SCHOOL OF
CIVIL ENGINEERING
INDIANA
DEPARTMENT OF HIGHWAYS

JOINT HIGHWAY RESEARCH PROJECT

Final Report

FHWA/IN/JHRP-90/4 - 1

THE USE OF BOTTOM ASH
IN HIGHWAY EMBANKMENTS,
SUBGRADES, AND SUBBASES

Wei-Hsing Huang

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

Final Report

FHWA/IN/JHRP-90/4 - 1

THE USE OF BOTTOM ASH
IN HIGHWAY EMBANKMENTS,
SUBGRADES, AND SUBBASES

Wei-Hsing Huang

FINAL REPORT

THE USE OF BOTTOM ASH IN HIGHWAY
EMBANKMENTS, SUBGRADES, AND SUBBASES

To: H. L. Michael, Director
Joint Highway Research Project

Feb. 15, 1990

Project: C-36-50I

From: C. W. Lovell and J. E. Lovell
Joint Highway Research Project

File: 6-19-9

Attached is the Final Report of the HPR Part II study titled "The Use of Bottom Ash in Highway Embankments, Subgrades, and Subbases." The report was prepared by Mr. Wei-Hsing Huang, Graduate Research Assistant, under our direction.

A total of eleven Indiana bottom ashes was selected, sampled from ten power plants, and tested extensively to provide information on the properties of Indiana bottom ashes. The results of detailed evaluations show that the properties of bottom ash compare favorably with conventional highway materials, and they would also meet specification requirements set for conventional materials.

The potential environmental effects of bottom ash utilization were evaluated by performing the EP toxicity test and an Indiana leaching method. It was found that bottom ash can be classified as nonhazardous according to the current EPA regulations. Also, bottom ash leachate would meet the requirements for the most restrictive type of waste site specified in the Indiana Administrative Code.

The report is submitted for review, comment and acceptance in fulfillment of the referenced study.

Respectfully submitted,

C. W. Lovell
Research Engineer

J. E. Lovell
Professional Research Assistant

cc: A. G. Altschaeffl	R. A. Howden	B. K. Partridge
J. M. Bell	M. K. Hunter	G. T. Satterly
M. E. Cantrall	J. P. Isenbarger	C. F. Scholar
W. F. Chen	J. F. McLaughlin	K. C. Sinha
W. L. Dolch	K. M. Mellinger	C. A. Venable
R. L. Eskew	R. D. Miles	T. D. White
J. D. Fricker	P. L. Owens	L. E. Wood
D. E. Hancher

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

1. Report No. FHWA/IN/JHRP-90/4	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle THE USE OF BOTTOM ASH IN HIGHWAY EMBANKMENTS, SUBGRADES, AND SUBBASES		5. Report Date Feb. 15, 1990	
		6. Performing Organization Code	
7. Author(s) Wei-Hsing Huang		8. Performing Organization Report No. FHWA/IN/JHRP-90/4	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, Indiana 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR Part II	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, Indiana 46204		13. Type of Report and Period Covered Final Report	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration.			
16. Abstract This research assessed those properties of power plant bottom ash likely to affect its use as highway fill or pavement material, based on laboratory investigation conducted on eleven Indiana bottom ashes. Laboratory tests included: chemical analysis, mineralogical study, microscopic examination of ash particles, specific gravity, grain size distribution, sulfate soundness, Los Angeles abrasion, permeability, shear strength, moisture-density relations, degradation under compaction, compressibility, and California bearing ratio. The various test values and properties were compared to those of representative granular soils or appropriate specifications. These comparisons provide information necessary for judging the suitability of bottom ash in Indiana highway construction. The potential environmental effects of bottom ash utilization were evaluated by performing leaching tests outlined in the EP toxicity test and an Indiana leaching method. Chemical analysis of the leachates showed that bottom ash is nonhazardous, and its effects on the quality of ground water are minimal.			
17. Key Words bottom ash, boiler slag, waste materials, highway materials, embankment, pavement, leaching test, leachate, ash disposal		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 269	22. Price

FINAL REPORT

THE USE OF BOTTOM ASH IN HIGHWAY
EMBANKMENTS, SUBGRADES, AND SUBBASES

by

Wei-Hsing Huang
Graduate Research Assistant

Joint Highway Research Project

Project No.: C-36-50I

File No.: 6-19-9

Prepared as Part of an Investigation

Conducted by the

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In cooperation with the

Indiana Department of Transportation

and the

U.S. Department of Transportation
Federal Highway Administration

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard specification or regulation.

Purdue University
West Lafayette, Indiana 47907

Feb. 15, 1990

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to his major professor, Dr. C. W. Lovell, for his valuable guidance and encouragement throughout the course of this study. Special thanks are expressed to Dr. A. G. Altschaeffl, Dr. T. D. White, and Dr. D. N. Winslow for serving on the advisory committee and critical review of the dissertation.

The author is indebted to Mrs. Janet Lovell for her valuable suggestions in the laboratory studies and comments pertaining to the final manuscript. Special thanks are due Mr. Bob Rahn of INDOT for his assistance and advice in this study. Appreciation is also expressed to Messrs. Te-Chih Ke, Ross Duckworth, and Joe Walters for their assistance in laboratory testing. Mr. Xiaotian Mao is acknowledged for his assistance in radioactivity testing. Part of the leachate analysis was performed by the Environmental Laboratory Division, Indiana State Board of Health, Indianapolis, Indiana.

The author also wishes to express his thanks to the staff at the power stations who provided invariable cooperation and guidance during the sampling of bottom ash in this project.

The financial support for this research project was provided by the Indiana Department of Transportation and Federal Highway Administration through the Joint Highway Research Project, School of Civil Engineering, Purdue University, West Lafayette, Indiana.

Finally, the author wishes to express his love and gratitude to his families, especially his wife Tzer-Min, for the continuous support, encouragement, and understanding given him during his study.

TABLE OF CONTENTS

	Page
LIST OF TABLES.	viii
LIST OF FIGURES	xi
ABSTRACT.	xvi
INTRODUCTION	1
Problem Statement	1
Research Objectives	4
Research Approach	5
Literature Review	5
Experimental Program	6
Environmental Evaluation	7
Economic Evaluation	8
LITERATURE REVIEW	9
Origin of Power Plant Ash	12
Collection of Ash	14
Pulverized Coal-Fired Furnaces	16
Cyclone Furnaces	17
Stoker-Fired Furnaces	18
Disposal of Ash	20
Production and Utilization	23
Properties of Bottom Ash	29
Physical Characteristics	30
Physical Appearance	30
Specific Gravity and Water Adsorption	31
Gradation	33
Chemical Properties	40
Chemical Composition	40
Trace Elements	45
Mineralogy	46
Engineering Properties of Bottom Ash	48
Soundness	48
Los Angeles Abrasion	50
Deleterious Materials	54
Angle of Shearing Resistance	58
Permeability	61
Compaction Characteristics	64
Compressibility	72

	Page
Stabilization	74
Mechanical Stabilization	74
Admixture Stabilization.	81
Environmental Aspects of Ash Utilization	86
Environmental Legislation	86
Environmental Impacts of Ash Utilization	89
Waste Classification	91
Characteristics of Corrosivity	93
Extraction Procedure Toxicity	
Characteristics (EPTC)	93
Toxicity Characteristics Leaching	
Procedure (TCLP)	96
Indiana Leaching Method	99
Leaching Properties of Ash	99
Leaching Mechanism	102
Attenuation Mechanisms	104
Leachate Content	105
Radioactivity	108
TESTING MATERIALS	112
Selection of Ash Sources	112
Sampling of Ash	115
Bottom Ash	117
Gibson Ash	118
Gallagher Ash	118
Wabash Ash	119
Brown Ash	119
Culley Ash	120
Schahfer Unit 17	120
Schahfer Unit 14	121
Mitchell Ash	121
Richmond Ash	122
Perry Ash	122
Stout Ash	123
Fly Ash.	124
LABORATORY TESTING PROGRAM	125
Introduction	125
Ash Characterization Tests	126
Chemical Analysis	126
Loss on Ignition	128
Microscopic Examination	129
X-Ray Diffraction	129
Grain Size Distribution	129
Specific Gravity	120
Aggregate Tests	131
Los Angeles Abrasion	131
Sulfate Soundness	131

	Page
Geotechnical Property Tests	132
Maximum and Minimum Densities	132
Permeability	132
Angle of Shearing Resistance	133
Compaction	133
Degradation	134
One-Dimensional Compression	134
California Bearing Ratio (CBR)	135
Stabilization	136
Compressive Strength	137
Leaching Tests	138
Extraction Procedure (EP) Toxicity	138
Indiana Leaching Method	139
Leachate Analysis	139
Radioactivity	140
RESULTS AND DISCUSSION	143
Shape and Surface Texture	143
Mineralogical Analysis	151
Chemical Analysis	154
Grain Size Distribution	160
Specific Gravity	176
Soundness	181
Los Angeles Abrasion	184
Relative Density and Void Ratio	187
Permeability	189
Angle of Shearing Resistance	191
Moisture-Density Relations	199
Degradation	207
One-Dimensional Compression	215
California Bearing Ratio (CBR)	219
Mechanical Stabilization	227
Densification Behavior	227
Load-Deformation Characteristics	235
Cement Stabilization	239
Leachate Properties	248
Radioactivity	253
ECONOMIC EVALUATION	256
Locations and Quantities Available	256
Cost Factors Influencing Ash Utilization	263
Disposal Costs	263
Processing Costs	264
Conventional Aggregate Costs	265
Transportation Costs	267
Assessment of Economic Potential	267

	Page
RECOMMENDATIONS FOR IMPLEMENTATION	270
Ash Selection Guidelines	270
Source Selection	271
Acceptance Criteria	274
Environmental Concerns	276
SUMMARY AND CONCLUSIONS	278
SUGGESTIONS FOR FURTHER STUDIES	282
BIBLIOGRAPHY	284
APPENDICES.	299
Appendix A: X-ray Diffraction Patterns of Bottom Ashes	299
Appendix B: Sample Form for Calculation of the Index of Crushing	310
Appendix C: Moisture-Density Curves for Various Ash Mixtures.	312
VITA.	316

LIST OF TABLES

Table		Page
1	Classification of coals by rank.	13
2	Quantities of coal ash collected at various locations.	20
3	End use profile for power plant ash in 1982. .	28
4	Grading and job-mix requirements for aggregate bases and subbases	38
5	Grading requirements for aggregate and soil-aggregate materials for subbases, base and surface courses.	39
6	Indiana grading requirements for base and subbase materials.	43
7	Chemical analysis of ash	45
8	Average trace-element contents of the ash from U. S. coals of various rank.	47
9	Typical specifications for sodium sulfate soundness test	51
10	Typical specifications for Los Angeles abrasion test.	55
11	Approximate values of ϕ for granular soils as affected by state of compaction, size, gradation, and angularity of grains.	60
12	Typical values of permeability coefficients. .	63
13	Classification of soils according to their coefficient of permeability.	64
14	Purpose of compaction in different highway components	65
15	Strength criteria for soil cement.	84

16	EPA Criteria pollutants - primary metals . . .	95
17	Additional toxicity characteristic contaminants and regulatory levels	98
18	Allowable concentrations of waste constituents using the EP toxicity test - Indiana	100
19	Allowable concentrations of waste constituents using the Indiana leaching method test	101
20	Bottom ash sources in the study.	115
21	Coal sources and ash type.	117
22	Index properties of selected fly ashes	124
23	Results of X-ray analysis on bottom ashes. . .	155
24	Glass in bottom ash.	156
25	Chemical composition of Indiana bottom ashes .	158
26	Unified soil Classification of bottom ashes. .	174
27	AASHTO classification of bottom ashes.	175
28	Specific gravity of bottom ashes	178
29	Specific gravity of the first ash sample using different methods.	180
30	Sulfate soundness of bottom ashes.	183
31	Results of the Los Angeles abrasion test . . .	185
32	Maximum and minimum void ratios and densities of selected bottom ashes	188
33	Coefficients of permeability of bottom ashes .	190
34	Results of direct shear tests on bottom ashes.	198
35	Moisture-density properties of bottom ashes. .	206
36	Degradation of bottom ashes under compaction .	214
37	CBR test results on selected bottom ashes. . .	221
38	Secant constrained modulus of bottom ashes . .	222

Table		Page
39	Compressive strength of cement stabilized bottom ashes and bottom ash-fly ash mixtures .	244
40	Results of the EP toxicity test on selected bottom ashes	249
41	Results of the Indiana leaching method test on selected bottom ashes.	251
42	Radium-226 activity of bottom ash.	254
43	Potential bottom ash sources in Indiana. . . .	259
44	Average bid prices for borrow and subbase materials in Indiana	266

Appendix Table

B-1	Sample form for calculation of the index of crushing from sieve analysis	311
-----	--	-----

LIST OF FIGURES

Figure		Page
1	Net generation of electricity by coal.	10
2	Coal consumption by electric utilities	11
3	Schematic diagram of the ash handling system .	15
4	Dry disposal of ash.	22
5	Ash production by electric utilities	24
6	Ash utilization trends - 1980 to 1985.	25
7	Coal consumption by Indiana electric utilities	27
8	Gradation range for dry bottom ash	34
9	Gradation range for wet bottom ash	35
10	Average gradations for dry and wet bottom ashes.	36
11	Gradations of dry and wet bottom ashes as compared with AASHTO M 147 Gradation D for base and subbase materials	41
12	Gradations of dry and wet bottom ashes as compared with AASHTO M 147 Gradation E for base and subbase materials	42
13	Typical moisture-density curve	67
14	Typical moisture-density curve for cohesionless soils	69
15	Grain structure of soil-aggregate mixtures . .	76
16	The possible effects of an ash deposit on human health and environment	92
17	Approximate locations of bottom ashes sampled in the study	114

13	Micrograph of Schahfer Unit 14 wet bottom ash.	144
19	Micrograph of Schahfer Unit 17 ash	144
20	Micrograph of Mitchell ash	145
21	Micrograph of Gibson ash	145
22	Micrograph of Gallagher ash.	146
23	Micrograph of Wabash ash	146
24	Micrograph of Brown ash.	147
25	Micrograph of Culley ash	147
26	Micrograph of Richmond ash	148
27	Micrograph of Perry ash.	148
28	Micrograph of Stout ash.	149
29	Micrograph of standard Ottawa sand	149
30	Typical X-ray diffraction pattern of dry bottom ash (Richmond).	152
31	Typical X-ray diffraction pattern of wet bottom ash (Schahfer Unit 14).	153
32	Variation in chemical constituents of bottom ash.	161
33	As-sampled gradations of Schahfer Unit 14 ash.	162
34	As-sampled gradations of Schahfer Unit 17 ash.	163
35	As-sampled gradations of Gibson ash.	164
36	As-sampled gradations of Perry ash	165
37	As-sampled gradations of Gallagher ash	166
38	As-sampled gradations of Mitchell ash.	167
39	As-sampled gradations of Wabash ash.	168
40	As-sampled gradations of Stout ash	169
41	As-sampled gradations of Brown ash	170
42	As-sampled gradations of Culley ash.	171

43	As-sampled gradations of Richmond ash.	172
44	Range of gradations for bottom and fly ashes .	177
45	Results of direct shear tests on Perry ash . .	192
46	Results of direct shear tests on Gallagher ash	193
47	Results of direct shear tests on Gibson ash. .	194
48	Results of direct shear tests on Schahfer Unit 17 ash	195
49	Results of direct shear tests on Schahfer Unit 14 ash	196
50	Moisture-density relations for Schahfer Unit 14 ash	200
51	Moisture-density relations for Schahfer Unit 17 ash	201
52	Moisture-density relations for Gibson ash. . .	202
53	Moisture-density relations for Gallagher ash .	203
54	Gradations of Schahfer Unit 14 ash before and after compaction	208
55	Gradations of Schahfer Unit 17 ash before and after compaction	209
56	Gradations of Gibson ash before and after compaction	210
57	Gradations of Perry ash before and after compaction	211
58	Gradations of Gallagher ash before and after compaction	212
59	One-dimensional compression curves for bottom ashes and a medium sand.	217
60	One-dimensional compression curves for bottom ashes and a medium sand.	218
61	Constrained modulus vs. vertical stress for bottom ashes and a medium sand	220
62	Moisture-density-CBR relations for Schahfer Unit 14 ash.	224

63	Moisture-density-CBR relations for Schahfer Unit 17 ash.	225
64	Moisture-density-CBR relations for Gibson ash.	226
65	Maximum density and optimum moisture for various proportions of Gibson bottom and fly ashes.	228
66	Maximum density and optimum moisture for various proportions of Schahfer 17 bottom and fly ashes.	229
67	Maximum density and optimum moisture for various proportions of Schahfer 17 bottom ash and Schahfer 14 fly ash.	230
68	Maximum density and optimum moisture for various proportions of Schahfer 14 bottom and fly ashes.	231
69	Densification behavior of various bottom ash- fly ash mixtures	233
70	Absolute volumes of bottom ash, fly ash, and voids in Gibson ash mixtures	234
71	CBR values and percent swelling of various proportions of Gibson bottom ash-fly ash mixtures	237
72	Maximum density and CBR values for various proportions of Gibson ash mixtures	240
73	Seven-day compressive strength for various proportions of Schahfer 17 bottom ash and Schahfer 14 fly ash.	241
74	Seven-day compressive strength for various proportions of Schahfer 14 bottom and fly ashes.	242
75	Compressive strength of cement stabilized Gibson ash mixtures.	245
76	Compressive strength of cement stabilized Schahfer 17 ash mixtures	246
77	Locations of coal-burning power plants in Indiana.	258
78	Areas lacking aggregates in Indiana.	262

Figure		Page
77	Location of coal-burning power plants in Indiana.	258
78	Areas lacking aggregates in Indiana.	262
79	Areas showing economic potential for use of bottom ash in highway fills.	269

Appendix

Figure

A-1	X-ray diffraction pattern of Schahfer Unit 17 ash.	300
A-2	X-ray diffraction pattern of Mitchell ash. . .	301
A-3	X-ray diffraction pattern of Gibson ash. . . .	302
A-4	X-ray diffraction pattern of Gallagher ash . .	303
A-5	X-ray diffraction pattern of Wabash ash. . . .	304
A-6	X-ray diffraction pattern of Perry ash	305
A-7	X-ray diffraction pattern of Stout ash (first sample).	306
A-8	X-ray diffraction pattern of Stout ash (second sample).	307
A-9	X-ray diffraction pattern of Culley ash. . . .	308
A-10	X-ray diffraction pattern of Brown ash	309
C-1	Moisture-density curves for various proportions of Gibson bottom ash-fly ash mixtures	313
C-2	Moisture-density curves for various proportions of Schahfer 17 bottom ash-fly ash mixtures	314
C-3	Moisture-density curves for fly ashes.	315

HIGHLIGHT SUMMARY

Interest in coal ash produced from power generating plants as a substitute for conventional construction material has increased considerably in recent years. The utilization of coal ash not only solves a waste disposal problem but also provides an economic construction material. In the past, studies on power plant ash have been concentrated on properties of fly ash. Very little has been developed on the productive use of bottom ash, primarily because of the lack of information on properties on this material. This report assesses those properties of bottom ash likely to affect its use in highway fill and pavement construction.

