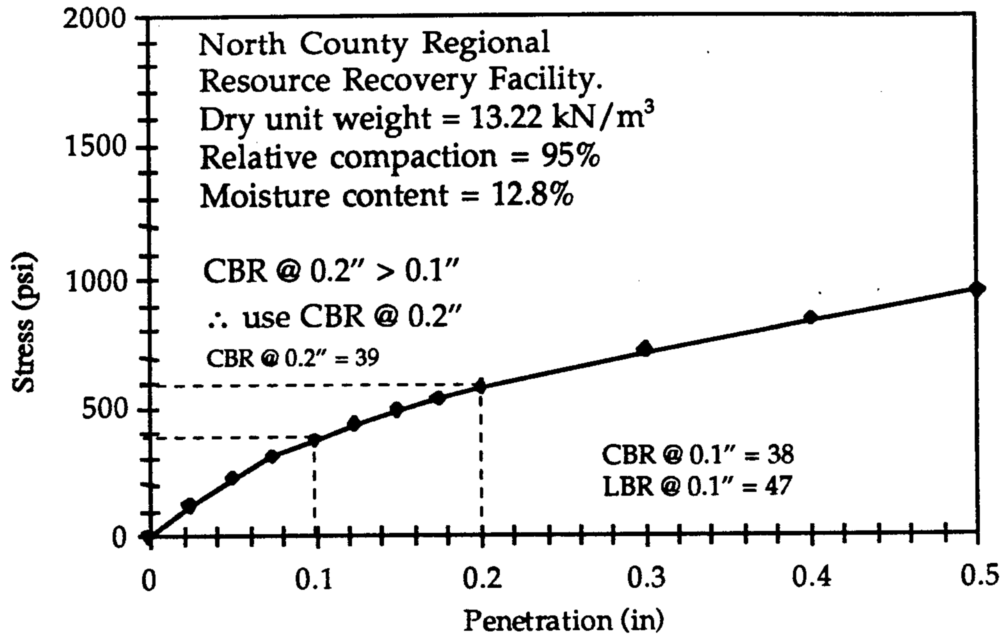
(d)

Figure E-17 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 13.9% (d) 15%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

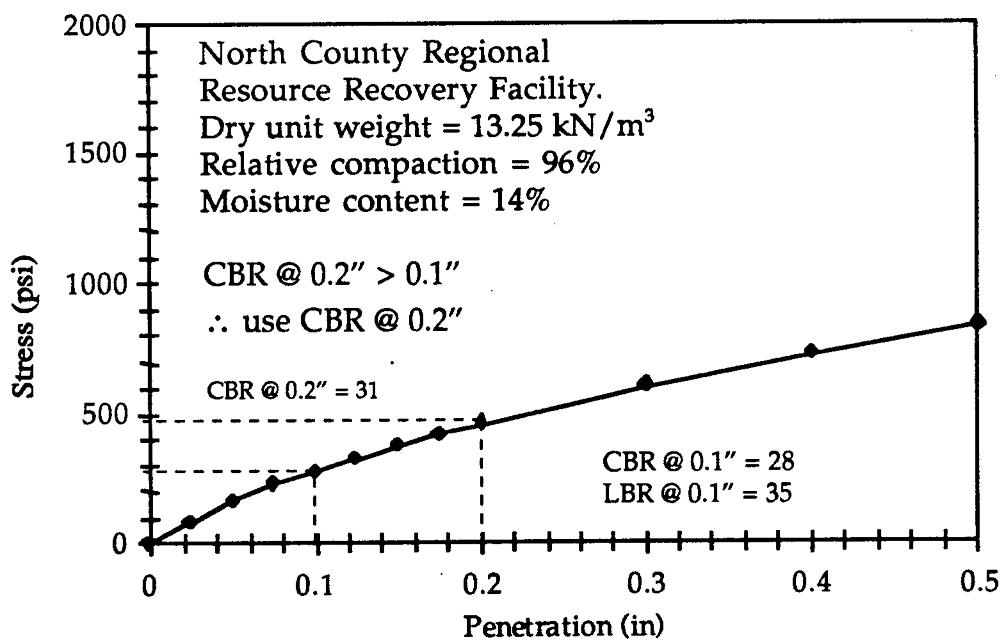


(e)

Figure E-18 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 17.2%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

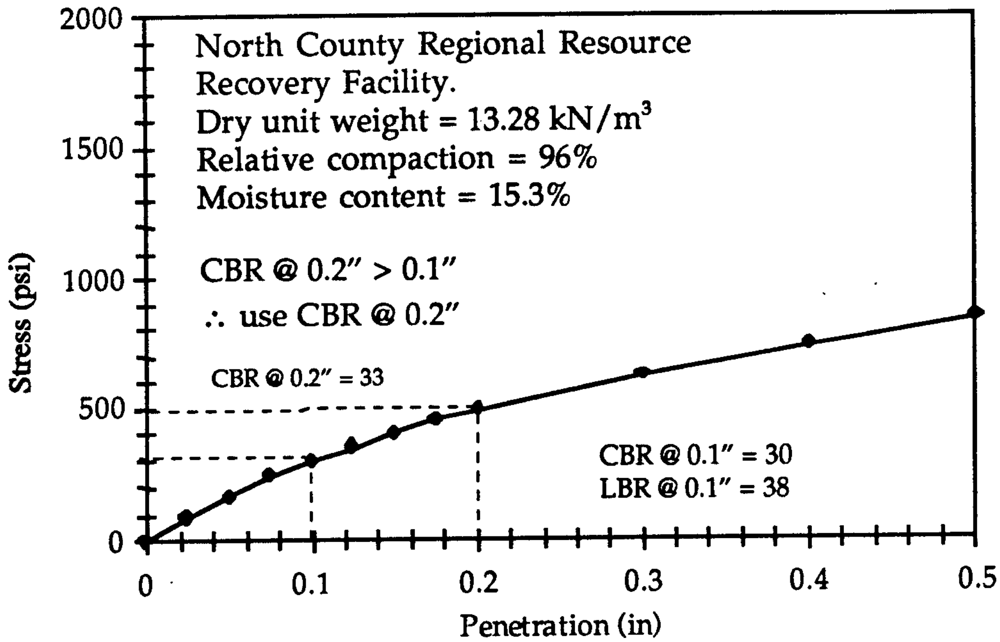


(a)

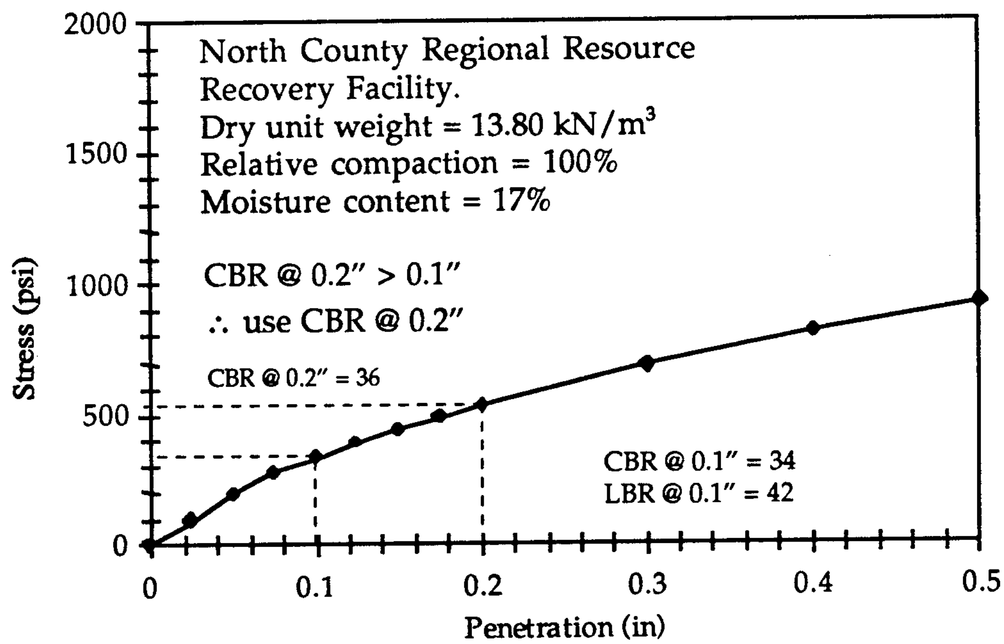


(b)