Laboratory investigations were conducted on eleven bottom ashes collected from all parts of Indiana. Chemical property tests included a complete chemical analysis and mineralogical analysis. Physical properties such as appearance, grain size distribution, and specific gravity of bottom ash were also studied. The assessment of mechanical performance involved a series of tests consisting of sulfate soundness, Los Angeles abrasion, permeability, shear strength, compaction characteristics, compressibility, and California bearing ratio. To evaluate potential highway construction uses, the

test results were compared with those of representative granular materials and appropriate existing specifications.

The potential environmental effects of bottom ash utilization center around possible leaching of heavy metals and soluble salts from ash-constructed embankments. Leaching tests were performed using the extraction procedure outlined in the EP toxicity test and an Indiana leaching method. Chemical analysis of the leachates generated from these tests showed that bottom ash is nonhazardous, and its effects on the quality of ground water are minimal.

The economic potential was assessed for Indiana bottom ashes based on the quantities available and their location with respect to potential market areas. A qualitative study of the cost factors determining the cost of bottom ash in place was also included.

Based on this laboratory investigation, it is concluded that the properties of bottom ash compare favorably with conventional granular materials. It is obvious that utilization of such extensively produced by-products of the power industry as an economic highway material should be encouraged in the immediate future. It is recommended that the Indiana Department of Transportation proceed to schedule the construction of experimental sections of embankment and pavement using bottom ash.

INTRODUCTION

Problem Statement

Power plant ash is the by-product produced from the burning of coal in utility power plants. The growing demand for electricity has resulted in the construction of many coal-fired power plants and as a result the production of power plant ash has continued to increase. For example, in the 10-year period of 1976 to 1986, the annual production of power plant ash increased from 54 to 67 million tons [1]. Disposal of power plant ash has become more costly to the power industry. Costs are ultimately transferred to the power consumer.

On the other hand, many areas of the United States are faced with a shortage of conventional construction materials. Most urban areas, where demands of construction material are high, are deficient in the supply of conventional aggregates [2]. In addition, zoning restrictions and environmental regulations often remove acceptable materials from availability. Usually these same urban areas are served by many power stations that produce large quantities of ash. Obviously, a favorable combination of circumstances is created for utilization of power plant ash as a partial or full

substitute for conventional aggregates in various applications.

The materials collected from the burning of coal at electric utility plants are referred to as power plant ash. These materials are produced in two forms: fly ash and bottom ash. Bottom ash is the slag which builds up on the heat-absorbing surfaces of the furnace, and which subsequently falls through the furnace bottom to the ash hopper below. Fly ash is the fine-grained dusty material that is recovered and collected from furnace flue gases by ash precipitators.

In view of the benefits to be gained from the utilization of power plant ash as a construction material, much research and other efforts devoted to exploring productive uses for this material in the construction of highways, buildings, and other structures is justified. In the past, much of the available research has focused on the properties and uses of fly ash. This is understandable because fly ash represents approximately two-thirds of the total ash production [1]. However, other studies [3,4] have indicated that engineering properties of many bottom ashes compare favorably with those of conventional highway construction materials.

Unfortunately, an extensive review of the literature reveals that the amount of laboratory and field data on the properties and performance of this material is very limited. Therefore, in order to develop productive uses of bottom ashes, a substantial data base on their properties is needed.

A potential problem associated with the use of power plant bottom ash is its variability. The variability occurs because of differences in: a) the type and origin of coal burned, b) boiler types, c) degree of coal pulverization, d) firing conditions in the furnace, and e) ash handling practices. Even bottom ash produced from a single source can be quite variable depending on the operating conditions and procedures. Therefore, there is a need for a systematic procedure to evaluate locally available bottom ashes for potential construction uses.

The Surface Transportation and Uniform Relocation Assistance Act [5] of 1987 included a strong endorsement of coal ash use in highway construction. Accordingly, the Federal Highway Administration is encouraging large-volume use of coal ash by providing an additional 5 percent Federal-aid match for highway projects that include more than 1,000 tons of coal ash [6]. It is expected that the trend to encourage the utilization of coal ash will continue with even more emphasis in the future. Since the state of Indiana is one of the eight largest ash-producing states in the United States [7], there is motivation for the Indiana Department of Transportation (INDOT) to use bottom ash in Indiana highway construction. This research program is designed to provide the necessary information and guidelines to INDOT for use of bottom ash.

Research Objectives

The primary objective of this research was to determine the various ways in which bottom ashes can be used in Indiana highways, with emphases on large tonnage uses such as highway fills, select subgrades, and stabilized or unstabilized subbases and bases. Based on laboratory investigations conducted on Indiana bottom ashes, this study assessed those properties of bottom ash that are likely to affect its use in highway fill and pavement construction. Specifically, these included index properties, moisture-density relationships, shear strength, and compressibility of bottom ash, as well as mechanical and chemical stabilization of the material. Characterization of representative Indiana bottom ashes needed be accomplished to provide guidelines in the selection of locally available bottom ashes for various highway applications. It was also intended to evaluate the potential environmental impacts resulting from bottom ash uses. Radioactivity of bottom ash and the leaching potential of the material were examined.

Another objective was to evaluate the validity and the extent of applicability of the conventional test methods and the pertinent material specifications in the utilization of bottom ashes. This is intended to establish general guidelines for the modifications of conventional test methods and material specifications as applied to bottom ash.

Research Approach

In order to accomplish the objectives, the following tasks were completed: a) a thorough literature review, b) a complete experimental program on physical, chemical, and engineering properties of Indiana bottom ashes, c) an evaluation of the potential environmental effects, and d) an examination of the economics of bottom ash use in Indiana.

Literature Review

More than 200 relevant documents were reviewed on the nature, production, properties, disposal and utilization, and service performance of power plant ash. This review focused on publications concerning:

1. Production and disposal of power plant ash.
2. Primary and supplementary areas of utilization.
3. Laboratory test results on the physical, chemical, and engineering properties of power plant ashes.
4. Environmental effects resulted from ash disposal and utilization.
5. Quantities and locations of available ashes.
6. Use of other waste materials in highway construction.

As mentioned earlier, most publications concentrated their attention on fly ash, with limited discussions on bottom ash. Nevertheless, these publications on power plant ash,

along with some on blast furnace slag and coal mine refuse, contributed significant information for this study.

Experimental Program

A total of 11 bottom ashes were collected for study from 10 power stations in Indiana, with consideration to: boiler type, type and source of coal, geographic distribution, and ash disposal method. First, these samples were subjected to a series of physical and chemical characteristic tests. The remainder of the experimental program was devoted to tests on the engineering properties of the ashes, especially those which would relate to their use in highway fills and pavements.

The characterization tests consisted of:

- complete chemical analysis of each bottom ash;
- mineralogical study using X-ray diffraction techniques;
- microscopic examination of the shape and texture of the particles;
- grain size distribution, ASTM C 136 [8];
- specific gravity, ASTM C 128 [9] and D 854 [10];

Selected bottom ashes were evaluated using the following tests:

- sulphate soundness, ASTM C 88 [11];

- Los Angeles abrasion, ASTM C 131 [12].
- maximum and minimum index density, ASTM D 4253 [13] and 4254 [14];
- falling head permeability;
- shear strength;
- standard Proctor compaction, ASTM D 698 [15];
- degradation under compaction;
- one-dimensional compressibility;
- California bearing ratio, ASTM D 1883 [16].

Finally, selected bottom ashes were subjected to mechanical and chemical stabilization to broaden the potential application of the material in pavement construction.

The test results were compared with those of representative granular materials, to further evaluate the potential of bottom ash for highway uses.

Environmental Evaluation

Representative bottom ash samples were subjected to leaching tests designated by Environmental Protection Agency (EPA) [17] to determine whether bottom ash is environmentally hazardous. Leachates generated from the Extraction Procedure (EP) toxicity tests conducted on bottom ashes were analyzed for heavy metals to predict their hazardous characteristics.

In addition, to evaluate the possible groundwater pollution potential of bottom ash, the Indiana leaching method

test [18] was performed. Similarly, the leachates were analyzed for the parameters specified in state regulations to determine the groundwater pollution potential.

The radioactivity of bottom ash was examined by determining the radium-226 activity and the results were compared to those of natural soils.

Economic Evaluation

The economic evaluation of the use of bottom ash in highway construction focuses on two phases:

1. An assessment of economic potential for Indiana bottom ash based largely on the quantities available and their location with respect to potential market areas.

2. A study of the factors that would determine the cost of bottom ash in place for development as a highway construction material.

LITERATURE REVIEW

More than 50 percent of the electrical energy produced in the United States comes from the burning of coal [19]. During 1988, approximately 756 million tons of coal were consumed by electric utilities [20]. Figure 1 shows the annual total generation of electricity and that generated by coal-burning from 1949 to 1988 [19]. Although the growth of electricity generation has slowed, indications are that coal will continue to play an increasing role in the future generation of electricity. As a result, the production of coal combustion by-products, including power plant ash, will certainly increase considerably.

Figure 2 shows the past and projected quantities of coal consumed by electric utilities [19,21]. Projections are based on future utility consumption estimates furnished by the American Coal Ash Association (ACAA) and the Department of Energy (DOE). These projections indicate that more than one billion tons of coal will be burned by electric utilities in 1995 and approximately 1.25 billion tons per year by 2000.

In the state of Indiana, the trend of increasing ash production by electric utilities is particularly true, because

Figure 1. Net generation of electricity by coal

Figure 2. Coal consumption by electric utilities

98 percent of the Indiana electricity is generated from the burning of coal [22].

Origin of Power Plant Ash

The by-products produced from the combustion of coal are the residual materials which consist primarily of the inorganic mineral matter in the coal, but also of organic matter which is not fully burned. These residual materials are referred to as power plant ash. The amount of ash produced by coal combustion is a function of the ash content of the coal. In general, higher ranks of coal will have less ash than lower ranks. Table 1 summarizes the ASTM classification of coal by rank [23]. By and large, the most important classes are:

- Anthracite
- Bituminous
- Subbituminous
- Lignite.

Generally, the bulk of bituminous coal used for power generation in the U. S. has an ash content within the range of 6 to 20 percent. Low values of 3 or 4 percent are encountered infrequently, and such coals find other commercial uses, particularly in the metallurgical field. On the other hand, some lignite coals may have an ash content as high as 30 percent [24].

Table 1. Classification of coals by rank^a

Class	Coal group	Fixed carbon limits, % (dry, mineral-matter-free basis)		Volatile matter limits, % (dry, mineral-matter-free basis)		Calorific value limits, Btu per pound (moist, mineral-matter-free basis)	
		Equal or greater than	Less than	Greater than	Equal or less than	Equal or greater than	Less than
Anthracitic	Meta-anthracite	98	-	-	2	-	-
	Anthracite	92	98	2	8	-	-
	Semianthracite	86	92	8	14	-	-
Bituminous	Low volatile bituminous	78	86	14	22	-	-
	Medium volatile bituminous	69	78	22	31	-	-
	High volatile A bituminous	-	69	31	-	14,000	-
	High volatile B bituminous	-	-	-	-	13,000	14,000
Sub-bituminous	High volatile C bituminous	-	-	-	-	11,500	13,000
	Subbituminous A	-	-	-	-	10,500	11,500
	Subbituminous B	-	-	-	-	9,500	10,500
Lignite	Subbituminous C	-	-	-	-	8,300	9,500
	Lignite A	-	-	-	-	6,300	8,300
	Lignite B	-	-	-	-	-	6,300

^a Source: ASTM D 388 [23]

The formation of ash takes place in the furnace of the boilers which produce the steam used in generating electricity. During the burning process, the organic component of coal is burned off quickly, whereas the incombustible material undergoes partial melting and tends to fuse together to form ash. A typical schematic of the ash-handling configuration at a coal-burning power plant is shown in Figure 3 [25]. The ash is collected in several areas, and the physical and chemical characteristics of the ash vary.

Bottom ash is the slag that is deposited on the heat-absorbing surfaces of the furnace and that subsequently falls into the furnace bottom. Ash hoppers or conveyers are under the furnace bottom to collect bottom ash which can be in either a solid or molten state.

Hoppers under the rear convection pass and air heaters of the boiler are called economizer and air-heater hoppers. It is here that smaller quantities of coarser ash drop from the gas stream with direction changes in the gas flow.

Fly ash is the fine-grained residue that is collected by ash precipitators and baghouses from the stream of combustion gases prior to its discharge into the atmosphere.

Collection of Ash

The type of bottom ash produced at a particular power plant is determined mainly by the design and operation of the boiler units. Depending upon the boiler type, the ash

Figure 3. Schematic diagram of the ash handling system

collected under the furnace bottom is categorized as "dry bottom" or "wet bottom" ash. If the ash is in a solid state at the furnace bottom, it is called dry bottom ash. Wet bottom ash refers to the molten state of the ash which leaves the furnace as a liquid. Wet bottom ash is more often called boiler slag.

At present, there are three categories of coal burning boilers which produce different types of bottom ash [24,25,26]. These are:

- (a) Pulverized coal-fired furnaces.
- (b) Stoker-fired furnaces.
- (c) Cyclone furnaces.

Pulverized Coal-Fired Furnaces

Pulverized coal-fired units are most widely used in the electrical utilities, especially for new power installations. Solid fossil fuels, varying from anthracite to peat, are all possible energy sources. The coal is pulverized (the recommended fuel fineness varies from 70 percent passing a No. 200-mesh sieve (75 μm) for lignite coal to 90 percent for bituminous coal), and then injected into the furnace where combustion takes place. Ash can be removed from the bottom of the furnace in a molten state and quenched in water (boiler slag) or in a solid granular form (bottom ash). If the ash is removed in a solid, granular form, the boiler is called "dry-

bottom"; and if the ash leaves the furnace in a molten state, the boiler is referred to as a "wet-bottom" or "slag-tap" boiler.

In a dry bottom boiler, the ash that is not fine enough to go up the stack with the boiler gases in the form of fly ash, solidifies and agglomerates into coarse particles. A certain amount of molten slag which forms on the internal surface of the boiler also drops into the ash hopper. Typically, 60 to 80 percent of the ash produced in a pulverized dry bottom boiler leaves the furnace in the flue gas stream of fly ash, and 20 to 40 percent of the ash falls to the furnace bottom to form dry bottom ash. The ash hopper is generally filled with water. When a sufficient amount of bottom ash drops into the hopper, it is removed by means of high pressure water jets, conveyed by a sluiceway to a coarse crusher, and on to a storage area.

In a slag-tap furnace, as much as 50 percent of the ash originally in the coal is retained in the furnace to form boiler slag. The other 50 percent of total ash leaves the furnace in the form of fly ash.

Cyclone Furnaces

Cyclone furnaces burn crushed coal that is 95 percent finer than the No. 4 sieve. The primary furnace is a relatively small horizontal cylinder, into which crushed fuel and air are introduced tangentially at high velocity. Heat is

released at extremely high rates and gas temperatures exceeding 1650°C (3000°F) are developed. These temperatures are sufficiently high to melt the ash into a liquid slag, which forms a layer on the walls of the cyclone. Molten slag, in excess of the thin layer retained on the walls, continually drains away and discharges to the boiler furnace, from which it is tapped into a slag tank. Here, it is quenched and breaks up into a granular form. Seventy to 85 percent of the ash melts and is tapped from the furnace as boiler slag, leaving 15 to 30 percent of the ash to be carried by the flue gases as fly ash.

Stoker-Fired Furnaces

Stoker-fired boilers are practical only for power plant generating less than 40 megawatts (MW) of electricity. Thus many small and medium-size boilers are fired with mechanical stokers. The stoker-fired units are designed mechanically to feed the coal into the furnace, to provide the air for combustion, and then to remove the unburned refuse. Mechanical stokers can be classified in four groups, based on the method of introducing fuel to the furnace:

- (1) Spreader stokers.
- (2) Underfeed stokers.
- (3) Water-cooled vibrating-grate stokers.
- (4) chain-grate or travelling-grate stokers.

The underfeed stoker is most suitable for use with coking coals; the travelling or chain-grate stoker is used primarily for those furnaces which burn anthracite or midwestern bituminous coal; and spreader stokers are used with a variety of coals.

In the fuel bed of a stoker, ash particles tend to become fused together. In a properly operating stoker burning a suitable coal, the passage of air and the agitation of the fuel bed serve to keep the ash more or less porous, and the ash is discharged to an ashpit in fairly large pieces. Therefore, the bottom ash produced by stoker-fired units is coarser than that produced by pulverized coal-fired units or cyclone furnaces.

The total amount of ash produced depends less on the ash content of the coal than on a number of factors relating to the source of coal and design and operating characteristics of the boiler. Underfeed stokers and travelling grate stokers will produce 10 to 20 percent fly ash with the remainder of the ash being collected as bottom ash. Fifteen to 55 percent of the total ash produced by spreader stokers is fly ash and, accordingly, 85 to 45 percent of the ash is produced as bottom ash.

Table 2 gives a typical distribution of coal ash over the various collection ports at a widely used pulverized dry-bottom boiler [27]. Because power plant ashes are generally considered as waste materials, the ash handling systems are

designed only to facilitate disposal and not to save ash quality. Although fly ash and bottom ash or boiler slag are collected separately, at many power plants these materials may be combined prior to or during waste disposal.

Disposal of Ash

Because the production rate at a given plant would be less than the rate at which the ash is used in a typical highway construction operation, stockpiling of the ash would be necessary. For example, an entire year's ash production at a plant may be used in a very short construction period. Again, the current stockpiling operations are not designed to maintain the quality of the ash, but to facilitate handling and disposal. Often, the primary purpose of the stockpiling is only to dispose of the ash.

Table 2. Quantities of coal ash collected at various locations^a

Ash type	percent
Bottom ash	20
Fly ash	
Economizer	3
Air heater	2
Precipitator	75
Total	100

^a Source: Baker [27]

The disposal of ash is accomplished either by a dry or a wet method [28,29]. Dry disposal implies transport and deposition of dry or moist ash. This may involve temporary storage of the ash in silos, subsequent hauling by trucks, and compacting at a disposal site. Most power stations in urban area handle their ash by the dry method, due to difficulties in land acquisition and environmental restrictions. Figure 4 illustrates a typical dry disposal system.

An alternative method of ash disposal is to add sufficient amount of water to produce a slurry and enable transport of the ash by pipeline to settling ponds or lagoons. The advantages of wet disposal are that ash ponds minimize dust problems and are simple to operate. On the other hand, ponding may produce undesirable segregation; however, this may also be used advantageously if it is used to settle out excessive fines [30].

According to information reported in 1981 by utility companies to the U. S. Department of Energy, at least \$370 million is expended annually by coal-burning utilities in the operation and maintenance of ash disposal areas [7]. On a national scale, ash disposal costs range from \$5 to \$10 per ton and the total cost of ash disposal to the electric utilities in 1980 ranged from \$375 to \$740 million [31].

Figure 4. Dry disposal of ash

Production and Utilization

The production of ash in the United States has steadily increased along with the increase in coal-fired generating capacity. Figure 5 shows a compilation by year of ash production by electric utilities in the U. S., based on data from the American Coal Ash Association (ACAA) [1]. Annual ash production has increased from 39.2 million tons in 1970 to 66.8 million tons in 1986 [1]. The use of high-ash content western coals and a switch to coal from other energy sources could further increase this figure [32,33].

Of the 17.5 million tons of bottom ash and boiler slag produced in 1986, 13.4 and 4.1 million tons were dry bottom ash and boiler slag, respectively. Only 26.7 percent of the dry bottom ash was used, whereas 51.9 percent of the boiler slag was used [34]. Figure 6 illustrates the trends in ash utilization in the 1980s expressed as a percentage of the amount of ash used [35]. An examination of the statistics indicates that the percent of bottom ash and boiler slag uses have remained unchanged in the 1980s, while the use of fly ash has improved significantly. These statistics also indicate that a substantial volume of ash must currently be placed in disposal areas each year. There is no reliable estimate of the quantity of ash that has been accumulated over the years in storage.

According to the reports prepared by the coal-burning utility companies and submitted to the Federal Energy

Figure 5. Ash production by electric utilities

Figure 6. Ash utilization trends - 1980 to 1985.
(Source: Golden [35])

Regulatory Commission on Form 67 in 1981, annual ash production in Indiana was 3.5 million tons, which made Indiana the fifth largest ash production state in the U. S. Approximately 2.4 million tons of fly ash and 1.1 million tons of bottom ash (dry bottom ash and boiler slag) were produced. Due to changes in the FERC Form 67, the state by state ash production figures are not available for later years.

Figure 7 shows the coal consumption by electric utilities in Indiana [22]. Because the coal consumption by electric utilities in Indiana shows an increasing trend, it is expected that ash production will increase accordingly. If the ash content of the coal presently burned in Indiana remains the same as in 1981, an estimate of current ash production can be made using the proportion of ash to coal. This results in an estimated ash production of 4.1 million tons which consists of 2.8 million tons of fly ash and 1.3 million tons of bottom ash in Indiana.

Table 3 gives data compiled by the ACAA on the end uses of power plant ash during 1982 [1]. A total of 8 ash utilization categories are included in this table. Boiler slag is widely used for applications such as blasting grit, roof granules, and snow and ice control. Bottom ash is used mainly as fill material, antiskid and ice-control material, and road base material.

Figure 7. Coal consumption by Indiana electric utilities

Table 3. End use profile for power plant ash in 1982^a
(millions of tons)

End Use	Fly Ash		Bottom Ash		Boiler Slag	
	Quantity Used	Percent of Use	Quantity Used	Percent of Use	Quantity Used	Percent of Use
Cement and Concrete Products	2.7	34	0.4	12	0.1	5
Structural Fills, Embankments	2.1	26	1.7	47	0.1	5
Road Base	0.3	4	0.7	19	0.1	5
Filler in Asphalt Mixes	0.1	1	-	-	0.1	5
Snow and Ice Control	-	-	0.6	16	0.7	35
Blasting Grit, Roofing Granules	0.1	1	-	-	0.7	35
Grouting	0.3	4	-	-	-	-
Miscellaneous	2.4	30	0.2	6	0.2	10
Total Utilized	8.8	100	3.6	100	2.0	100
Total Produced		47.9		13.1		4.4
Percent Utilized		16.7		27.5		45.4

^a From National Coal Ash Association [35]

Properties of Bottom Ash

Published data on the physical, chemical, and engineering characteristics of bottom ash are somewhat limited. A major portion of the information available on bottom ash characteristics has been generated through research conducted on West Virginia bottom ashes. However, not all bottom ash is the same, because of the basic variations in: a) the type and origin of coal burned, b) boiler types, c) degree of coal pulverization, d) firing conditions in the furnace, and e) ash handling practices.

The information on bottom ash characteristics has been reported in the literature by Seals, et. al. [3], Moulton, et. al. [36], Moulton [37], Anderson, et. al. [33], Usmen [38], and Majidzadeh, et. al. [4]. It has been emphasized by most of these authors that bottom ash has quite variable physical, chemical, and engineering characteristics. These characteristics of bottom ash can vary not only from one plant to another, but also from day to day production within a single plant over time. Therefore, the values for various characteristics reported by researchers apply only to the ash samples tested by those researchers and must not be taken as absolutes.

Usually, the variation within the same plant is quite predictable, provided that the coal source and plant operations remain the same [39]. In other words, laboratory and field data on characteristics of bottom ash from a given

source are valid as long as the plant's operating parameters do not change. Bottom ashes obtained from different sources must be tested separately and care must be taken to insure that the samples are representative of the entire supply.

As mentioned earlier, there are two different types of bottom ash: dry bottom ash and wet bottom boiler slag. In this section, the two types of ash will be discussed separately, since their characteristics are somewhat different. Generally, wet bottom boiler slag tends to have more uniform characteristics than dry bottom ash. This is true in terms of both plant-to-plant variations and variations within the same plant [33], because dry bottom ash is the direct product of burning while boiler slag is solidified from the molten slag.

Physical Characteristics

Physical Appearance

Due to the differences in the formation of the two types of ash, bottom ash and boiler slag have distinctly different physical appearances. Wet bottom ash is composed of hard and angular to subangular particles with a shiny black color and a smooth surface texture much like crushed glass. Some coarser particles may be porous, if gases are trapped in the slag as it is tapped from the furnace [30]. In addition, a small portion of the particles are spherical or rod-shaped.

Most of the boiler slag particles feature fractured faces, as a result of the rapid quenching as the molten slag flows from the furnace bottom into the water-filled hopper. Boiler slag produced from the burning of lignite and sub-bituminous coals tends to be more vesicular than that of eastern bituminous coals [40].

Dry bottom ash is gray to black in color, is quite angular, and has a porous structure and rough surface texture. Some of the particles resemble boiler slag, i.e., black and glassy in appearance, especially in the smaller sizes. These glassy particles represent the molten slag from the internal surface of the boiler. The predominant material is gray in color with an irregular shape.

Particle shape and surface texture will significantly affect the frictional characteristics of material and, in turn, the stability of earthworks [41]. Angularity contributes to particle interlock, and a rough surface texture inhibits movement of one particle on another. Therefore, materials with greater angularity and rough surface texture are preferred in highway bases and subbases [42]. In this context, bottom ash compares favorably with conventional highway materials.

Specific Gravity and Water Adsorption

The specific gravity of bottom ash depends on the chemical compositions of the ash as well as the porosity of

the ash particles. Obviously, those ashes with high iron contents will have correspondingly higher specific gravities. The specific gravities reported in the literature for dry bottom ash range from 2.0 to 2.6 with an average of 2.35 [3,4,33,37,38]. A dense dry bottom ash may have a specific gravity as high as 2.8, while a poor ash with high percentages of porous and popcornlike particles may exhibit a specific gravity as low as or even lower than 1.6, as emphasized by Anderson, et. al. [33]. Therefore, it was suggested that the specific gravity of bottom ash might be used as an indicator of the material's quality, because higher specific gravity generally indicate a denser ash that contains smaller quantities of porous and popcornlike particles.

Due to its dense nature, wet bottom boiler slag tends to have a higher specific gravity than dry bottom ash. The specific gravities reported in the literature for boiler slag vary from 2.6 to 2.9 with an average of about 2.75 [3,4,37].

Water adsorption data vary considerably depending on the porosity and surface texture of the ash. Dry bottom ash generally shows higher water adsorption values, ranging from 0.5 to 8 percent by weight, than those for boiler slag, due to the porous surface texture of the material [3,4,37,38]. Boiler slag, having a glassy texture, exhibits lower water absorptivity varying from 0.4 to 3 percent [3,4,42].

Gradation

As described by many researchers [3,4,33], bottom ash and boiler slag have quite different gradation characteristics. Generally, bottom ash is a well-graded material with a gradation ranging from 1 inch (25.4 mm) to the No. 200 sieve (75 μm). The portion of bottom ash passing the No. 200 sieve, typically ranges from 0 to 10 percent by weight, is essentially coarse fly ash, and is nonplastic. Figure 8 shows the range of particle size distribution of 12 bottom ashes found in the literature [3,4,37,38,43]. It should be noted that it is not unusual to obtain bottom ash samples that have quite different grain size distributions, especially if the ashes have been stockpiled in ash ponds for some time.

In contrast to dry bottom ash, the grain size distribution of boiler slag is quite uniform, with a majority of the sizes falling within a narrow range between the No. 4 (4.75 mm) and the No. 30 (600 μm) sieves. Except for the oversized material, boiler slag is generally lacking in the coarser sizes. Figure 9 shows the range of the grain size distribution of 9 boiler slags reported in several studies [3,4,38,44]. In Figure 10, the average grain size distributions of the 12 bottom ashes and 9 boiler slags are compared. The differences between the gradation of the two ash types are readily apparent.

The grain size distribution is normally expressed as relative percentages of the total weight. For materials that

Figure 8. Gradation range for dry bottom ash

Figure 9. Gradation range for wet bottom ash

Figure 10. Average gradations for dry and wet bottom ashes

have variable specific gravities dependent on particle sizes, the standard "percent finer by weight" plots may result in misleading interpretation of the material's gradation [45]. Indeed, some coal ashes, especially ponded ashes that contain both bottom and fly ashes, were found to have different specific gravities in different size ranges [46]. In such cases, it would be physically more meaningful to plot particle sizes as a function of solid volume rather than weight, because volume is generally the parameter of interest [46]. In other words, a grain size distribution based on "percent finer by solid volume" would provide a more realistic indication of the gradation.

Due to its highly porous structure, bottom ash is likely to have variable specific gravities dependent on particle size. This is particularly true for bottom ashes that contain large amount of lightweight particles. Unfortunately, the specific gravities of bottom ash in different size ranges are not available in the literature.

The grain size distribution has been considered as a key factor in determining the behavior of base and subbase materials, since it affects the stability, drainage, and frost susceptibility of highway bases and subbases [47]. Experience has shown that a wide variation of gradations may be successfully used for highway bases and subbases depending on the type of base or subbase sought [47,48].

Generally, the gradation specifications for materials are expressed in the form of gradation bands which consist of the allowable ranges of weight percentages passing a series of sieve sizes. Table 4 indicates the gradation and job-mix requirements for aggregate material to be used for bases and subbases for highways or airports, as given by the ASTM Designation D 2940 [49]. The gradation requirements for aggregate and soil-aggregate materials for use in subbases, base and surface courses are given in AASHTO Designation M 147 [50] and ASTM Designation D 1241 [51], and are presented in Table 5. These gradation requirements are of national rather than local character. Hence they should be regarded primarily as guides rather than an absolute standard [52].

Table 4. Grading and job-mix requirements for aggregate bases and subbases^a

Sieve Size (Square Openings)	Over-all Percentages Passing (Master Ranges)	Job-Mix Tolerances	
		Bases	Subbases
2 in. (50 mm)	100	-2	-3
1 1/2 in. (37.5 mm)	88 to 100	±5	±5
3/4 in. (19.0 mm)	60 to 100	±8	±10
3/8 in. (9.5 mm)	40 to 77	±8	±10
No. 4 (4.75 mm)	25 to 60	±8	±10
No. 30 (600 m)	7 to 24	±5	±8
No. 200 (75 m)	0 to 10	±3	±5

^a From ASTM Designation D 2940 [49]

Table 5. Grading requirements for aggregate and soil-aggregate materials for subbases, base and surface courses^a

Sieve Size (Square Openings)	Weight Percent Passing Square Mesh Sieves					
	Type I			Type II		
	Gradation A	Gradation B	Gradation C	Gradation D	Gradation E	Gradation F
2 in. (50 mm)	100	100	...	...	...	...
1 in. (25.0 mm)	...	75 to 95	100	100	100	100
3/4 in. (9.5 mm)	30 to 65	40 to 75	50 to 85	60 to 100	...	...
No. 4 (4.75 mm)	25 to 55	30 to 60	35 to 65	50 to 85	55 to 100	70 to 100
No. 10 (2.00 mm)	15 to 40	20 to 45	25 to 50	40 to 70	40 to 100	55 to 100
No. 40 (425 μ m)	8 to 20	15 to 30	15 to 30	25 to 45	20 to 50	30 to 70
No. 200 (75 μ m)	2 to 8	5 to 20 (5 to 15) ^b	5 to 15	5 to 20 (8 to 15) ^b	6 to 20 (6 to 15) ^b	8 to 25 (8 to 15) ^b

^a AASHTO Designation M 147 [50] and ASTM Designation D 1241 (except as noted)

^b Figures in parentheses indicate percent passing No. 200 sieve according to ASTM D 1241.

Figure 11 and 12 show two gradations in the AASHTO Designation M 147 reproduced in the form of gradation bands, along with the average gradation curves for dry bottom ash and boiler slag. Comparing the average gradations of dry bottom ash and boiler slag to the AASHTO specifications, it is found that most dry bottom ashes would meet some of the gradation requirements; boiler slag, however, seems to be so uniform that it needs to be blended with other bottom ashes or fly ashes to meet the gradation requirements for base and subbase materials.