Figure E-19 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 12.8% (b) 14%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

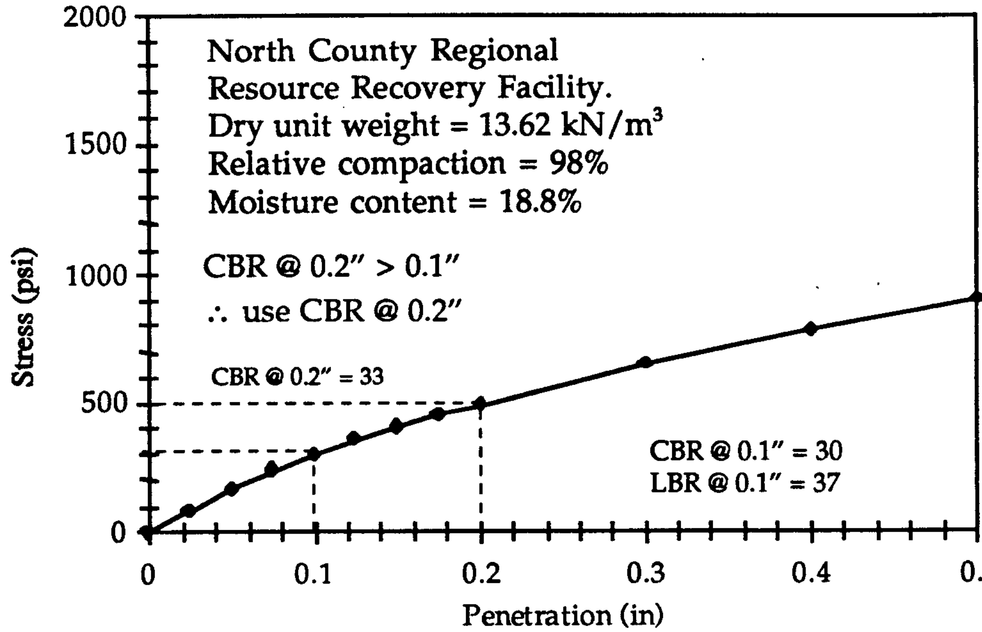


(c)



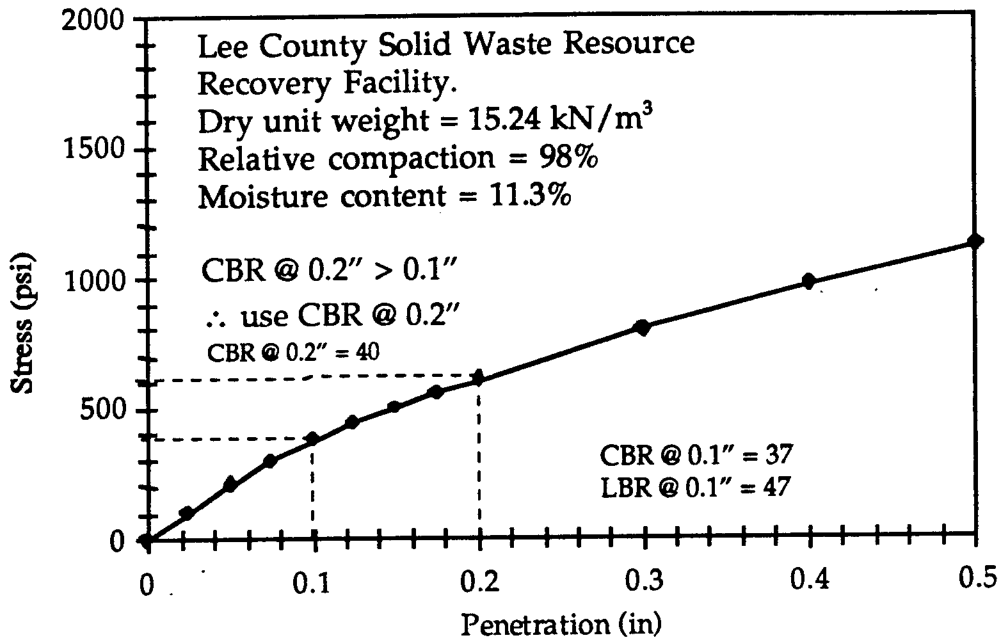
(d)

Figure E-20 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 15.3% (d) 17%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

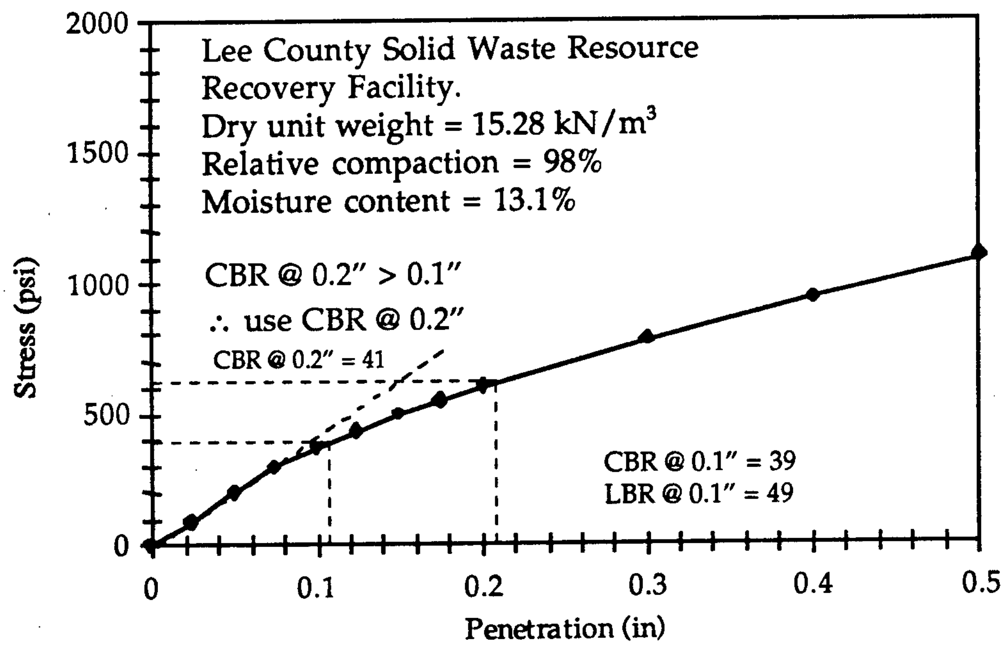


(e)

Figure E-21 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 18.8%
(1 pcf = 0.157 kN/m³, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