Each of the state highway departments also has standard specifications for base and subbase materials. The local experience and availability of materials are important factors in the determination of these specifications. Table 6 presents the gradation requirements specified by the Indiana Department of Transportation (INDOT) for base and subbase materials [53]. In general, the INDOT specifications are very similar to those of AASHTO M-147, except that the INDOT specifications allow fewer fines (minus No. 200 sieve) in the materials.

Chemical Properties

Chemical Composition

The composition of ash materials is controlled primarily by the source of the coal and not by the type of the furnace.

Figure 11. Gradations of dry and wet bottom ashes as compared with AASHTO M 147 Gradation D for base and subbase materials

Figure 12. Gradations of dry and wet bottom ashes as compared with AASHTO M 147 Gradation E for base and subbase materials

Table 6. Indiana grading requirements for base and subbase materials^a

Total Percent Passing Sieves Having Square Openings										
Approximate Permissible Top Size	2-1/2"	2"	1-1/2"	1"	3/4"	1/2"	No. 4	No. 8	No. 30	#200 ^b
2 inch	100	95-100	75-98	60-90	50-85	40-80	25-60	15-45	8-30	3-8
1-1/2 inch		100	95-100	75-98	60-90	45-85	25-65	15-50	8-30	3-8
1 inch			100	90-100	75-98	60-90	30-70	20-55	8-30	3-8
1/2 inch			100	---	---	90-100	50-80	30-70	10-40	3-8
No. 4						100	95-100	80-95	20-55	3-8
No. 30						100	---	---	85-100	0-7

^a Source: Indiana Department of Highways [53]^b In addition to other requirements, the amount passing the No. 200 sieve shall not exceed 2/3 the amount passing the No. 30 sieve.

The Bureau of Mines has investigated the occurrence of mineral matter in coal which forms the common constituents of coal ash [54,55]. Ten major constituents were determined from more than 600 ash samples from commercial coals which are representative of coal produced throughout the United States. The main constituents are silica (SiO_2), ferric oxide (Fe_2O_3), and alumina (Al_2O_3). Smaller quantities of calcium oxide (CaO), potassium oxide (K_2O), sodium oxide (Na_2O), magnesium oxide (MgO), titanium oxide (TiO_2), phosphorous pentoxide (P_2O_5), and sulfur trioxide (SO_3) are also present in coal ash. Although these constituents are reported as oxides, they occur in ash as a mixture of silicate, oxides, and sulfates with small quantities of phosphates and other compounds [55].

The chemical composition of over 600 coal ashes is compiled in Table 7 along with results obtained from West Virginia and Kentucky bottom ashes. The average analysis of coal ash for the three main constituents SiO_2 , Al_2O_3 , and Fe_2O_3 is 45.7, 26.0, and 18.1 percent, respectively. In other words, these three constituents make up almost 90 percent of the ash from bituminous coals. Lignite and some subbituminous coal ashes have relatively high percentages of CaO and MgO and, correspondingly, have larger amounts of sulfur in the ash as SO_3 [55].

The loss on ignition serves as an indication of the unburned carbon content in the ash. This is dependent upon the efficiency of the particular boiler unit and the fineness

to which the coal is pulverized. Old boilers, stokers, etc., tend to produce higher carbon ash than the new, more efficient units [56]. From an engineering point of view, unburned carbon is considered a contaminant in the ash.

Trace Elements

Almost any trace element which is present in the earth's crust may be present in coal. Therefore, a large number of trace elements can be present in coal ash depending on the source of the coal. The trace elements commonly found in coal

Table 7. Chemical analysis of ash

Constituents	Percent by weight		
	686 coal ashes ^a	W. Virginia bottom ash ^b	Kentucky bottom ash ^c
SiO ₂	20-60	45-54	34-54
Al ₂ O ₃	10-35	21-28	15-28
Fe ₂ O ₃	5-35	6-15	14-45
CaO	1-20	1-2	1-13
MgO	0.3-4	4-5	0.6-1.3
Na ₂ O	0-2	0.7-1.2	0.2-0.5
K ₂ O	0.1-3	0.1-0.4	1.3-2.7
TiO ₂	0.5-2	...	0.7-1.3
P ₂ O ₅	0.5-3	...	...
SO ₃	0.1-12	...	...

^a From Selvig and Gibson [54] and Abernethy, et al. [55]

^b From Seals, et al. [3]

^c From Rose, et al. [44]

ash are: antimony, arsenic, barium, beryllium, boron, cadmium, cesium, cobalt, chromium, copper, fluorine, germanium, lead, magnesium, manganese, mercury, molybdenum, nickel, selenium, sodium, tin, titanium, vanadium, and zinc. Table 8 presents data on the average trace element contents of ash from U.S. coals of various ranks [57].

Mineralogy

The mineralogy of a coal ash is important to its utilization or disposal. Ash reactivity during utilization results in interaction between the crystalline and glassy phases that make up the ash and the matrix into which it is placed. The crystalline and glassy phases and their behavior must be known in order to go beyond simple empirical testing as the basis of product design. For disposal, it is the mineralogy of the ash, and its water-reacted products, that controls the release rate of the potentially harmful trace elements [58,59].

The mineralogical analysis of coal ash reveals that the major chemical constituents are present in either a crystalline form or as a glass. Mineralogical examination shows that the silica is present partly in the crystalline forms of quartz (SiO_2) and in association with the alumina as mullite ($2\text{SiO}_2 \cdot 3\text{Al}_2\text{O}_3$), the rest being present mostly in the glassy phase. The iron appears partly as the oxides magnetite (Fe_2O_3) and hematite (Fe_3O_4); the remainder is in the glassy

Table 8. Average trace-element contents of the ash from U.S. coals of various rank^a (ppm)

Element	Anthracite	Low Volatile Bituminous	Medium Volatile Bituminous	High Volatile Bituminous	Lignite and Sub-bituminous
Silver	<1	<1	<1	<1	<1
Boron	90	123	218	770	1,010
Barium	866	740	896	1,253	5,027
Beryllium	9	16	13	17	6
Cobalt	81	172	105	64	45
Chromium	304	221	169	193	54
Copper	405	379	313	293	655
Gallium	42	41	--	40	23
Germanium	<20	<20	--	--	--
Lanthanum	142	110	83	111	62
Manganese	270	280	1,432	120	688
Nickel	220	141	263	154	129
Lead	81	89	96	183	60
Scandium	61	50	56	32	18
Tin	962	92	75	171	156
Strontium	177	818	668	1,987	4,660
Vanadium	248	278	390	249	125
Yttrium	106	152	151	102	51
Ytterbium	8	10	9	10	4
Zinc	--	231	195	310	--
Zirconium	688	458	326	411	245

^a Source: Los Alamos Scientific Laboratory [57]

phase. Actually, the greater proportion of coal ash is glass. Typical glass contents of fly ash range from 66 to 83 percent [60,61].

Engineering Characteristics of Bottom Ash

Soundness

The soundness of aggregates is considered a measure of the material's resistance to disintegration caused by weathering actions such as alternate freezing and thawing, wetting and drying, heating and cooling, and action of aggressive waters [62]. Most specifications for materials include a provision for soundness which is designed to ensure the selection of material that is durable in freezing and thawing.

The most widely used method for determining the soundness of materials is the sodium or magnesium sulfate soundness test, which is described in ASTM Designation C 88 [11]. Unfortunately, the test method often appears to be unreliable for distinguishing sound aggregate from that which is unsound [41]. It has been suggested that the sulfate test may be used for acceptance of material but that rejection should be based on other determinations such as freezing and thawing tests [64]. A low loss in sulfate soundness test is usually, but not always, evidence of good durability, while a high loss

places the material in a questionable category until performance data become available [62].

Sulfate soundness data on wet bottom ash may vary between 0.5 and 20 percent, typical values are less than 6 percent [3,4,37]. A significant difference between the sulfate soundness losses of the coarse (plus No. 4 sieve) and fine (minus No. 4 sieve) fractions of wet bottom boiler slag was observed by Usmen et. al. [65] and Majidzadeh et. al [4]. An explanation of this phenomenon is the build-up of high thermal stresses in wet bottom ashes during the quenching and solidification processes which may result in the formation of internal fracture planes [4,33]. This may yield, in turn, an anomalously high soundness loss due to the effects of thermal cycling and energy release, rather than to the expansive forces of the sodium or magnesium sulfate [33]. On the other hand, the finer fraction of boiler slag, having been fractured to smaller sizes, shows lower soundness loss because of the relief of the residual stresses.

The soundness loss for dry bottom ash, ranging from 2 to 30 percent, tends to be higher than for wet bottom ash. It was reported that many of the pores in dry bottom ash are so large that the sulfate solution readily drains from the ash particles before it can crystalize to form expansive forces during drying [33,38]. Consequently, the test does not discriminate for bottom ash quality. Therefore, the sulfate

soundness test, while often criticized, is especially criticized for its applicability to dry bottom ash.

In spite of the continuing belief that the sodium or magnesium sulfate soundness test is not precise, the test is generally required to evaluate conventional aggregates. Table 9 summarizes typical specification limits of percent sulfate soundness loss after 5 cycles. On the basis of these limits, most bottom ashes (dry and wet) would meet the specifications for all types of uses.

Los Angeles Abrasion

The qualities of a material known as hardness and toughness have been regarded as two desirable properties of aggregate. According to Shelburn [66], hardness is made up by abrasion resistance, and toughness is the ability of a material to resist fracture under impact. Unfortunately, there is no truly satisfactory test for measuring the hardness and toughness of a material. The Los Angeles abrasion test is by far the most commonly used test that is related to the hardness and toughness of aggregates.

The percentage of "wear" obtained from the Los Angeles abrasion test is considered as an indicator of the resistance of a material to breakdown under processing and handling, construction rolling, and service traffic [47]. Aggregate breakdown may take place from concentrated loads at points of contact between aggregate particles and by abrasive action

Table 9. Typical specifications for sodium sulfate soundness test

Source of Specification	Use of Material	Maximum loss (%)
ASTM C 33	concrete aggregates	10 (15)
ASTM D 1073 AASHTO M 29	fine aggregates for bituminous paving mixture	15 (20)
ASTM D 692 AASHTO M 283	coarse aggregates for bituminous paving mixture	12 (18)
ASTM D 693	crushed stone, crushed slag, and crushed gravel for pavements	20
AASHTO M 6	fine aggregates for portland cement concrete	10
AASHTO M 80	coarse aggregates for portland cement concrete	12 (18)
AASHTO M 45	fine aggregate for masonry mortar	10 (15)
Indiana DOT	aggregate for all variety of uses	12-20

^a Numbers in parenthesis represent maximum losses by use of magnesium sulfate

between the individual pieces moving with respect to one another [64].

Wear or loss in the Los Angeles abrasion test is the result of impact and surface abrasion in the drum. Impact is likely to cause more loss, especially during the early stage of the test where essentially no fines have been produced to cushion the impact forces. To some extent, harder minerals tend to fracture more than softer minerals because soft minerals are better in absorbing the impact forces. On the other hand, softer minerals are expected to be more susceptible to the wearing of the particle surfaces. In this case, the result of the degradation action in the drum will be more of a powdery dust rather than the larger angular pieces resulting from the fracturing of hard particles [65].

Values for percentage of wear by Los Angeles abrasion test for dry bottom ash varies from 27 to 53 percent. Exceptional values as high as 78 percent were obtained from bottom ash containing degradable popcorn type particles [4,67]. Los Angeles abrasion data for wet bottom ash range from 24 to 47 percent, which are comparable to those of dry bottom ash.

Visual inspection of the fines produced by the Los Angeles abrasion test from bottom ash (dry and wet) reveals that the fines are intermediate in size and appear as small broken pieces of the larger particles, with sharp edges and porous surfaces [65]. This suggests that the mechanism of

degradation for bottom ash is primarily a fracturing process rather than the surface wearing of the particles.

The applicability of the Los Angeles abrasion test to bottom ash has also been questioned on the grounds that the test is performed only on the coarse fraction of the ash material, which is not representative of the total sample [4,65]. As mentioned earlier, the coarse and fine fractions of bottom ash have different degrees of vesicularity, and the degree of vesicularity has an important bearing on the toughness of the material. Generally, the coarser fraction of bottom ash is more porous than the finer fraction, and subsequently has a higher abrasion potential in the Los Angeles test. Therefore, results obtained from abrasion on coarse aggregate only may not be representative of the abrasion potential of the total sample.

It should also be noted that the Los Angeles abrasion test was designed for four gradation limits, on the assumption that the gradation of the material being tested would fall within these limits. With materials like many bottom ashes, having predominantly fines (minus No. 8 sieve), only a small amount of the sample may fall within the gradation limit and be used for the test. Since different ashes have different gradations, the percentages of samples tested by the method varies from one ash to another, making the comparison of test results very difficult [4].

Table 10 shows a collection of specification limits on Los Angeles abrasion test. Generally, the percent wear values for dry bottom ash and boiler slag would seem to satisfy most specifications. However, in some cases, bottom ash would be considered close to the border-line between an acceptable and unacceptable material for surface courses and bituminous paving mixtures.

Deleterious Materials

It is generally recognized that the presence of certain substances in aggregates is undesirable, and these substances are considered deleterious. Most of the literature dealing with deleterious materials has focused the effects of deleterious particles on the durability of portland cement concrete. Very little discussion on deleterious materials appears in the literature with regard to aggregates used in subbases and bases.

A wide variety of materials may be regarded as deleterious depending on the use of aggregate. In dealing with aggregates for bases and subbases, deleterious materials can be classified in four groups according to their composition or physical properties.

1. Material finer than 75- μm sieve are determined by the wash test described in ASTM C 117 [68] or AASHTO T 11 [69]. Excessive fines in an aggregate increase the mixing water requirement of portland cement concrete and subsequently

Table 10. Typical specifications for Los Angeles abrasion test

Source of Specification	Use of Material	Max. Wear (%)
ASTM D 1241	soil-aggregate subbase, base, and surface course	50
ASTM C 33	concrete aggregates	50
ASTM D 692 AASHTO M 283	coarse aggregates for bituminous paving mixture	surface:40 base:50
ASTM D 693	crushed stone, crushed slag, & crushed gravel for pavements	surface:40 base:50
AASHTO M 80	coarse aggregates for portland cement concrete	50
AASHTO M 147	aggregate base and subbase	50
Indiana DOT ^a	aggregate for all variety of uses	40-50

^a 1988 Specification [53]

result in low strength of the hardened concrete [70]. The material finer than the No. 200 sieve is especially important in evaluating base course aggregates for the determination of potential susceptibility to frost action [71].

2. **Clay lumps** are lumps of clay and silt in the aggregate which remain cohesive during processing. These lumps survive the processing of a concrete mix but may breakdown from freezing and thawing [71]. Base course aggregates containing clay lumps which degrade during handling and construction may increase the amount of deleterious plastic fines in the aggregate.

3. **Friable particles** are characterized by a poor bond between the grains, hence they break down easily into many smaller pieces. Large quantities of friable particles in the aggregate cause a reduction in concrete strength, and small quantities downgrade the abrasion resistance of concrete significantly [41]. Friable particles in base course aggregates are subjected to degradation under construction and traffic.

4. **Lightweight particles** are highly porous particles which float on a liquid with a high density, typically 2.0. These particles are considered unsound and lacking frost resistance because they are easily saturated with water [41].

Published data on the deleterious materials in bottom ash are relatively limited. Usmen [38] investigated the deleterious materials in two dry bottom ashes and one boiler

slag and found that dry bottom ash and boiler slag have high percentages of lightweight particles but are free of clay lumps. The amount of friable particles in bottom ash varies.

An examination of the lightweight particles floated on the heavy liquid reveals that the majority of the lightweight bottom ash particles are highly vesicular [38]. Vesicularity of the particles is judged to be the major factor affecting the lightweight particle content of bottom ash. On the other hand, the amount of popcornlike particles, i.e. poorly agglomerated particles, present in the ash materials determines the percentage of friable particles.

Current specifications for deleterious materials cover a wide variety of deleterious substances and the requirements vary depending on the use of aggregate. For example, ASTM Designation D 692 [72], the Standard Specification for Concrete Aggregates, include rigid quantitative requirements on various deleterious materials. But in the specification for base and subbase materials, no quantitative restrictions on deleterious materials are stipulated. Actually, the deleterious materials are covered in the general requirements section with a qualitative statement which reads "... shall consist of hard, durable particles ..., materials that break when alternately frozen and thawed or wetted and dried shall not be used". This recognizes that small amounts of deleterious materials are not as harmful to bases and subbases as they are to portland cement concrete.

Angle of Shearing Resistance

The strength parameter of granular soil is the angle of internal friction or, preferably, angle of shearing resistance. It has an important bearing on analyzing the stability of slopes and embankments; it significantly influences the bearing capacity of a foundation; and governs the lateral pressure a backfill exerts against a retaining structure. The angle of shearing resistance also affects the magnitude of the earth load on underground structures such as culverts and sewers. Besides, it indirectly affects other characteristics of a material, such as modulus of subgrade reaction [71].

The grain strength of a cohesionless soil is usually sufficient that the grains themselves do not fail until extremely high stresses are reached. Therefore, failure of such a soil requires that the grains slide over one another. In this case, the angle of shearing resistance is analogous to the angle of sliding friction between two sliding blocks. However, in addition to the mineral-to-mineral frictional resistance, the interlocking of the soil grains contributes significantly to the shear resistance of cohesionless soils [73].