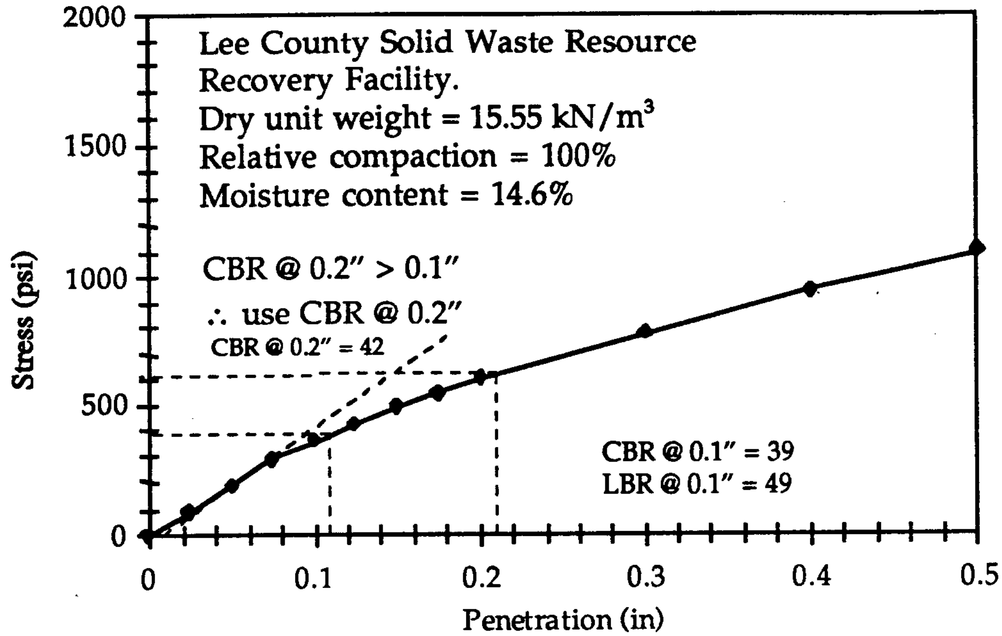


(a)

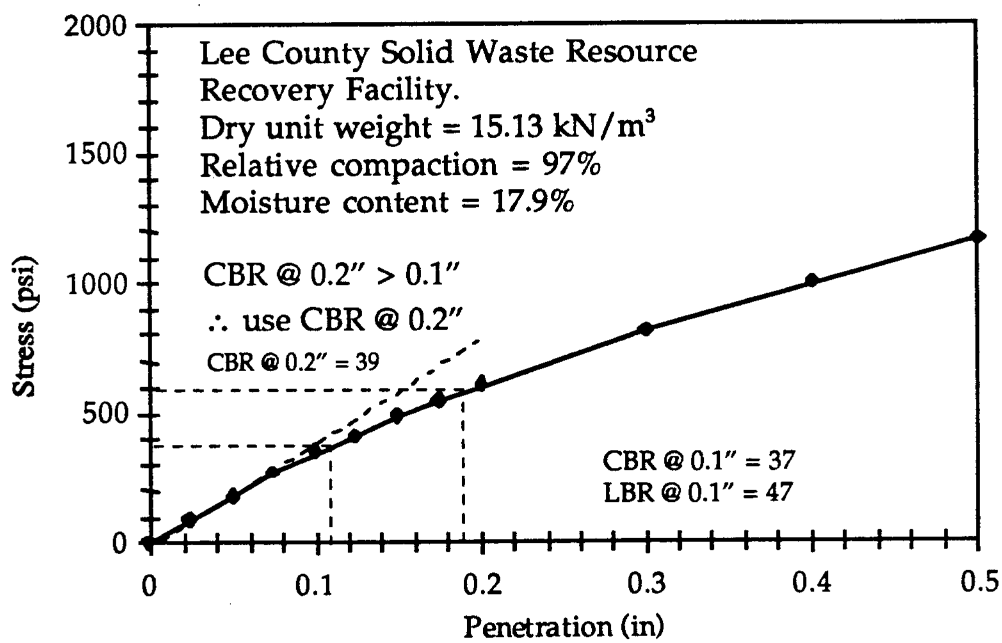


(b)

Figure E-22 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11.3% (b) 13.1%
(1 pcf = 0.157 kN/m³, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

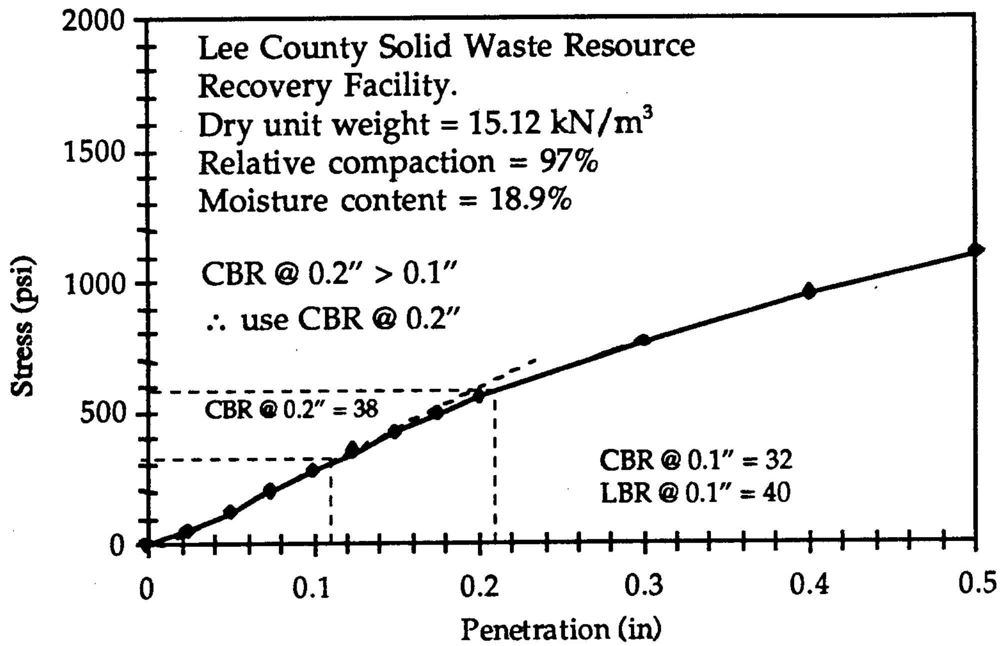


(c)



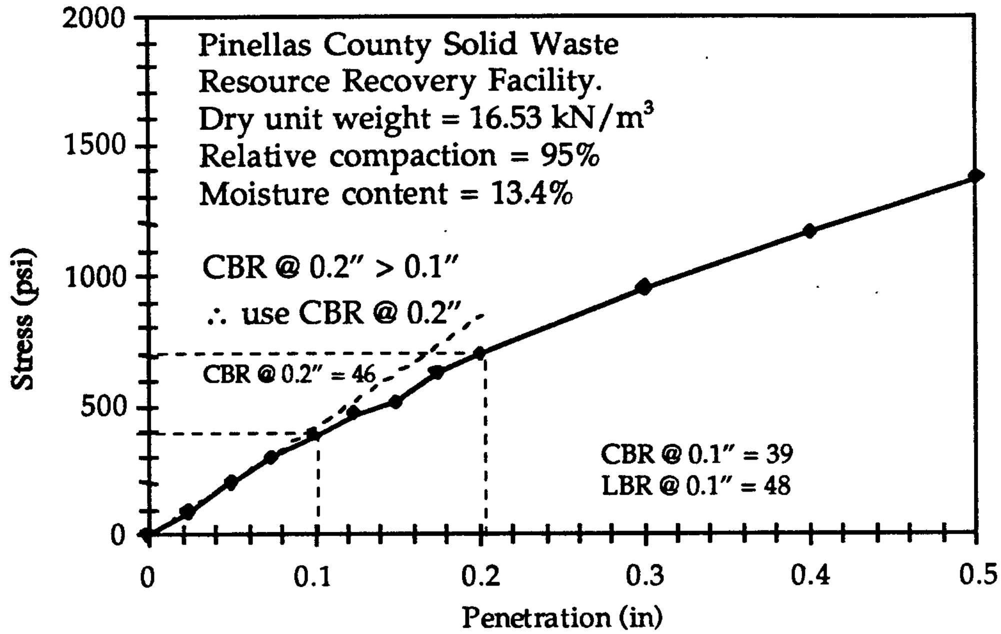
(d)

Figure E-23 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 14.6% (d) 17.9%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

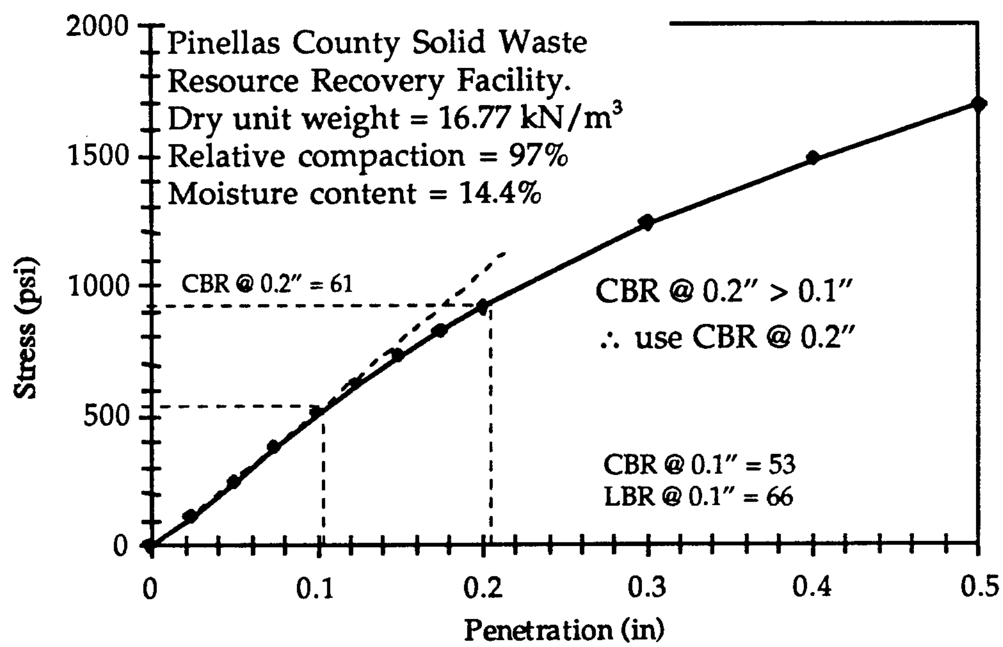


(e)

Figure E-24 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 18.9%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

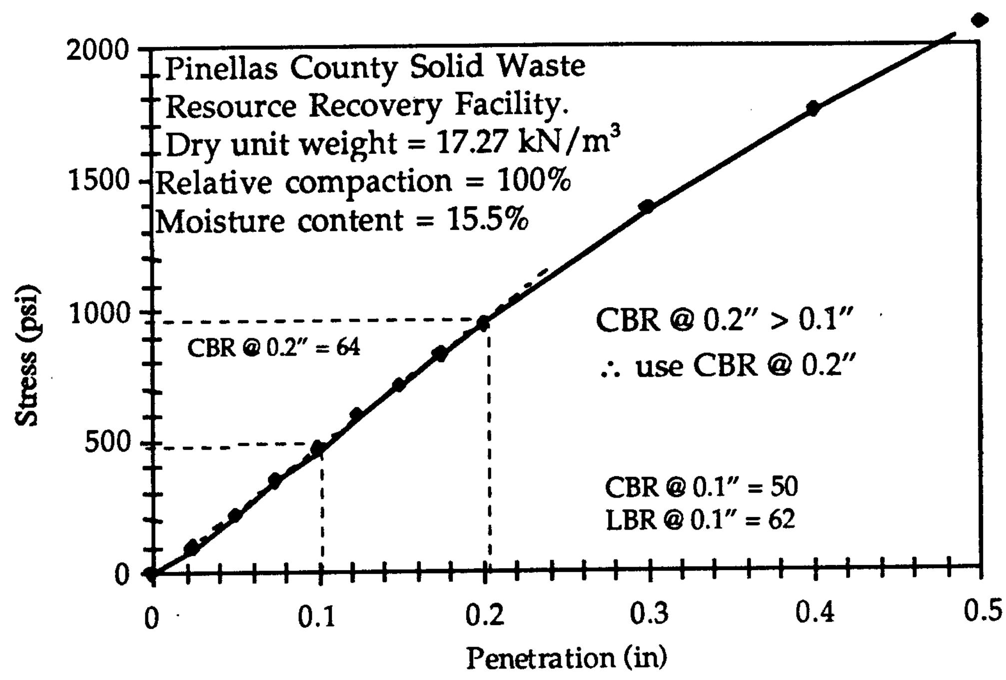


(a)

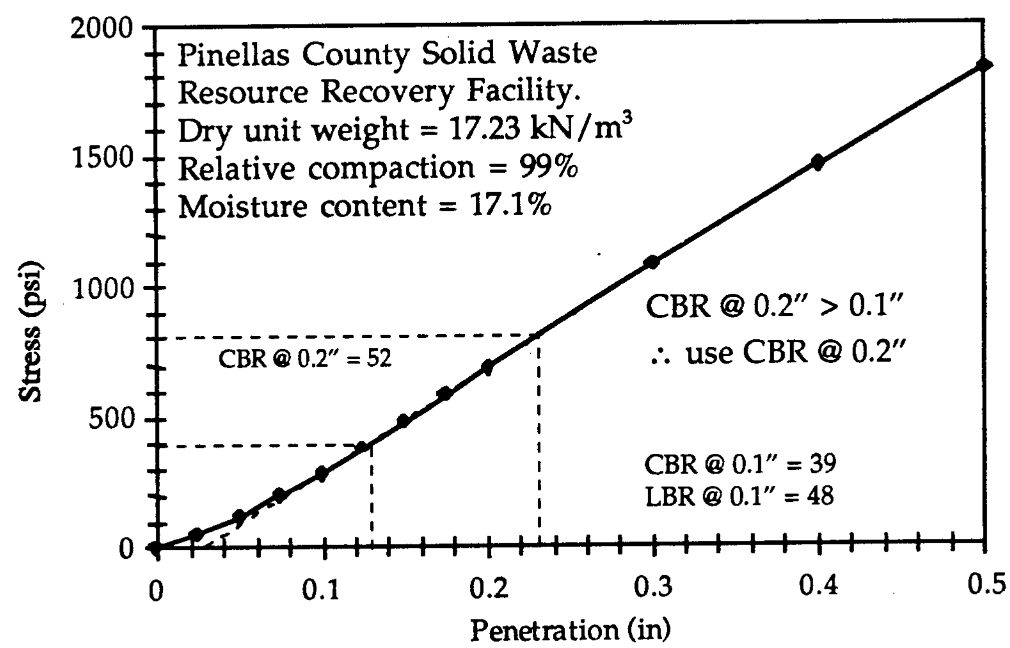


(b)

Figure E-25 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 13.4% (b) 14.4%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)



(c)



(d)

Figure E-26 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 15.5% (d) 17.1%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