In general, the factors that influence the angle of shearing resistance of a soil are numerous and can be divided into two groups. The first group includes those factors that affect the angle of shearing resistance of a given soil.

These are: void ratio or relative density of the soil, the confining stress, the type of test used in the determination of the angle, criterion for failure, and the rate of load application. The second group consists of those factors that cause the angle of shearing resistance to differ from sand to sand. These are: grain size distribution, and the size, shape, and surface texture of the particles making up the soil. Among all of these factors, void ratio is perhaps the most important single parameter that affects the angle of shearing resistance.

A greater angle of shearing resistance can be obtained in well-graded materials than in uniformly graded materials because higher density can be achieved in the well-graded material. Angular particles can be fitted together in a very dense condition which results in a high degree of interlocking, whereas rounded or spherical particles cannot be so fitted. Particle size affects the shearing resistance by influencing the amount of shearing displacement required to overcome interlocking and to bring the grains to a free-sliding position [74]. For a coarse material, the amount of movement required for this purpose is, of course, greater than that for a finer material.

Table 11 gives typical values of the angle of shearing resistance for granular soils [75]. As discussed above, the angle of shearing resistance increases with relative density or degree of compaction, angularity of grains, and grain size.

Table 11. Approximate values of ϕ for granular soils as affected by state of compaction, size, gradation, and angularity of grains^a

Size of grains	Values of ϕ , deg		
	State of compaction	Rounded grains, uniform gradation	Angular grains, well graded
Medium sand	Very loose	28-30	32-34
	Moderately dense	32-34	36-40
	Very dense	35-38	44-46
Sand and gravel			
65% G-35% S	Loose	-----	39
65% G-35% S	Moderately dense	37	41
80% G-20% S	Dense	-----	45
80% G-20% S	Loose	34	
Blasted rock fragments			
			40-55

^a From Leonards [75]

Also, the angle of shearing resistance is larger for well-graded than for uniformly graded granular soils.

Data appearing in the literature on the angle of shearing resistance for bottom ash were measured by means of the direct shear test [3,4]. Friction angles obtained from dry bottom ashes in loose conditions vary from 32 to 44 degrees. Data reported on boiler slag ranges from 37 to 46 degrees, which are slightly higher than those for dry bottom ash. Comparing these values with those derived from natural granular materials, it is found that bottom ashes have friction angles that are comparable to well-graded angular sands, and are higher than Ottawa sand and other similar uniform, rounded sands.

Permeability

Permeability of soils is dependent upon the nature of the pore system, including number, size, continuity, and tortuosity, within the soil. Since it is very difficult to measure the pore system, a common practice is to relate permeability of granular soils to particle size, gradation, and relative density. In the drainage design for highway embankments, bases, and subbases, permeability is of considerable importance.

The coefficient of permeability for soils ranges from 1×10^{-9} cm/sec to 1×10^2 cm/sec. There is no other engineering property of construction materials that has so wide a range.

Because of such large variation, the numerical value of permeability for a soil is considered only as an order of magnitude. Table 12 lists the coefficient of permeability for various types of soils [74]. Table 13 gives a classification of soil on the basis of permeability, as suggested by Terzaghi and Peck [76].

Logic and experimental data suggest that the finer particles in a soil have the most influence on permeability. Hazen [77] established an empirical equation correlating the coefficient of permeability to the effective grain size, D_{10} . This correlation assumes that there is a consistent relationship between D_{10} and the pore size of clean granular materials. For clean sands (less than 5 percent passing the No. 200 sieve) with D_{10} size between 0.1 and 3.0 mm, the coefficient of permeability k is

$$k = C D_{10}^2$$

where the units of k are in cm/sec, and D_{10} in mm. The constant C ranges from 0.4 to 1.2 with an average of 1.0.

Relatively limited data are available on the coefficient of permeability of dry bottom ash and boiler slag. Seals et. al. [3] measured the coefficients of permeability for six bottom ashes and found them to vary from 5.0×10^{-3} cm/sec to 9.4×10^{-2} cm/sec, which falls in a medium permeability range. These values are also comparable to the corresponding values for sand. The values of Hazen's C for bottom ashes vary from

Table 12. Typical values of permeability coefficients^a

	Particle size range, (mm)		"Effective" size		Coefficient of permeability, k
	D _{max}	D _{min}	D ₁₀ (in.)	D ₁₀ (mm)	
Clean, fine to coarse GRAVEL	80	10	1/2	--	10
Fine, uniform GRAVEL	8	1.5	1/8	--	5
Very coarse, clean, uniform SAND	3	0.8	1/16	--	3
Uniform, coarse SAND	2	0.5	---	0.6	0.4
Uniform, medium SAND	0.5	0.25	---	0.3	0.1
Clean, well-graded SAND & GRAVEL	10	0.05	---	0.1	0.01
Uniform, fine SAND	0.25	0.05	---	0.06	40 x 10 ⁻⁴
Well-graded, silty SAND & GRAVEL	5	0.01	---	0.02	4 x 10 ⁻⁴
Silty SAND	2	0.005	---	0.01	10 ⁻⁴
Uniform SILT	0.05	0.005	---	0.006	0.5 x 10 ⁻⁴
Sandy CLAY	1.0	0.001	---	0.002	0.05 x 10 ⁻⁴
Silty CLAY	0.05	0.001	---	0.0015	0.01 x 10 ⁻⁴
CLAY (30 to 50% clay sizes)	0.05	0.0005	---	0.0008	0.001 x 10 ⁻⁴
Colloidal CLAY (~2μm ≥ 50%)	0.01	10A	---	40A	10 ⁻⁹

^a From Hough [74]

Table 13. Classification of soils according to their coefficient of permeability^a

Degree of Permeability	Value of k (cm/sec)
High	Over 10^{-1}
Medium	10^{-1} to 10^{-3}
Low	10^{-3} to 10^{-5}
Very low	10^{-5} to 10^{-7}
Practically impermeable	less than 10^{-7}

^a From Terzaghi and Peck [76]

0.1 to 2.8 with an average of 1.2. Considering the wide range of k , the Hazen's formula is valuable in estimating the k value for bottom ashes, at least within an order of magnitude. When testing is not practicable, the Hazen's formula can be used for bottom ash to obtain an approximate coefficient of permeability.

Compaction Characteristics

Compaction is the densification of soil and soil-aggregate mixture by the application of mechanical energy. The objective of the compaction is twofold: to provide a stable material and to provide a material whose properties are predictable, at least within limits [47]. Investigation and experience have shown that physical properties of a soil mass are greatly affected by increases in unit weight or degree of density brought about by compaction. There are several advantages which occur through compaction: a) soil strength

increases and slope stability can be improved, b) detrimental settlements can be reduced, c) bearing capacity of structural fills or pavement subgrades can be improved, and d) undesirable volume changes may be controlled [78].

The purpose of the compaction differs in different structures. Thus the density requirements necessary to satisfy the needs for the conditions involved may be different. Table 14 lists the purpose of compaction in different highway components [79]. It is important to identify the purpose of compaction in the structure so that the compaction specifications can be properly prescribed.

Table 14. Purpose of compaction in different highway components^a

Highway component	Purpose of compaction
Embankments	to prevent detrimental settlement to aid improving stable slopes
Subgrade materials	to provide bearing capacity to control volume change to provide uniformity
Bases and subbases	to provide uniform high bearing capacity

^a From Highway Research Board [79]

There are a number of factors which influence the density obtained by compaction. Those of primary importance are: a) the moisture content of the soil, b) the characteristics of the soil, and c) the type and level of the compactive effort. Other factors influencing density, but to a lesser extent, are: a) the temperature of the soil and b) the amount of manipulation given the soil during the compaction process [79].

The compaction characteristics of soils are commonly discussed in terms of their moisture-density relations. If a soil is compacted with a given type and amount of compactive effort at various moisture contents, a moisture-density curve such as the one in Figure 13 is obtained. Such a curve clearly indicates that the density obtainable for a given soil and compactive effort is dependent on the moisture content at time of compaction. As the water content increases from a low level, soil particles develop larger and larger water films around them, which tend to lubricate the particles and allow them to slide, one particle against another, to produce a denser packing [47,78]. However, a point is eventually reached such that increases in water content result in decreases in density. At this point, water starts to displace soil particles and the density decreases. Thus, the curve develops a more or less well-defined peak which indicates the optimum moisture content at which a maximum dry density may be obtained for each type of soil and compactive effort.

Figure 13. Typical moisture-density curve.
(After Krebs and Walker [47])

If a second set of soil samples is compacted by a different effort at various moisture contents, a similar moisture-density curve will be produced but with a different optimum moisture and maximum density. For any particular type of soil, the greater the effort, the higher the maximum density and the lower the optimum moisture content. Thus it is obvious that both maximum density and optimum moisture content must be related to compactive effort.

The compaction behavior described as above is typical of cohesive soils for both field and laboratory compaction. The curves will vary somewhat in the shapes and positions on the density versus water content plot, but the response will be similar to that shown in Figure 13. However, cohesionless soils do not respond to variation in water content and compactive effort in the manner characteristic of cohesive soils.

Because cohesionless soils are relatively pervious even when compacted, they are not affected significantly by their water content during the compaction process. Figure 14 shows the typical moisture-density curve for cohesionless soils [80]. For a given compactive effort on cohesionless soils, the dry density obtained is high when the soil is dry and high when the soil is saturated, with somewhat lower densities occurring when the soil has intermediate amounts of water. This phenomenon is known as bulking [73,80,81]. Under these circumstances, water acts like an antilubricant. At low water

Figure 14. Typical moisture-density curve for cohesionless soils. (After Foster [80])

content some menisci begin to form in the partially saturated soil. These menisci formed by capillary stresses cause an apparent cohesion between particles [82], thus increasing the shear strength which, in turn, resists rearrangement of the sand grains. Upon the addition of more water, the negative pore water pressure and the antilubrication effect come in balance. At water content larger than those at which significant negative pore water pressure exists, the water produces a lubrication effect on the soil particles and causes an increase in density. The limit of lubrication of the particles is reached when the voids become filled with water [83,84].

The influence of compactive effort on the moisture-density relation is much less for cohesionless soils than for cohesive soils. For example, according to data reported by Highway Research Board [79], an increase in compactive effort from standard Proctor effort (ASTM D 698) to modified Proctor effort (ASTM D 1557) results in an increase in maximum density of 12 pcf for clay and 2 pcf for sand. The corresponding decreases in optimum moisture content are 6 percent and 1 percent for clay and sand, respectively.

Some materials have been observed to exhibit irregularly shaped moisture-density compaction curves. Johnson and Sallberg [85] indicated that relatively free draining materials may show no consistent relationship between moisture content and dry density or may show an increase in dry density

with increase in moisture content to a saturated condition during compaction. Spenser et. al. [86] reported that very irregular moisture-density curves were found in performing the standard compaction test for open-graded or predominantly one-sized materials. The materials either exhibited no distinct optimum at any water content or yielded the highest dry density at the maximum moisture content used. Lee and Suedkamp [84] confirmed the existence of irregularly shaped compaction curves by testing 35 soil samples, and established four types of compaction curves. In addition to the typical single-peak compaction curve, their results indicated a $1\frac{1}{2}$ -peak curve, a double-peak curve, and a curve with no distinct optimum water content or an oddly shaped curve. It was also found that soils with a liquid limit greater than 70 or less than 30 produced irregularly shaped compaction curves.

Available data on the compaction characteristics of dry bottom ash and boiler slag obtained from different investigators show wide variations in both the optimum moisture content and maximum density. Seals et. al. [3] and Usmen [38] presented data obtained from West Virginia bottom ashes. The standard Proctor maximum densities for dry bottom ash varied between 74 and 117 pcf; the optimum moisture content ranged from 12 to 34 percent. For boiler slags, the maximum densities were between 91 and 102 pcf, and the optimum moisture contents varied from 14 to 22 percent. Data reported by Majidzadeh et. al. [4] indicated that the optimum moisture

contents for dry bottom ash range from 13 to 18 percent and those for boiler slag vary between 6 and 8 percent, which are considerably lower than those reported by Seals et. al.

Because of the complex pore structure of particles, bottom ash may produce irregularly shaped compaction curves [87]. Usmen [38] suggested a "pore saturation point" to explain the erratic moisture-density relation observed on a very vesicular bottom ash in the lower moisture content range. Majidzadeh et. al. [4] reported that the "optimum" moisture content of each ash actually occurred within a zone rather than exhibiting a clear optimum value.

Compressibility

The compressibility of a fill or embankment determines the magnitude of the vertical deformation at the surface of the fill or embankment. Consider the case where granular materials are one-dimensionally compressed; an example would be the deformation caused by a fill covering a very large area. Because of the high permeability of granular materials, the deformations take place in a very short time. Practically, the compression of sands and gravels occurs during construction and most of the settlements have taken place by the time the structure is completed. However, it should be noted that, for structures that are sensitive to rapid settlements, small total settlements can be detrimental if they occurs rapidly [78].

The deformation of granular soils is caused by two mechanism: distortion and crushing of individual particles, and relative motion between particles as the result of sliding or rolling [73]. Sliding between particles occurs at all stress levels. Crushing and fracturing of particles begins in a minor way at very small stresses, but becomes evident when some critical stress is reached [88]. This critical stress is dependent upon the particle size, the angularity of particles, the strength of the individual particles, and the gradation.

Previously published work on sand compression have been reported by Roberts and DeSouza [88], Schultze and Moussa [89], Hendron [90], and Lee and Farhoomand [91]. The results of each of these investigations are qualitatively the same. In general, a uniformly graded soil compressed more than a well-graded soil; and an angular sand is more compressible than a rounded sand. Roberts and DeSouza [88] observed that, at moderately low pressures, angular sands crushed and compressed more than rounded sands; but at very high pressures the compression behavior of angular and rounded soil is very similar. Lee and Farhoomand [91] tested different granular soils and found that coarse soils compressed more and showed more particle crushing than fine soils.

Seals et. al. [3] performed one-dimensional compression tests on West Virginia bottom ashes. It was found that, at low stress levels, the compressibility of bottom ash is

comparable to natural granular soils placed at the same relative density.

Stabilization

Soil stabilization, in a broad sense, is the alteration of any property of a soil to improve its engineering performance. Engineering properties such as strength, compressibility, permeability, volume change characteristics, frost susceptibility, and durability may be improved by many stabilization techniques, including mechanical, chemical, electrical, or thermal treatments. In this section, only mechanical and chemical stabilization will be discussed.

Mechanical Stabilization

Mechanical stabilization is the improvement of the soil by changing the gradation. It is usually accomplished by blending the existing soil with other suitable soil to obtain a composite material which is superior to either of its components.

A stable soil texture is considered to be made up of two components. The portion of the mixture that is coarser than some arbitrary limit, such as a No. 40 sieve or a No. 200 sieve, is usually termed aggregate. Its principal functions are to provide internal friction and incompressibility. The best aggregates are those which are composed of hard, angular,

durable particles. The gradation of the aggregate is important because well-graded materials can be more readily compacted than poorly graded mixtures and generally have greater stability after compaction [92]. The finer portion of the mixture, often referred to as "binder", contributes cohesion and imperviousness. Ideally, the binder soil should have sufficient plasticity to develop high cohesion but not so much that it tends to cause excessive volume change with change in moisture constant [92,93].

The relative amounts of aggregate and binder determine the physical properties of the compacted stabilized soil. When small amounts of binder soil are added to an aggregate, the strength is increased due to the increase in density. The density is increased because the binder fills the voids between aggregate particles. However, with excessive amount of binder, the strength of the soil-aggregate mixture can be markedly reduced [94]. In order to produce acceptable stabilized mixtures with adequate strength and incompressibility, the choice of a proper proportion of the aggregate to binder is considered to be essential [92,93,95]. Based on test results on the internal friction and cohesion of a series of soil-aggregate mixes, Miller and Sowers [96] showed the grain structure for different amounts of aggregate and binder, as in Figure 15.

An aggregate that contains little or no fines is illustrated in Figure 15a. It has high internal friction and

a. Compacted aggregate alone with grain to grain contact.

b. Aggregate with small amount of binder. Binder highly compacted between contact points of aggregate, and loose in voids.

c. Aggregate with sufficient binder to fill voids loosely.

d. Aggregate floating in a matrix of well-compacted binder.

Loose binder

Well-compacted binder

Highly compacted binder

Figure 15. Grain structure of soil-aggregate mixtures.
(From Miller and Sowers [96])

is relatively incompressible because the loads are carried by grain-to-grain contact of bulky particles. Having no fines present, it is quite permeable and non-frost susceptible. However, this material is unstable and difficult to compact, unless it is in a confined condition [47,48].

Figure 15b shows the grain structure of a mixture with small amount of fines. Some of the binder is highly compacted between the contact points of the aggregate but some of the aggregates still make direct contact and the grain-to-grain friction persists. Part of the voids are loosely filled with binder while the remainder of the voids are still open. In the meantime, the cohesion of the mixture begins to increase.

Figure 15c illustrates an aggregate with sufficient binder to fill voids loosely. There is highly compacted binder between the contact points of the aggregate and partially compacted binder filling the voids. The optimum amount is reached when the compacted binder fills the voids without destroying all the grain-to-grain contact of bulky particles. The result is an increase in cohesion, a slight decrease in the angle of internal friction, slightly greater compressibility, and lower permeability [93,96].

In Figure 15d the aggregate particles are surrounded by compacted binder and the grain-to-grain contact is virtually nonexistent; that is, the aggregate floats in the binder. In this case, the strength of the mixture drops to that of the

binder alone [96]. In addition, the stability of this type of mixture is greatly affected by adverse water conditions [48].

It is apparent that the stability of a soil-aggregate mixture is dependent on the size distribution of the particles. Theoretically, for maximum stability, a soil-aggregate mixture should have sufficient fines to just fill the voids among aggregate particles, with the entire gradation curve representing a very dense mixture resembling that of the Fuller's maximum density curve [97]. Data published on the strength characteristics of soil-aggregate mixtures showed that the optimum fines (finer than the No. 200 sieve) content ranged from 7 to 22 percent depending on the character of the aggregate [94,96,98]. Important factors affecting the optimum fines content include the gradation of aggregate, particle shape, and size of the largest aggregate pieces.

In a study by Yoder and Woods [94,99], various amounts of binder soil were added to several granular materials to determine the maximum compaction density and California bearing ratio (CBR). It was found that both density and CBR increased as the size of aggregate increased, but optimum soil content decreased. It was also indicated that maximum CBR resulted when the quantity of soil was about 0 to 3 percent less than that the optimum required for maximum density. Yoder and Witczak [48] later pointed out that the use of a criterion of density as a measure of stability could be misleading if the gradation is not known. Mixtures on the

"rich" side of optimum soil content have considerably less strength than those on the "lean" side of optimum soil content. This is due to the fact that in rich mixes the stability is provided primarily by the cohesive binder while in lean mixtures it largely depends on grain-to-grain contact of aggregate particles.

The working principles employed in mechanical stabilization with reference to the gradation of the particles and the cohesive properties of the binder soil are empirical. Although a wide variation of gradations may be successfully used for highway bases and subbases depending on the prevailing conditions, knowledge on the subject has not progressed to the point where a soil-aggregate mixture can be designed on a rational basis. AASHTO Designation M 147 and ASTM Designation D 1241, as reproduced in Table 5, cover the gradation requirements for soil-aggregate mixtures for use in subbase, base, and surface courses. However, it was pointed out by Miller and Sowers [96] that the gradation specifications could result in both a very strong mixture and a weak one. It appears that total reliance upon these rigid specifications in all instances may not always be satisfactory. Local practice and experience with the material and experimental tests provide the best guide for proper proportion of soil-aggregate mixtures [100,101].

Since bottom ash and fly ash are both by-products from coal-burning power plants, it is logical to use fly ash as the

binder for mechanical stabilization of bottom ash. Often, bottom ash is more finely graded than the coarse aggregate generally specified for use in most soil-aggregate compositions. As a result, a greater percentage of fines (finer than No. 200 sieve) are needed to achieve the maximum density. As previously discussed, optimum fines content for conventional aggregates can normally be expected to range from 7 to 22 percent by weight of dry mix. In bottom ash-fly ash mixes, optimum fines content could range from 25 to 40 percent [21,36].

There have not been many applications of mechanically stabilized bottom ash in highway bases and subbases. These uses have been on private or municipal types of construction projects [3,21,36].

In the construction of West Virginia Route 2 base course, bottom ash from the American Electric Power Company's Mitchell plant was blended with blast furnace slag in order to satisfy the gradation requirements of the West Virginia Department of Highways for class 1 crushed-aggregate base course [36]. Percentages of slag varying from 15 to 40 percent by weight were used to construct the base course.

Also in West Virginia, several proportions of bottom ash-fly ash mixtures were used as base course for the reconstruction of the access roads to the Fort Martin Station of Allegheny Power System [36]. Finally, a 60-40 bottom ash-fly ash combination was proved to be satisfactory for the

construction. Field densities ranged from 96 to 106 percent of standard Proctor maximum density were achieved at wet-of-optimum moisture conditions. It should be pointed out that the percentage of fly ash (fines) used in this project would not satisfy those specified for base course materials. Thus, considering the unique engineering properties of bottom ash, strict adherence to standard specifications may not be reasonable in all instances.

Admixture Stabilization

Admixture stabilization is the physical mixing and blending of a stabilizing agent with a soil. A number of stabilizing agents have been used in highway engineering. As indicated by Yoder and Witczak [48], the various types of stabilizing agents can be categorized according to properties imparted to the soil. Thus, the more important of these admixtures can be classified in three categories: cementing agents, modifiers, and waterproofing agents. Selection of stabilizing agents is based on the type of soil and the intended use of stabilized soil. In general, the use of relatively large quantities of the agents is intended to produce substantial increase in strength by bonding soil particles together, whereas smaller quantities are used to modify the plasticity and water-holding capacity of the soil [38].

Portland cement has been used successfully in stabilizing all types of soils except organic materials. Bitumen is used as a waterproofing agent as well as a cementing material. Granular materials can be readily stabilized with bitumen while plastic clays are difficult to treat, and require a high level of bitumen. Lime stabilization has been principally applied to materials containing sizable quantities of plastic fines. Lime increases soil strength by pozzolanic action. It also functions as a soil modifier by reducing soil plasticity, making the soil more easily handled in the field. Fly ash (class F) is frequently added to lime stabilized soil to speed the pozzolanic action. Class C fly ash, being self-cementing, has been used in stabilizing base course aggregates as the sole stabilizing agent [102-104].

Almost any inorganic soil can be successfully stabilized with cement, although the stabilization mechanism differs somewhat for the two principal types of soil [47,101,105]. In granular materials, the cementing action produced by the hydration of Portland cement approaches that found in concrete except that the cement paste does not fill the voids between aggregates. Instead, the particles are cemented only at points of contact. In this way, the increase in strength depends on not only the amount of cement, but also the degree of compaction. In the case of fine-grained materials, the cement particles develop strong linkages upon hydration among mineral grains and soil aggregates, forming a matrix which

effectively encases the soil aggregates. The strength of the soil is thus increased because the particles are fixed in the matrix. Also, the surface chemical effects of cement reduce the plasticity and water affinity of clayey soils. As a result, the soil resists swelling and softening upon absorption of moisture. For any type of soil, the quality of the resulting cement-stabilized product is dependent to a large degree on the molding water content and the density achieved by compaction, as well as the curing conditions [101,105].

Lime stabilization is most effective when applied to clayey soils but the rate of strength gain is considerably slower than that of cement. Two types of chemical reactions occur when lime is mixed with moist soil [47,101,106]. The first is the cation exchange and flocculation which cause immediate improvement in soil plasticity, workability, uncured strength, and load-deformation properties. The second type of reaction is a slow, long-term cementation of compacted mixtures of soil and lime. The cementing action, known as pozzolanic reactions, involves interaction between the hydrated lime and the reactive aluminous and siliceous minerals in soils. Pozzolanic reactions are time and temperature dependent. They can be greatly accelerated by adding a material high in alumina and silica such as fly ash.

Soil-cement mixtures have been commonly evaluated in the laboratory by strength and durability tests for determining

minimum cement requirements. However, because of the complexity and time consuming nature of the durability tests such as freezing-and-thawing and wetting-and-drying tests, many agencies have adopted only the unconfined compression test to evaluate soil-cement mixtures. As cited by Yoder and Witczak [47], the states of Texas and California as well as the United Kingdom have based their quality criteria on unconfined compression strength. In general, the unconfined compression strength requirement will insure adequate durability of soil-cement mixtures. Only in extreme cases will it be considered necessary to perform the durability tests [48]. Table 15 shows the criteria for soil-cement as established by various agencies.

The engineering properties of cement-stabilized bottom ash are essentially the same as those of cement-stabilized conventional aggregates. Of particular concern are the strength development and durability characteristics, especially resistance to freezing and thawing.

Table 15. Strength criteria for soil cement

Agency	7-day unconfined compression strength (psi)
Texas	650
California, Class A, up to 5% cement	750
California, Class B, up to 4% cement	400
British, light traffic	250
British, heavy traffic	400

Applications of cement stabilized bottom ash have been focused on base and subbase courses. The first known large-scale application of a cement stabilized bottom ash base course in the U.S. was the 1971-72 relocation and reconstruction of West Virginia Route 2 south of Wheeling. The aggregate for this project was a blend of 46 percent by dry weight of the boiler slag from one power plant and 54 percent bottom ash from another power plant nearby. This blend was necessary in order to meet the West Virginia gradation specification for class 5 cement-treated aggregate base course. The aggregate blend was stabilized with 5 percent portland cement by weight of dry aggregate [36].

In Australia, the base and subbase courses of two trial sections were constructed using stabilized bottom ash. In these field trials, 6-in to 14-in thick layers of bottom ash were stabilized with 3 to 6 percent of lime (CaO). It was concluded that bottom ash is in its natural form a good subbase material and in its stabilized form is an excellent base course material [107].

In 1985, a highway demonstration project on the by-pass section of Georgia Route 22 near Crawfordville was completed. In this project, the base course of a 1000 ft. long test section was constructed using pond ash (fine and coarse) stabilized with 11 percent Type I portland cement. The cement content was determined based on a minimum compressive strength of 400 psi after 7 days of curing. According to Georgia

Department of Transportation, handling of the cement treated pond ash was found to be superior to typical soil-cement [108].

Environmental Aspects of Ash Utilization

Environmental Legislation

Besides evaluating the suitability of the ash material as a highway construction material, there is also considerable interest on the part of federal and state regulatory agencies on the environmental acceptability of ash utilization. In fact, the national interest in solid waste disposal was expressed by Congress in the Resource Conservation and Recovery Act (RCRA) of 1976 [109]. The two basic objectives of the RCRA are: 1) protection of public health and the environment, and 2) the conservation of valuable material and energy resources. The Act set forth cooperative efforts among federal, state, and local agencies to achieve these objectives by improving solid waste management practices. The provisions of the Act include: 1) requirements for control of the generation, transportation, treatment, storage and disposal of hazardous waste, 2) establishment of environmentally sound disposal practices for all wastes, and 3) investigation and creation of incentives for resource recovery and conservation activities.

The basic need to use recovered materials, including power plant ash, while at the same time to alleviate the problem of disposal, will continue to draw increased attention in the future. However, Subtitle C of the RCRA also requires the U. S. Environment Protection Agency (EPA) to promulgate regulations to identify hazardous wastes and to set standards for generators, transporters, and management facilities for such wastes. The RCRA definition of solid waste is quite broad, and a material is a RCRA solid waste irrespective of whether it is discarded, used, recycled, reused, reclaimed, stored or accumulated [110]. The major component in implementing Subtitle C of the Act lies in the definition of hazardous waste [109]:

Hazardous waste is a "solid waste", which because of its quantity ... or physical, chemical ... characteristics may ... pose a substantial present or potential hazard to human health or the environment when improperly ... disposed of, or otherwise managed.

Thus, by definition, "hazardous waste" is a subclass of "solid waste" causing or significantly contributing to death or illness, or posing a hazard to human health or the environment when improperly managed. In amendments made to RCRA in May of 1980, Congress specifically exempted conventional coal combustion wastes (including fly ash, bottom ash, boiler slag, and flue gas desulfurization sludge) from regulation as a hazardous waste until further studies were conducted [111]. This temporary exemption holds until the EPA

completes studies to establish actual environmental impacts of waste management of coal combustion wastes, and issues a final decision as to the hazardous or non-hazardous nature of these materials. Because of the large quantities of solid waste produced by electric utilities, a classification under the hazardous waste provisions could cost the industry billions of additional dollars [112]. It is believed that the coal combustion wastes are exempted because their regulation could cause significant increases in energy costs [112,113]. Although coal combustion wastes are presently exempted from regulation under RCRA, they may still be regulated in the future.

In the meantime, state requirements on solid waste disposal facilities have become more restrictive. The issue of protecting groundwater quality from chemical contamination caused by solid waste has been common to all state and federal regulation debates [112]. Awareness of the environmental risks has drawn increased attention to groundwater quality degradation by coal combustion wastes.

At present, power plant ash is treated differently in the various states. In some states, no special requirements are placed on the use of power plant ash as a construction material. In other states, power plant ash is considered to be a solid waste and is subject to appropriate requirements for disposal. Those disposal procedures may require a permit to build a structural fill or embankment. In other words, the

fill or embankment is treated as a disposal site, and the environmental requirements for utilization are as strict as for disposal. In general, the permit will require ground water monitoring to determine if compounds are leaching from the site [6].

Environmental Impacts of Ash Utilization

Considerable attention has been focused on the environmental acceptability of using power plant ash as construction materials, and in particular, the degree of impact these materials have on the environment when used as a construction material. Because of some similarities between structural fills and landfills, certain environmental aspects of ash disposal are also mentioned in this section.

The most immediately obvious environmental effect of the disposal or utilization of power plant ash is spreading of dust and the appearance of ash deposits as an aesthetically undesirable feature of the landscape. Because typical bottom ash has less than 10 percent fines, dust spreading is not expected to be a significant problem. Also dust can be prevented by rapid covering of exposed ash surfaces, and by appropriate handling during construction, e.g., sprinkling.

The principal environmental concern about the use of power plant ash is the possible leaching of toxic substances or other potentially harmful constituents from the ash and the possibility of ground water degradation as a result of such

leaching. Power plant ash, like the coals from which it is produced, does contain trace amounts of certain elements which, if released in sufficient concentrations, may be harmful to the environment. These contaminants are leached out by and carried along with percolating precipitation and possibly penetrating groundwater and surface water. The leachate released to the groundwater or surface water may contaminate present and future drinking water supplies.

The degree of environmental impact is determined by the amount of these elements leached from an ash deposit. Small amounts of heavy metals released to the environment may constitute a hazard both to health and environment. The high content of salts may adversely affect the quality of ground water, although it does not constitute any danger to human health. These salts are primarily calcium and sulfate. Sodium, potassium, magnesium, and chloride also contribute to high contents. The salts are easily soluble and, as a result, are leached relatively rapidly. In most cases, this means a hundred years or so [114]. Heavy metals in the ash are not as readily soluble as the salts, but are nevertheless soluble to such an extent that the content of heavy metals in the leachate is noticeably elevated. An important difference in comparison with the salts is that the elevated levels remain for a very long time, viz., several thousand years [114].

Environmental risks due to radioactivity are present only in deposits of certain peat ashes [114]. Radioactivity can be

limited by covering the ash deposit with a low radioactivity material.

In summary, the environmental effects which need to be considered in either utilization or disposal of coal combustion wastes are:

- the release of salts to groundwater and surface water
- the release of heavy metals to groundwater and surface water
- spreading of dust from the deposit or from construction
- radioactive emission from the deposit
- the aesthetical influence on the surrounding landscape.

A schematic of the possible effects of ash deposit on human health and environment is shown in Figure 16.

Waste Classification

In implementing Section 3001 of the RCRA, EPA has promulgated procedures for determining whether a waste will be classified as hazardous. A waste may be classified as hazardous in three ways: 1) it is a listed waste, 2) it is a mixture containing listed waste, or 3) it has any of four specific characteristics defined in the RCRA for hazardous wastes. An unlisted waste is classified as hazardous if it exhibits one of the four properties: 1) ignitability, 2) corrosivity, 3) reactivity, and 4) extraction procedure toxicity [115]. Since power plant ash is very inert, it is not likely that it would be ignitable or reactive. Therefore

Figure 16. The possible effects of an ash deposit on human health and environment. (Source: Lundgren and Elander [114])

only the categories of corrosivity and toxicity will be reviewed.

Characteristics of Corrosivity

According to EPA's regulations, a solid waste exhibits the characteristics of corrosivity if a representative sample of the waste has either of the following properties:

- 1) it is aqueous and has a pH less than or equal to 2 or greater than or equal to 12.5.
- 2) it is a liquid and corrodes steel (SAE 1020) at a rate greater than 6.35 mm (0.25 in.) per year at a temperature of 55°C (130°F).

Extraction Procedure Toxicity Characteristics (EPTC)

The accurate prediction of ash leachate composition (contaminants and concentrations) is not possible at present. The chemical composition of the ash is important to the leaching processes, but it forms an insufficient basis for an estimate of the leachate composition. Furthermore, leaching of waste materials will generally occur very slowly in the environment. Therefore the challenge in assessing leachability is to develop a quick and inexpensive laboratory test that can accurately predict the long term leaching behavior in the field. A number of testing protocols have been proposed and investigated. The EPA has adopted a

regulatory method known as the Extraction Procedure (EP) toxicity test. The EP toxicity test was developed to provide a method for classifying wastes as hazardous or nonhazardous under standard conditions, rather than for predicting the amount of contamination that could occur from the waste. Three major postulates of EP toxicity are chosen: 1) groundwater as the exposure pathway, 2) landfill as the particular disposal environment model, and 3) multiples of drinking water standards as thresholds indicative of unacceptable levels of contamination [116].