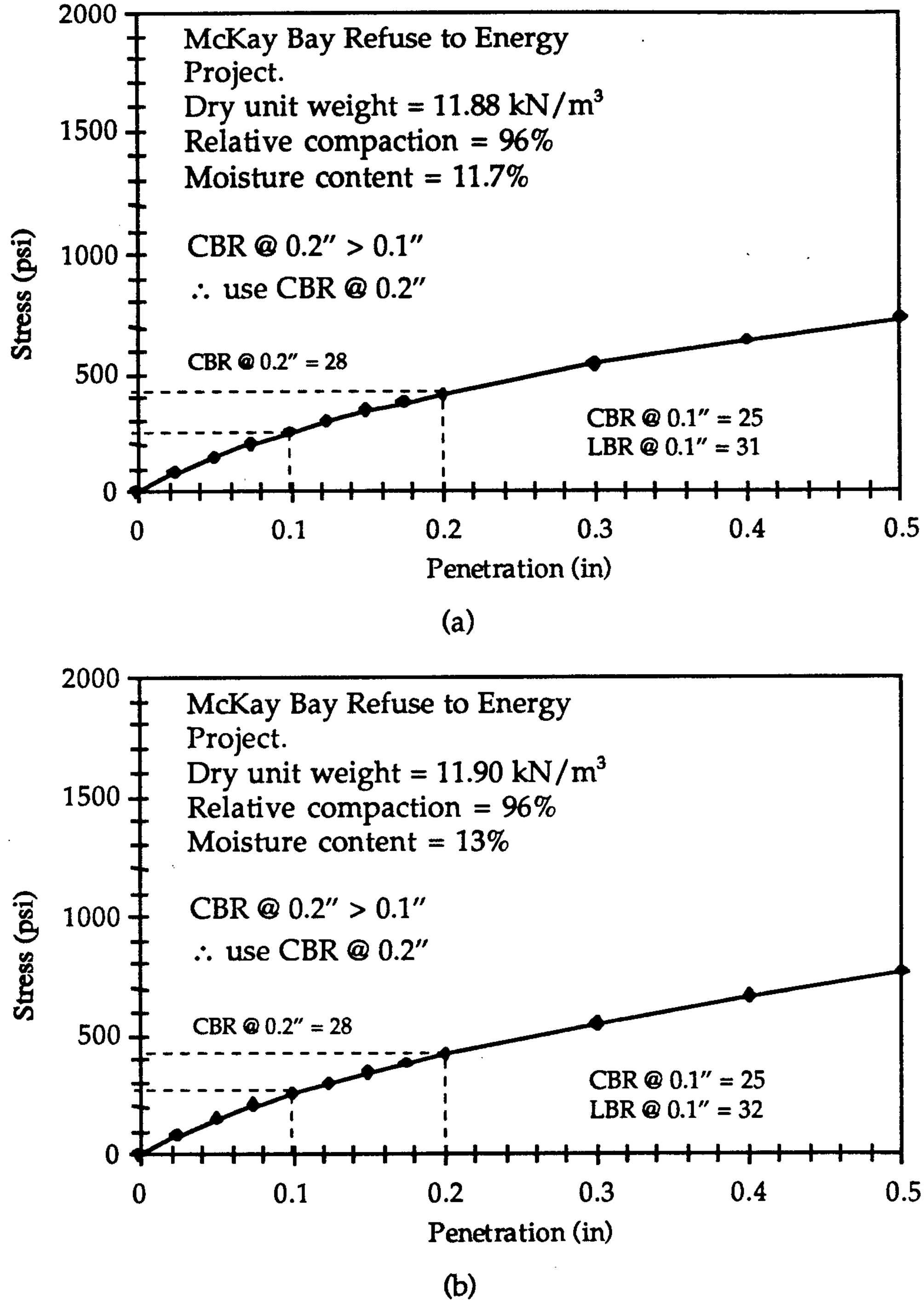
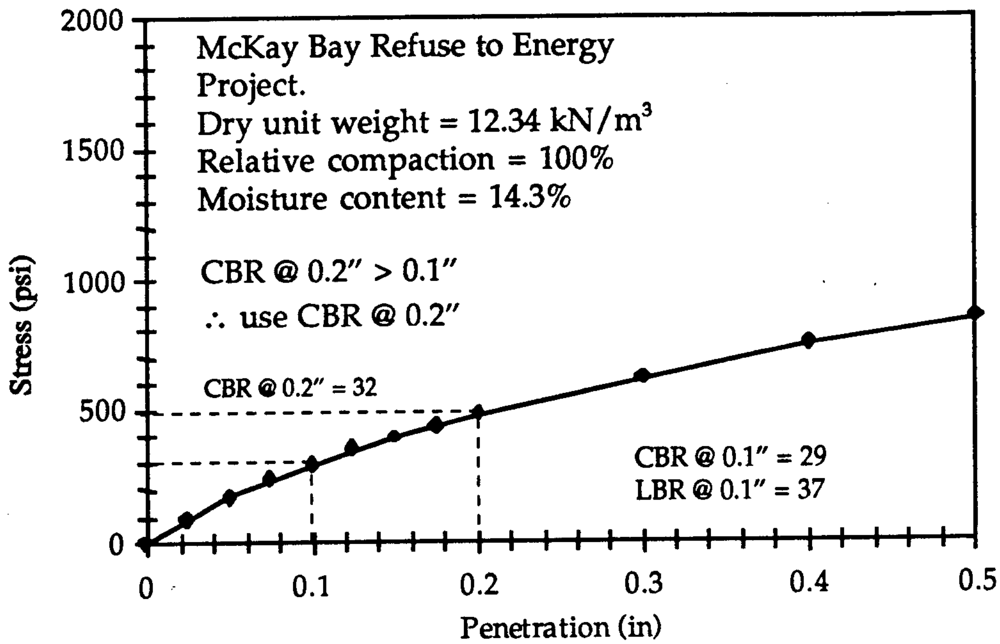
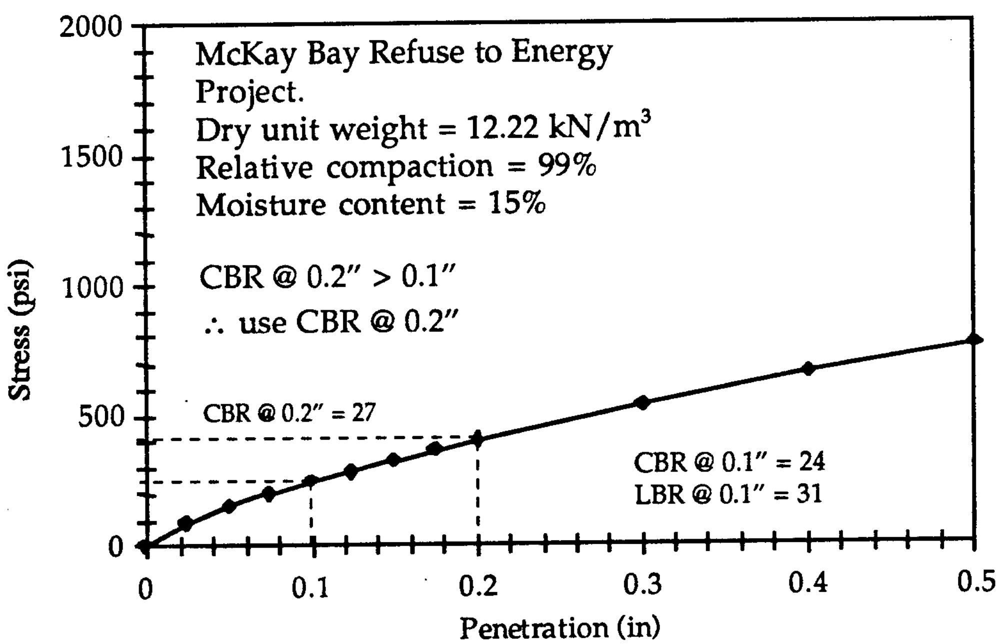


Figure E-27 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11.7% (b) 13%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

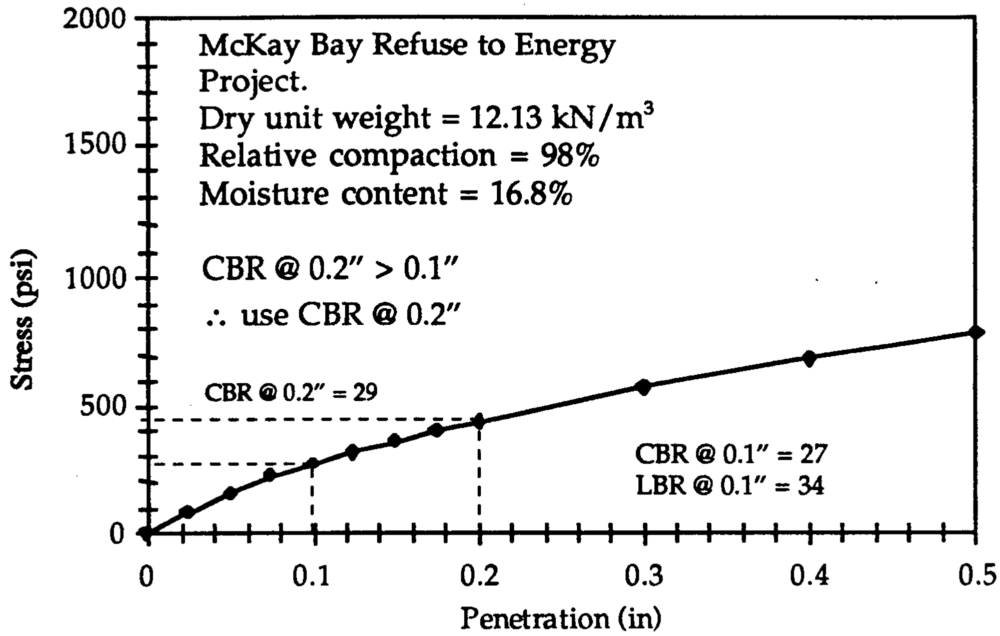


(c)



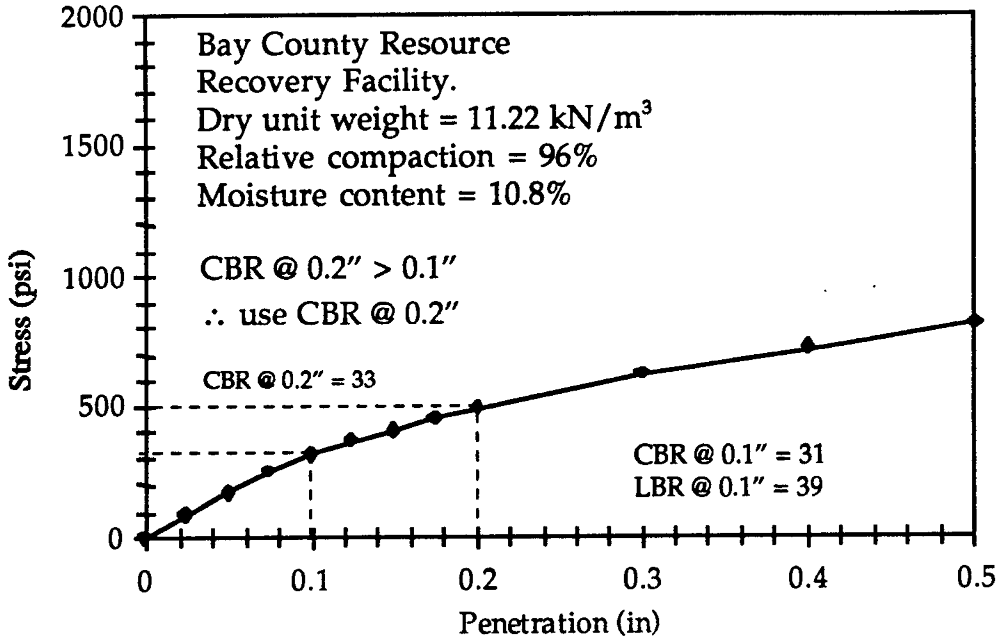
(d)

Figure E-28 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 14.3% (d) 15%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

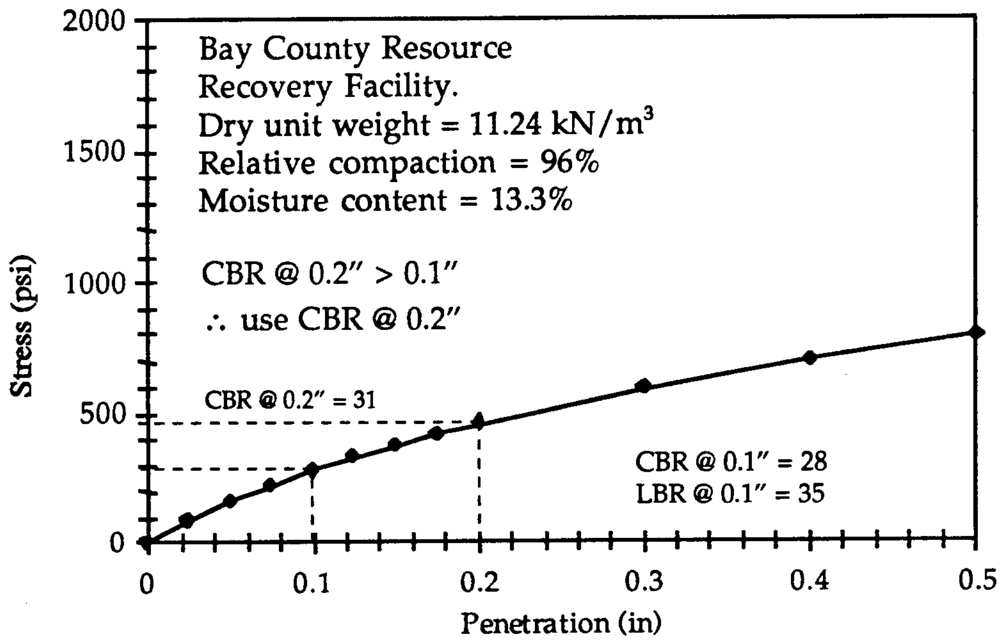


(e)

Figure E-29 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 16.8%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

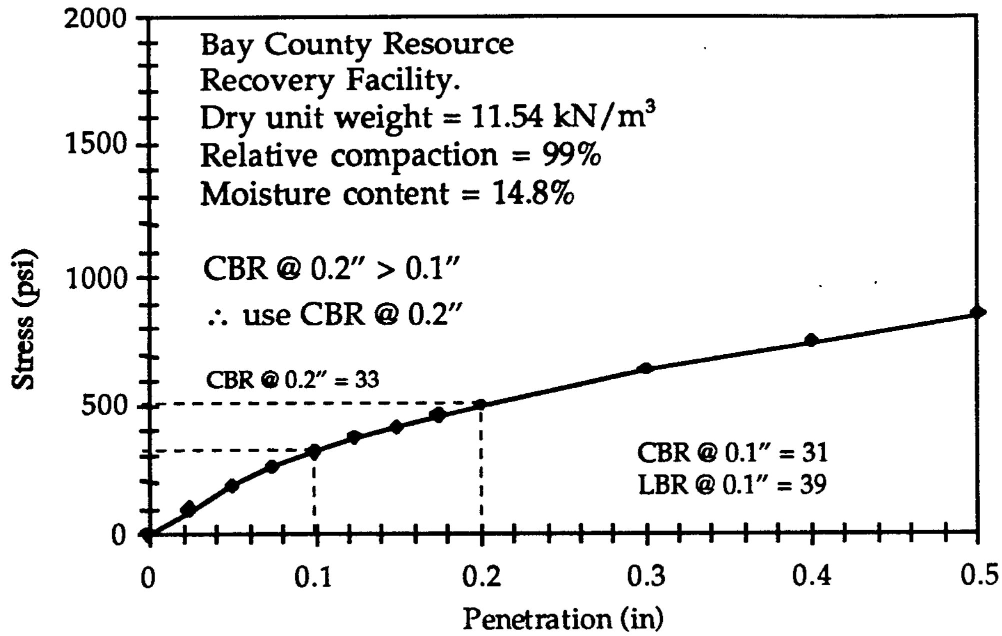


(a)