In the EP toxicity test, a representative sample of a solid waste is extracted with deionized water maintained at a pH of 5 using acetic acid [117]. The extract derived from the EP toxicity test is then analyzed for eight elements to determine if the waste is classified as hazardous or nonhazardous. The maximum contaminant levels specified for characterizing hazardous waste are such that they are one hundred (100) times the National Primary Drinking Water Standards [118]. The test also considers six herbicides and pesticides which are not found in coal combustion wastes. Table 16 lists the maximum acceptable extract concentrations for a nonhazardous waste, along with the Primary Drinking Water Standards.

The EP test were designed to model the performance of wastes in a co-disposal situation, wherein the waste to be tested is leached in an acidic environment similar to that

which could occur when the waste is co-disposed with municipal wastes [119,120]. In the EPA's view, such a test serves as a "worse case" scenario and reflects the maximum leaching effects which could result from the mismanagement of wastes. If this occurs in actual practice, it may lead to exposing the wastes to an acidic leach medium as the municipal waste decomposes. Because the majority of utility wastes are disposed in well engineered landfills, the electric utility industry has vigorously opposed the use of the EPA's "worse case" disposal scenario [119].

Table 16. EPA criteria pollutants - primary metals

Contaminant	Primary Drinking Water Standard ^a (mg/litre)	EP toxicity Maximum acceptable amount ^b (mg/litre)
Arsenic	0.05	< 5
Barium	1.0	<100
Cadmium	0.01	< 1
Chromium	0.05	< 5
Lead	0.05	< 5
Mercury	0.002	< 0.2
Selenium	0.01	< 1
Silver	0.05	< 5

^a EPA Interim Primary Drinking Water Standards [118]

^b Extract concentrations equal to or exceeding one or more of the levels given will classify the solid waste as hazardous from EPA [115]

Toxicity Characteristics Leaching Procedure (TCLP)

In 1984, the RCRA amendments dramatically changed the nature of hazardous waste regulation [121]. The characteristic of toxicity was expanded to include a wide range of volatile and non-volatile organic compounds. The same amendments also required the EPA to examine the deficiencies of the EPTC and develop a more accurate leaching test. The new test was first presented to the public in April 1985 [122]. Three modified versions of the test have been published by EPA since [123,124,125]. None has appeared in a final version as the replacement for the EPTC. The new test is known as the Toxicity Characteristics Leaching Procedure (TCLP). Differences between the EPTC and the TCLP can be grouped into three general classes: 1) changes in the equipment, 2) leach medium, and 3) regulated analytes. These differences are discussed in the following paragraphs.

Changes in Equipment. The TCLP includes volatile and non-volatile organic compounds as analytes in the classification of wastes, whereas the EPTC did not. Therefore the TCLP requires that all equipment be made of materials inert towards organic and inorganic analytes.

The filter in the EPTC is a 0.45 micron nitrocellulose membrane while the TCLP specifies a 0.7 micron glass fiber filter containing no binders. The TCLP also introduces the zero headspace extractor which is designed to run the leach

testing of a waste without losing the volatile components during the extraction.

Leach Medium. The TCLP requires a determination of the appropriate extraction fluid be carried out before running the TCLP. Once the extraction fluid has been selected, the extraction fluid is added to the waste at one time. Thus the constant pH monitoring of the slurry, as required by the EPTC, is not necessary.

Regulated Analytes. As previously noted, the EPTC classifies wastes based on the concentrations of eight metals and six herbicides and pesticides found in the EPTC leachate. The TCLP includes organic compounds in the classification. The list of TCLP regulated organic compounds and their current regulatory levels is given in Table 17. Note that the regulatory levels for some components are footnoted. These compounds are regulated at the lowest level of current analytical methods. The EPA intends to lower these levels still further when they believe the analytical methods are reliable. Nickel and thallium are added to the list of inorganic analytes but no regulatory level is given.

An important impact of the TCLP on the classification of coal combustion wastes is economic. It is estimated that the cost for the analysis of metals by the TCLP is approximately equal to or less than the EPTC. However, the cost for the analysis of volatile and semi-volatile organics is estimated to be three to six times the cost for metals determination

Table 17. Additional toxicity characteristic contaminants and regulatory levels^a

Contaminants	Regulatory Levels (mg/L)
Acrylonitrile	5.0
Benzene	0.07
Bis(2-chloroethyl) ether	(0.05) ^c
Carbon Disulfide	14.4
Carbon tetrachloride	0.07
Chlordane	0.03
Chlorobenzene	1.4
Chloroform	0.07
o-Cresol	10.0
m-Cresol	10.0
p-Cresol	10.0
1,2-Dichlorobenzene	4.3
,4-Dichlorobenzene	10.8
1,2-Dichloroethane	0.40
1,1-Dichloroethylene	0.1
2,4-Dinitrotoluene	(0.13) ^c
Heptachlor (and its hydroxide)	0.001
Hexachlorobenzene	0.13
Hexachlorobutadiene	0.72
Hexachloroethane	4.3
Isobutanol	36
Methylene chloride	8.6
Methyl ethyl ketone	7.2
Nickel	--- ^b
Nitrobenzene	(0.13) ^c
Pentachlorophenol	3.6
Phenol	14.4
Pyridine	5.0
1,1,1,2-Tetrachloroethane	10.0
1,1,2,2-Tetrachloroethane	1.3
Tetrachloroethylene	0.1
2,3,4,6-Tetrachlorophenol	1.5
Thallium	--- ^b
Toluene	14.4
1,1,1-Trichloroethane	30
1,1,2-Trichloroethane	1.2
Trichloroethylene	0.07
2,4,5-Trichlorophenol	5.8
2,4,6-Trichlorophenol	0.30
Vinyl Chloride	(0.05) ^c

^a From Federal Register [125]^b no value proposed^c Values in parenthesis will be lowered as analytical methods improve

[119]. Therefore, the possibility of running less expensive screening tests as permitted under section 1.2 of the TCLP [125] is being investigated by the industry.

Indiana Leaching Method

According to Indiana's regulations (Title 329 of Indiana Administration Codes, Article 2) [18], coal ash and flue gas desulfurization sludge may be disposed at a restricted waste site type I without testing. But for disposal at restricted waste site types II, III, or IV, these wastes are required to be analyzed by both the EP toxicity test and the Indiana leaching method test. The Indiana leaching method test is conducted as specified for EP toxicity testing, except with no addition of acetic acid. The contaminants and corresponding concentrations for each restricted waste site type are tabulated in Table 18 and Table 19 for the EP toxicity test and Indiana leaching method test, respectively.

Leaching Properties of Ash

The extent to which a waste is hazardous to the environment is dependent upon the amount of contaminants that will be released from a deposit. At present, the prediction of ash leachate properties is not possible because leaching of ash materials is a very complex process. In general, the leachate properties are governed by the physical-chemical

Table 18. Allowable concentrations of waste constituents using the EP toxicity test - Indiana^a

Parameter	Concentrations (milligrams per liter)			
	Type IV	Type III	Type II	Type I
Arsenic	≤0.05	≤0.5	≤1.25	<5.0
Barium	≤1	≤10	≤25	<100
Cadmium	≤0.01	≤0.1	≤0.25	<1.0
Chromium	≤0.05	≤0.5	≤1.25	<5.0
Lead	≤0.05	≤0.5	≤1.25	<5.0
Mercury	≤0.002	≤0.02	≤0.05	<0.2
Selenium	≤0.01	≤0.1	≤0.25	<1.0
Silver	≤0.05	≤0.5	≤1.25	<5.0

^a Source: Indiana Register [18]

Table 19. Allowable concentrations of waste constituents using the Indiana leaching method test^a

Parameter	Concentrations (milligrams per liter)			
	Type IV	Type III	Type II	Type I
Barium	≤1	≤10	≤25	* ^b
Boron	≤2	≤20	≤50	*
Chlorides	≤250	≤2,500	≤6,250	*
Copper	≤.25	≤2.5	≤6.25	*
Cyanide, Total	≤.2	≤2	≤5	*
Fluoride	≤1.4	≤14	≤35	*
Iron	≤1.5	≤15	*	*
Manganese	≤.05	≤.5	*	*
Nickel	≤.2	≤2	≤5	*
Phenols	≤.3	≤3	≤7.5	*
Sodium	≤250	≤2,500	≤6,250	*
Sulfate	≤250	≤2,500	≤6,250	*
Sulfide, Total	≤1	≤5	≤12.5	*
Total Dissolved Solids	≤500	≤5,000	≤12,500	*
Zinc	≤2.5	≤25	≤62.5	*

Parameter	Acceptable range (standard units)			
	Type IV	Type III	Type II	Type I
pH	6 - 9	5 - 10	4 - 11	*

^a Source: Indiana Register [18]

^b Testing is not required

characteristics of the ash and the soil-water matrix through which the leachate flows. In order to estimate the leachate quality at any point, one must know the laboratory leachate properties and the specific attenuation-translocation factors of the soil-ash system [126].

Leaching Mechanism

The majority of power plant ashes and desulfurization products are alkaline in character to the extent that the first leachate has a pH above 7.0. The alkaline and buffer substances in the waste are also dissolved and removed, and the pH of the pore water in the deposit will gradually fall. Calculations based on laboratory tests indicate that this will take a very long time, and consequently the leachate will continue to be alkaline in character.

During its slow downward passage, the leaching water progressively dissolves components until a state of chemical equilibrium is reached. Substances already in solution may be precipitated, as the water constantly passes through zones of differing pH. The contaminants exist in different parts of the ash. Some exist in the form of easily-soluble particles, others are bound in vitrified silicate matrices. Thus they have varying solubilities under the varying conditions in the deposit.

The first leachate from coal combustion wastes contains relatively high concentrations of dissolved salts. In

laboratory tests, these high concentrations rapidly fall off. However, when scaled up to the real size of a deposit, this can be equivalent to several hundred years' leachate production.

The alkaline and buffer character of the ash results in slow leaching of trace elements (heavy metals). This also leads to comparatively low concentrations of trace elements in the leachate, but at the same time it means that leaching will continue for a very long time. Easily-soluble trace elements are the first to be leached. Consequently, the highest trace element concentration appear in the leachate that is first produced. As time increases, the less soluble trace elements are also released. In consequence, trace element concentrations in the leachate will be elevated for thousands of years. Eventually, when the pH-buffer substances in the ash are consumed, acid conditions may arise in the deposit, which may result in an increased leaching of trace elements. Before that time, at least the easily leached fraction of the elements will be leached, which compensates for increased concentrations.

However, coal ashes can also be acid in character. The acidity is due to the sulfur dioxide that has been sorbed to the ash and occurs as sulfate or free SO_3 . It is easily leached and the ash thereby turns neutral or alkaline in character. As long as the acid conditions in the deposit

remain, leaching is more rapid and the trace element concentrations in the leachate produced will be elevated.

Attenuation Mechanisms

There are various physical and chemical attenuation mechanisms that are believed to generally prevent any contaminants leached into the ground from concentrating in groundwater at significant levels. The mechanisms contributing to the reduction of concentrations of the leachate contaminants in soil-groundwater systems can be grouped into two categories:

- adsorption and precipitation of contaminants in soil and/or rock
- dispersion and dilution of leachate in groundwater and surface water.

The adsorption and precipitation of contaminants to/on soil particles involve complex physical and chemical processes. Knowledge of these processes is not complete and the prediction of their effects on leachate attenuation is very difficult, if not impossible. In fact, these processes vary greatly due to differences in soil/rock type, pH environment, and elements of contamination [114]. Dilution and dispersion reduce leachate concentrations by adding to the volume in which the leachate is contained [21].

A study performed by the Illinois Geological Survey used a dispersed soil technique with soils of varying character. It was found that the contaminants in coal waste leachates were attenuated to a great degree by each of the soils [127].

Leachate Content

As earlier stated, the potential environmental hazard of a waste is determined by the amount of contaminants leached from a deposit or from utilization. The concentrations of different contaminants in the leachate may vary within wide limits for ashes from different sources. This is also true for ashes produced from the same plant at different times. The reasons for this are varying contents of trace elements in the coal, along with differing conditions during combustion.

Groundwater Monitoring There are very limited published groundwater monitoring data from ash fill and embankment sites. Groundwater monitoring data reported from four embankment and fill construction sites have been summarized by the Valley Forge Laboratories. These sites include two fly ash highway embankments and two fly ash structural fills. None of the groundwater quality measurements from these sites has approached or exceeded the maximum toxicity levels defined in the RCRA for hazardous waste. In fact, the levels of contaminants in samples from monitoring wells showed either no noticeable change or insignificant increases compared to pre-operational conditions [21].

Groundwater monitoring work performed at power plant ash disposal sites has produced results that are essentially similar to those described for construction sites. In the majority of cases, the data from monitoring of disposal sites showed little adverse effect on drinking water quality. Only a small percentage of the data showed a potential variation attributable to the disposal sites from either the primary or secondary drinking water standards. None of the data was found to exceed the RCRA toxicity standards [128].

However, in 1980, the water from a domestic well near a closed fly ash disposal site in Chisman Creek watershed, Virginia was found to contain elevated levels of several trace elements, notably vanadium and nickel. In 1983, EPA placed the site on the Superfund List and the Chisman Creek Superfund Site became the only ash disposal site on the National Priority List. Virginia Power closed three ash disposal pits at the site and the remedial action cost \$8.6 million [129]. It should be noted , from the Chisman Creek case, that samples of fly ash taken from the site did not contain hazardous concentrations of trace metals, as determined by the EP toxicity test. Virginia Power also contended that fly ash has been exempted from EPA regulation by RCRA. However, the court ruled that EPA could list sites containing any wastes, exempted or otherwise [129].

Laboratory Evaluations Most of the experimental work on environmental effects of ash utilization has been restricted

to laboratory evaluations, and analyses have been limited to inorganic contaminants. Repeated laboratory studies have been performed by EPA, Department of Energy, Electric Power Research Institute, and utility companies to analyze the presence of trace metals in leachates from fly ash. The findings of these studies, as cited by Valley Forge Laboratories, have demonstrated consistently that "... heavy metals and other elements have a very low potential of leaching from coal combustion wastes" [21]. Leaching tests conducted according to EPA's extraction procedure show that the concentrations of the elements in leachate do not exceed RCRA toxicity standards, and rarely even exceed the primary drinking water standards.

There are very limited data reported on the analysis of leachate from bottom ash samples. In a study performed by the Radian Corporation for the U. S. Department of Energy, seven bottom ash samples were analyzed. Again, none of the concentrations has exceeded the RCRA toxicity standards. Only four analyses on trace elements, out of a possible 56 analyses, were in excess of the primary drinking water standards, and all of these excesses were less than ten times the drinking water standard limits. Although these data were obtained from limited sources of bottom ash, they do indicate that not only is bottom ash not hazardous, but that the concentration levels for leachate from bottom ash generally appear to be lower than those for fly ash.

A laboratory investigation was conducted by Western Research Institute to compare the results on utility wastes of the proposed Toxicity Characteristic Leaching Procedure with the Extraction Procedure Toxicity Test [119]. The study examined a total of 41 coal combustion waste samples in duplicates. The analytical results from the TCLP showed about 83 percent of the mean concentrations to be equal to or greater than the EPTC concentrations, and all materials tested fell into the nonhazardous class. It was also found that regulated organic constituents are associated with coal combustion wastes. While the differences were significant when comparing one test with the other, there was no significant difference when the two tests were compared against the regulatory levels. In all cases, the concentrations of regulated analytes, both organic and inorganic, were well below the regulatory threshold, in most cases one to three orders of magnitude lower.

Radioactivity

Each atom of matter is composed of a nucleus surrounded by a cloud of electrons. An atom is called radioactive if its nucleus can emit one or more energetic radiations.

Starting with a collection of identical radioactive atoms, the time it takes for one-half of them to decay is called the half-life. The decay of uranium-238 is the first step in a chain of successive decays of radioactive isotopes,

with radium-226 and radon-222 as intermediate products. The decay chain finally terminates when a stable isotope, lead-206 is reached. Omitting minor sidesteps, this decay chain is [130,131,132]:

The lines with arrows specify the nuclei in the chain, and the numbers underneath the arrows are their half-lives, in years (y), days (d), minutes (m), or seconds (s). The standard chemical symbols are used: U for uranium, Th for thorium, Pa for protactinium, Ra for radium, Rn for radon, Po for polonium, Pb for lead, and Bi for bismuth.

The decay rate has traditionally been specified in Curies (Ci). The original curie unit was based on the decay rate of one gram of radium-226, which is approximately 37 billion (3.7×10^{10}) disintegrations per second [133]. It is often convenient to use a smaller unit, the picocurie (pCi), where $1 \text{ pCi} = 10^{-12} \text{ Ci}$.

Uranium and its daughter, radium-226, are ubiquitous in the earth's crust, being present in almost all forms of rock and soil, including coal. Therefore, they are also present in

coal ash. When an atom of radium-226 decays, an atom of radon is formed. The radon, chemically a gas, can then diffuse out of ash deposits into the atmosphere. A rough average radium concentration in the soil is 0.8 pCi/g [134].

Radon-222 is a colorless, odorless, noble gas which happens to be radioactive. Radon hazards come primarily from radioactive products formed in the decay of radon-222. These products, called the "radon daughters," are also radioactive but, unlike radon, they are atoms of heavy metals and readily attach themselves to whatever they contact. Inhalation of radon, or more specifically the radon daughters, leads to deposition of radioactive atoms on the walls of the lung [135]. If a radioactive ash is soluble, atoms of radon and its daughters can pass into the blood and settle in bone tissue [136].