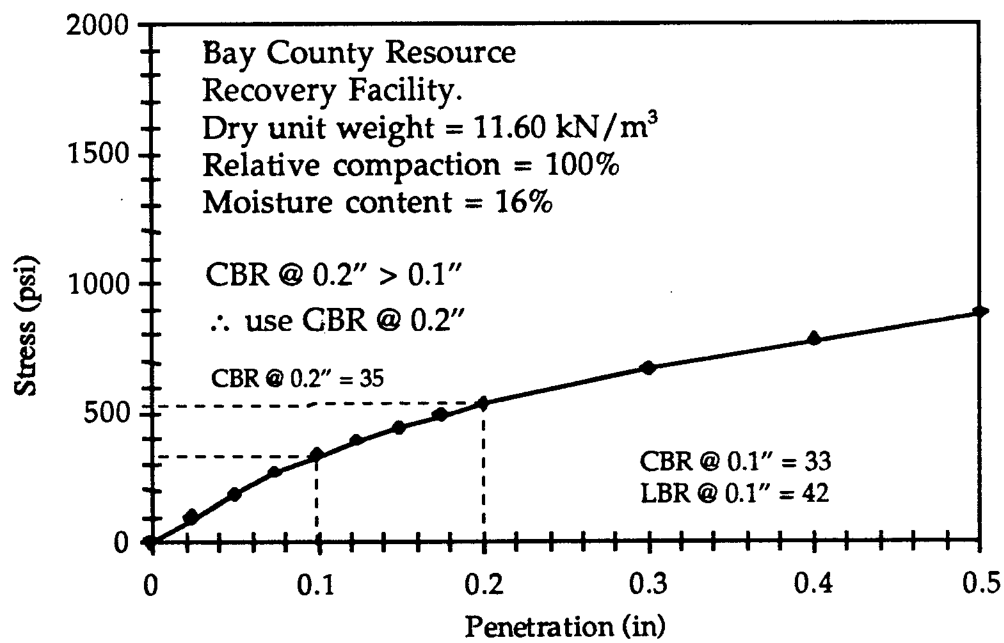


(b)

Figure E-30 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 10.8% (b) 13.3%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

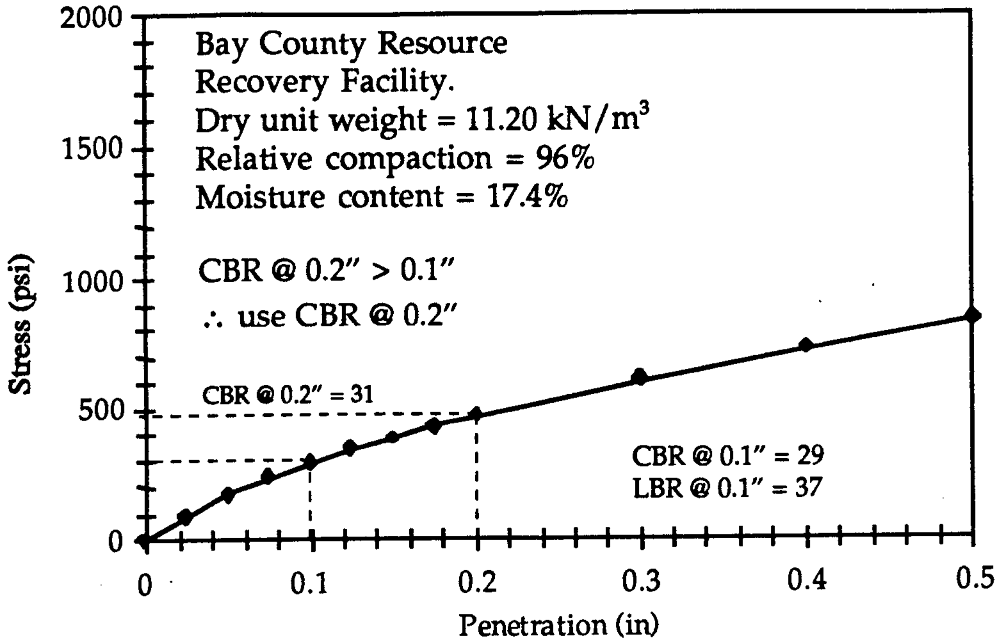


(c)



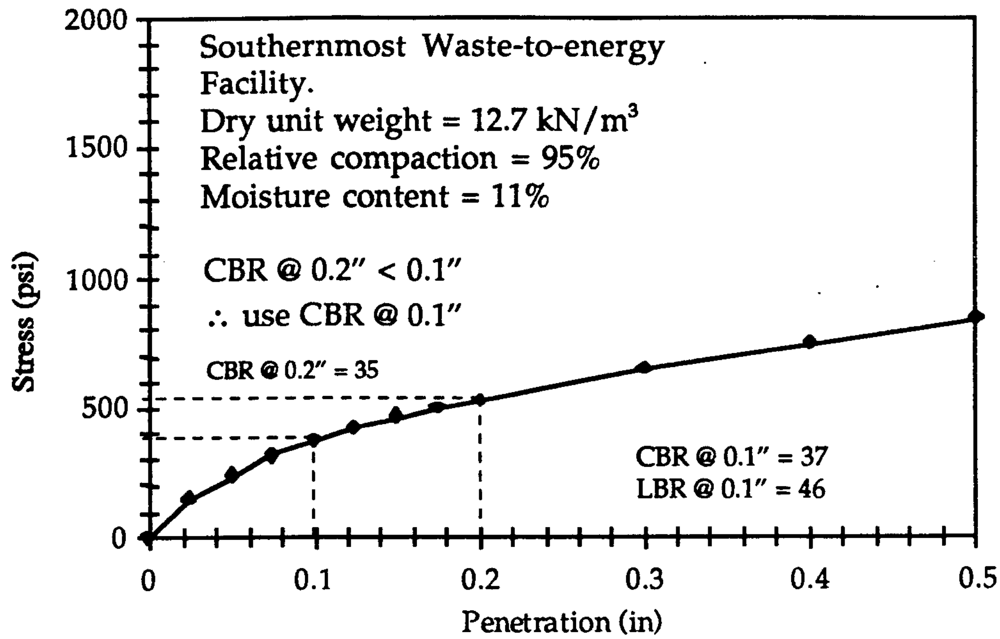
(d)

Figure E-31 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 14.8% (d) 16%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

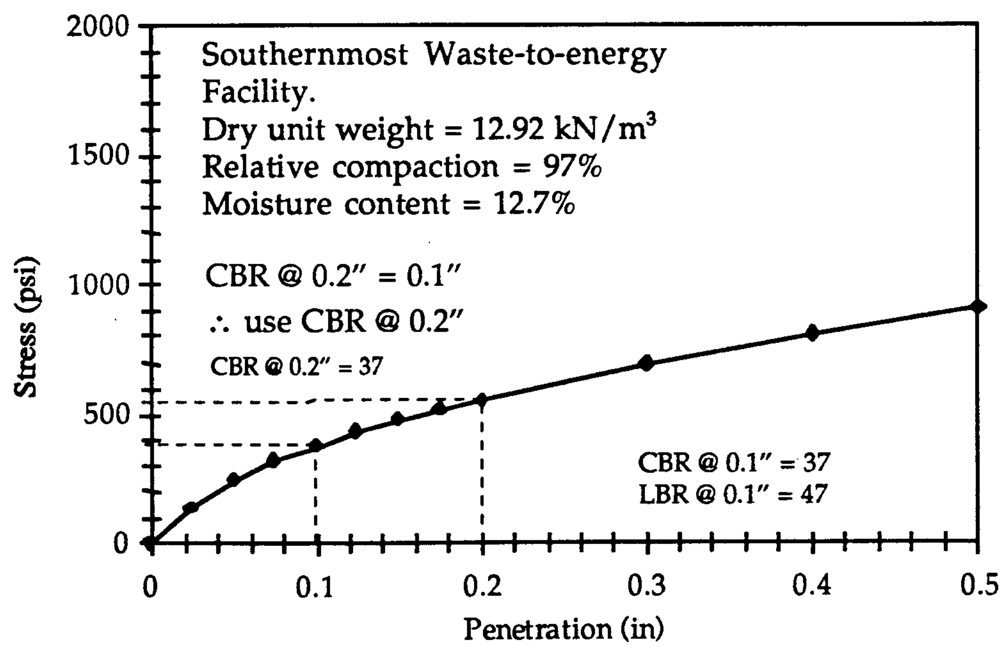


(e)

Figure E-32 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 17.4%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

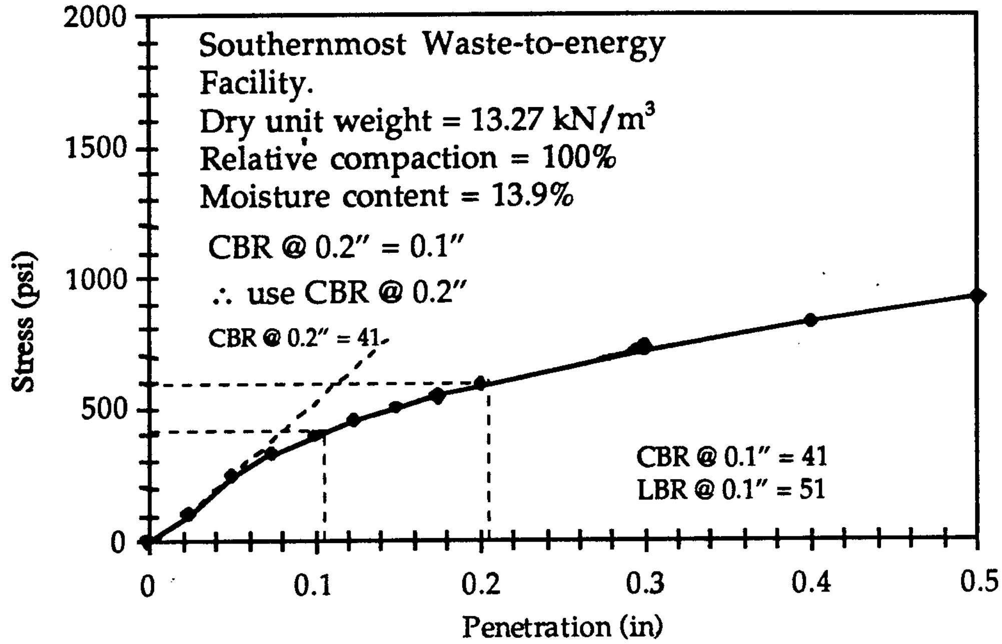


(a)

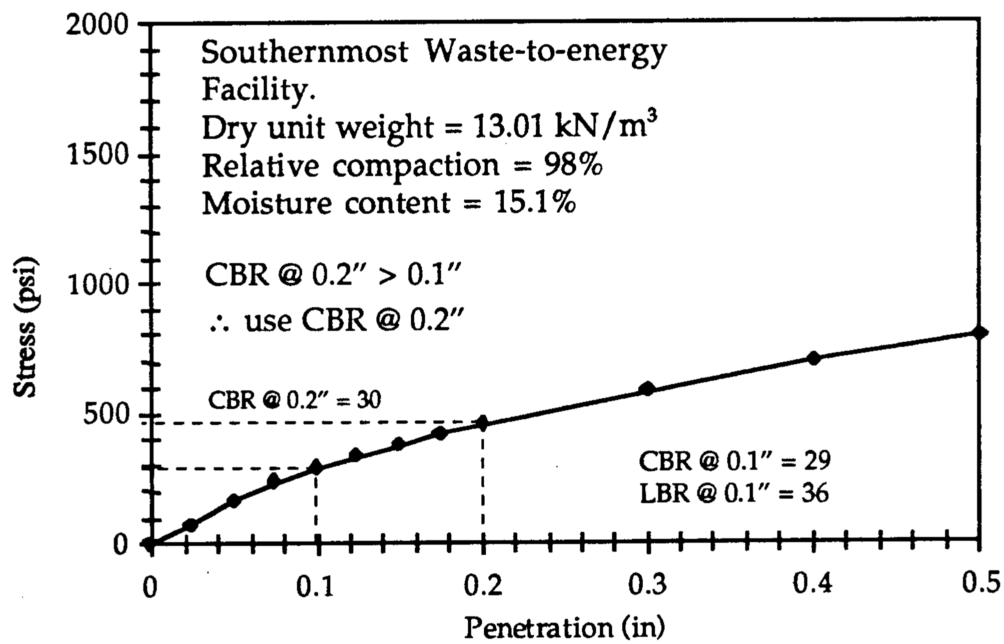


(b)

Figure E-33 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (a) 11% (b) 12.7%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)

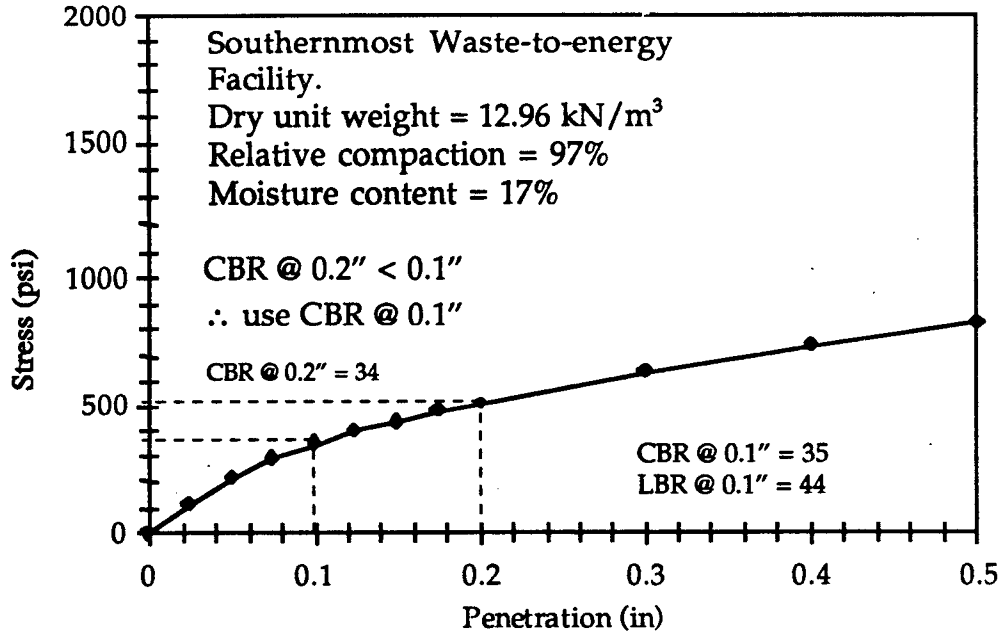


(c)



(d)

Figure E-34 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (c) 13.9% (d) 15.1%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)



(e)

Figure E-35 Stress versus penetration to compute unsoaked CBR and LBR values (ASTM D 1883-73) for combined ash passing # 3/4 in sieve compacted utilizing ASTM D 698-78 with moisture content (e) 17%
(1 pcf = 0.157 kN/m^3, 1 psi = 6.895 kPa, 1 in = 25.4 mm)