Prior to December 1978, solid wastes were classified as radioactive if the radium-226 activity was above 5 pCi/g. Currently, no regulatory criterium exist for solid waste radioactivity. If sluice water from ash ponds is of concern, the maximum alpha particle activity defined in the National Primary Drinking Water Standards [118] is 15 pCi/l.

A study of 69 eastern and western fly ashes showed that the mean radium-226 activity was 3.7 pCi/g for ash produced from eastern coal and 2.6 pCi/g for ash from western coal. Only seven of these ashes had values greater than 5 pCi/g, with a maximum value of 7 pCi/g [137]. The results of a

separate study determined that 6 out of 12 fly ashes from western bituminous and lignite coal had radium-226 activity levels above 5 pCi/g [138]. Another study on the radioactivity of power plant sluice-pond water showed the alpha radioactivity ranged from 1 to 9 pCi/l for the 10 power plants studied [139].

No data have been reported on the radioactivity of bottom ash. However, it is believed that radioactive emissions from power plants are proportional to particulate release [136]. Therefore, the radioactivity of bottom ash is expected to be less than the values reported for fly ashes.

TESTING MATERIALS

Eleven different bottom ashes from ten utility stations were selected for laboratory testing in this study. The ash materials consisted of nine dry bottom ashes, one wet bottom ash, and a source which was a combination of both wet and dry ashes. The ash ranged in character from gray, friable, and porous to black, durable, and glassy.

Selection of Ash Sources

The selection of the source of each ash was based on a previous study completed in 1985 on Indiana fly ashes [140]. Because some chemical properties of fly and bottom ashes are expected to be similar, it would be advantageous to select bottom ash from power plants at which the properties of the fly ash had been studied. For example, if bottom ash and fly ash are to be mixed for utilization, knowledge of the properties of the fly ash may save the time and effort of repeated testing.

As the utilization of ash material will be economic only on a regional or local basis, one of the important criteria for the selection was the geographic distribution of the sources. A reasonable geographic balance among the eleven

ashes selected for study was accomplished, with three bottom ashes identified as being from northwestern Indiana, four from central Indiana, and 4 from southern Indiana. The approximate locations of the selected ash sources are shown in Figure 17.

Another criterion for selection was with respect to the utility companies. It was intended to obtain bottom ash from at least one generating station operated by each of the franchised power utilities in the state, and also bottom ash from at least one municipal power station. The final collection covered four franchised utilities, and included three bottom ashes from stations of Public Service Indiana (PSI), three from Northern Indiana Public Service Company (NIPSCO), two from Indianapolis Power and Light Company (IPL), and two from Southern Indiana Gas and Electric Company (SIGECO). In addition, one bottom ash was obtained from Richmond Power and Light (RPL), which is a municipal-owned power station.

It was also decided to sample bottom ash from stations of varying sizes, in terms of generating capacity, from the smallest to the largest. The stations sampled ranged from the 46 MegaWatt (MW) Perry K. Station to the 3340 MW Gibson station, the latter being the largest in the state. Table 20 lists the stations sampled in the study, together with their location and rated capacity.

Figure 17. Approximate locations of bottom ashes sampled in the study

Table 20. Bottom ash sources in the study

Utility Company	Station	Location (county)	Capacity (megawatts)
NIPSCO ^a	R. M. Schahfer, Unit 14	Jasper	370 ^b
NIPSCO	R. M. Schahfer, Unit 17	Jasper	420 ^b
NIPSCO	D. H. Mitchell	Lake	505
PSI ^c	Gibson	Gibson	3,340
PSI	R. A. Gallagher	Floyd	500
PSI	Wabash River	Vigo	788
SIGECO ^d	A. B. Brown	Posey	500
SIGECO	F. B. Culley	Warrick	395
RPL ^e	Whitewater Valley	Wayne	100
IPL ^f	C. C. Perry	Marion	46
IPL	E. W. Stout	Marion	750

^a Northern Indiana Public Service Co.

^b total capacity of Schahfer station is 1943 megawatts

^c Public Service Indiana

^d Southern Indiana Gas and Electric Co.

^e Richmond Power and Light

^f Indianapolis Power and Light

Sampling of Ash

In most power plants, bottom ash is transported to a disposal lagoon as a slurry flowing through closed conduits. The closed ash transport and handling systems are seldom equipped with sampling ports at convenient locations. In such cases, bottom ashes were collected as grab specimens from ash deposits at the outlet of sluice pipes. In fact, at power plants where bottom and fly ashes are co-disposed, the ash sampled represented the coarse fraction of the ash in the lagoon. Only two stations disposed their ash by the dry method. In this case ashes are temporarily stored in storage

silos, before being trucked to landfills. Sampling of all ashes was guided by the information and advice provided by plant staff in charge of ash handling and disposal for each power station.

Of the eleven ashes used in the study, two ashes were sampled from bottom ash silos, four were from ash lagoons storing bottom ash only, and five were from ash lagoons or landfills containing both bottom and fly ashes. As previously discussed, it is likely that bottom ash needs to be stockpiled before it is reclaimed for large-volume uses. Therefore, the sampling techniques used in this study are judged to be representative of the materials to be reclaimed.

The actual collection on site was performed by hand-loading of 10-gallon plastic cans. Care was taken to obtain as representative a sample as possible. Each sample was properly tagged, returned to the laboratory, and carefully stored in a designated area for subsampling. Each ash source was sampled at two different times to study the potential variability of bottom ash produced from the same source. Four bottom ashes were selected for detailed testing on engineering properties, and a third sample was obtained from each of these four sources. These included Gibson, Schahfer Unit 14, Schahfer Unit 17, and Perry ashes. Fly ash was also sampled from these four sources for testing bottom ash-fly ash mixtures for pavement material.

Bottom Ash

Most of the power plants were burning Illinois Basin bituminous coals at the time of sampling. Generally, coal was supplied from a major source and was supplemented from various minor sources. Very few plants burned single-source coal. Table 21 summarizes the major source of coal being burned at the time of sampling, along with the resulting type of bottom ash. The following sections describe the ash handling method used in each power station as well as the physical appearance of each ash.

Table 21. Coal source and ash type

Power station	Coal type and source	Bottom ash type
Schahfer		
Unit 14	Western lignite	wet
Unit 17	Illinois bituminous	dry
Mitchell	Western lignite ^a	dry
Gibson	Illinois bituminous	dry
Gallagher	Indiana bituminous	dry
Wabash	Indiana bituminous	dry
Brown	Indiana bituminous	dry
Culley	Indiana bituminous	dry
Richmond	Indiana bituminous	dry
Perry	Indiana bituminous	dry
Stout	Indiana bituminous	wet & dry

^a From Wyoming

Gibson Ash

This generating station is the largest in the state, and is located in southwestern Indiana. The ash was produced from burning Illinois basin bituminous coal in a pulverized dry bottom furnace. Bottom ash is sluiced to the ash pond, and the pipe position is periodically moved to facilitate ash storage. A considerable amount of ash has been accumulated in the ash pond and the station is producing bottom ash at a rate of 200,000 tons per year. Bottom ash and fly ash are stored separately at the station. The bottom ash lagoon is easily accessible by trucks and other construction equipment. This ash exhibited a dull appearance and some particles showed a shiny luster resembling wet bottom ash particles. At the time of sampling, the ash was being mined by a concrete block firm to supplement natural aggregate.

Gallagher Ash

This ash was produced at the R. A. Gallagher Station of Public Service Indiana near New Albany, Indiana. The coal burned here was a bituminous coal from southwestern Indiana; occasionally a small amount of western Kentucky coal was also burned. This dry bottom ash was sluiced to the ash lagoon and mixed with the fly ash. The appearance of this ash was of a dull nature, with a light gray color. There are filled and abandoned ash lagoons, which indicate abundant quantities of

ash stored on site. The access to ash deposits at Gallagher Station is good, but bottom ash was not being marketed at the time of sampling.

Wabash Ash

This ash was obtained from the Wabash River Station at Terre Haute, Indiana. It was produced from coal obtained from the Hawthorn Mine in southern Indiana. The ash is of the dry bottom type, and was not being marketed commercially at the time of sampling. This ash resembled the Gallagher ash, as it was light gray in color and dull in appearance. It was estimated that there was over three million tons of ash on site, and the access to the filled lagoon is in good condition.

Brown Ash

This ash was obtained at the A. B. Brown Station of the Southern Indiana Gas and Electric Co. (SIGECO), near Evansville, Indiana. It was produced from coal acquired from the Old Ben I mine in southern Indiana. The station has been burning this single source of coal since its installation in 1978, and the plan is to continue the use of that coal for the indefinite future. The 16-acre ash pond in this station is, in fact, a natural valley on the Ohio River. Bottom ash and fly ash here have different sluiceways and different outlets

which are located about 50 yards apart in the pond. Bottom ash was sampled near the outlet of the bottom ash sluiceway. It was a hard, dense material of dark gray color, with traces of shiny luster. The ash was not being marketed at the time of sampling.

Culley Ash

The F. B. Culley Station of SIGECO was the source of this ash. Several different Indiana coals were burned in the station. Bottom ash is separated from fly ash in lagoons, and ash lagoons are periodically emptied by trucking ash to a landfill, where the bottom and fly ashes are mixed randomly. Bottom ash sample was obtained from the bottom ash lagoon. This material has high specific gravity and unit weight, with a dull appearance. The ash was not marketed at the time of sampling.

Schahfer Unit 17

This unit, part of the large R. M. Schahfer Station of the Northern Indiana Public Service Co. (NIPSCO), burned pulverized Illinois bituminous coal in a dry bottom furnace. Bottom ash was sluiced to a well-engineered ash pond which was maintained in good condition. The ash pond received bottom ash only and a representative sample was obtained from the pond. This bottom ash was composed of clean sand and gravel

sizes, with no fines. It had relatively high porosity and a dark gray color. Fly and bottom ashes were stored separately.

Schahfer Unit 14

This bottom ash was sampled from a companion unit of the Schahfer Station. The unit burned western lignite coal in a cyclone furnace and produced wet bottom ash. This was the only material in the study that was exclusively wet bottom ash. Bottom ash was stored separately from fly ash, and was being marketed through an ash broker using the trademark "black beauty".

Physical appearance of this wet bottom ash was very different from those of dry bottom ashes. The ash was hard, dense, and shiny black in color. The gradation was very uniform, and there were small amount of needle-shaped particles present in the ash. Unlike dry bottom ash, wet bottom ash particles had smooth surface texture and appeared much like crushed glass.

Mitchell Ash

This material was obtained from the D. H. Mitchell Station of NIPSCO at Gary, Indiana. It was produced from burning two different western lignite coals from Wyoming. The content of the uncombustible material in this coal was so high that the bottom ash had traces of foreign substance such as

rock fragments and pebbles. Bottom ash was transported through pipes to ash pits which stored both fly and bottom ashes. Access to the ash pits was very poor. The station would need to remove a portion of the dike in order to truck the ash, and then reconstruct the dike. The ash was not being marketed at the time of sampling.

Richmond Ash

The ash was obtained from the Whitewater Valley Station of Richmond Power and Light Co. The majority of the coal burned at this station was Indiana bituminous coal from the Miller Creek mine. About 20 percent of the coal burned was from other sources. Bottom ash was produced in a pulverized dry bottom furnace. It was crushed and then flushed to a dewatering bin for transportation. Bottom ash was sampled directly from trucks while being loaded from the bottom ash bin. This ash was predominantly sand in size, with very few gravel-sized particles. Bottom ash and fly ash were trucked separately to an old quarry where they were mixed together. The access to the quarry is good.

Perry Ash

This ash originated from the C. C. Perry Station (Section K) of Indianapolis Power and Light Co. (IPL) in downtown Indianapolis. This station was sampled three times in 1987,

1988, and 1989, respectively. Each time the station was sampled, it was burning different sources of coal. Bottom ash here was produced in stoker furnaces and temporarily stored in silos before it was trucked to a landfill. The ash was sampled from a port underneath the ash hopper. Hence, this was the only ash sampled that had never been washed by water. Bottom ash and fly ash were stored separately in silos at the station, but subsequently they are combined at the landfill several miles away. Access to the landfill is good.

The physical characteristics of Perry ash were quite different from the other dry bottom ashes. This ash had so low a specific gravity that some particles floated in water. Ash particles were light weight, highly porous, and appeared red to brown in color, with a popcorn-like surface texture. Some particles were very friable, and crushing of these particles with fingers was easily accomplished.

Stout Ash

The E. W. Stout Station of IPL was the source of this bottom ash. The coal burned was a mixture of several Illinois Basin bituminous coals from southern Indiana. The bottom ash was stockpiled with fly ash in the lagoon. Two wet bottom and three dry bottom furnaces contributed ash to the ash pond. The overall appearance of the ash was of a dull nature with a gray color. The ash sample was obtained near the outlet where a significant amount of coarse ash had accumulated. The

access to the ash lagoon is fairly good. The ash was not being marketed at the time of sampling.

Fly Ash

Fly ash was also obtained from four sources, namely, Gibson, Schahfer Unit 14, Schahfer Unit 17, and Perry, when the third bottom ash sample was taken from each of the four sources in spring 1989. Most of the fly ashes were classified as Class F. Only fly ash from Schahfer Unit 17 was an ASTM Class C material.

Fly ashes were sampled from the fly ash transfer line at Gibson and Schahfer stations. Perry fly ash was obtained from pipe connecting to the temporary storage silo. Some index properties of these fly ashes are summarized in Table 22. The moisture-density relations of fly ashes are presented in Appendix C.

Table 22. Index properties of selected fly ashes

Property	Gibson	Schahfer Unit 14	Schahfer Unit 17
Classification ^a	Type F	Type C	Type F
Specific gravity	2.394	2.850	2.502
Plasticity Index	NP ^b	NP	NP
Percent retained on No. 200 sieve	9.4	14.9	21.6

^a ASTM Designation C 618 [141]

^b Denotes non-plastic

LABORATORY TESTING PROGRAM

Introduction

The experimental program of this study consisted essentially of a laboratory investigation aimed at testing bottom ash samples by standard as well as nonstandard methods. The objective of the laboratory testing program was to evaluate bottom ash both as a soil material and as an aggregate for highway construction, viz., highway embankments, subgrades, subbases, and bases.

This chapter primarily describes the experimental methods or procedures used in the course of the laboratory investigations. Some of the methods used were the standard ASTM or AASHTO tests. For such methods, the ASTM or AASHTO Designation is given and only a brief description of the procedures is provided. In cases where nonstandard testing procedures were used, a more detailed description of the procedures is presented.

A large number of diverse laboratory measurements were performed to develop an overall profile of the characteristics of each bottom ash. The laboratory testing program was implemented in three phases. The first phase was to conduct a characterization analysis of the ash materials. A means of

classifying these materials is desirable since ash varies so greatly from source to source. The second phase consisted of testing the bottom ash materials for their geotechnical properties. Since time would not allow testing each ash source for its geotechnical properties, only selected bottom ashes were subject to the second phase testing. The third phase of the testing program was a laboratory evaluation of potential environmental effects of bottom ash utilization. This involved laboratory leaching tests and chemical analysis of the leachates.

Two replicate tests were performed throughout the course of the testing program to verify reproducibility. In case significant disagreements existed between the two consecutive test results, additional replicates were performed. The material behavior during the preparation and testing operation was critically observed as part of the laboratory studies. It was believed that these observations would assist the appropriate interpretation of the test results obtained on bottom ashes.

Ash Characterization Tests

Chemical Analysis

The chemical analysis of bottom ashes was performed primarily by means of atomic absorption spectrophotometric methods (Varian SpectrAA-20). All bottom ashes were analyzed

for a total of eight elements. Among these, iron, sodium, and potassium were analyzed by the flame emission method; and the analysis of aluminum, magnesium, silicon, and calcium was performed by the atomic absorption method. Finally, in the analysis of sulfur trioxide, procedures described in the ASTM Designation C 311 [142] were followed.

Procedures for chemical analysis of bottom ashes were complicated by the difficulty in dissolving all ash particles. The dissolution of ground bottom ash was by fusion with lithium metaborate at 900°C in a gold crucible. The weight ratio of the ignited ash to lithium metaborate in the fusion was 1 to 10, and 5 ml lanthanum (0.36 M) was added to the solution. The solution was then diluted to 250 ml, and the resulting solution was used for elemental analysis.

The same dissolution technique was used in the analysis of sulfur trioxide. In this case, the melt of ash and lithium metaborate was filtered using a filter paper, and the filtrate was slightly acidified with HCl. The 250 ml solution was boiled and about 10 ml of hot barium chloride (BaCl_2) (100 g/liter) was added to the solution. After the solution was digested overnight, the precipitate was filtered using a ceramic filter. The ceramic filter was finally oven-dried to determine the weight of the precipitate (barium sulfate) so that the sulfur content could be determined.

Analyses for all of the eight elements were converted to their equivalent oxides and expressed as weight percentages on

an oven-dried basis. The sum of these elemental percentages should be equal or close to 100. This provided a good indication of the overall validity of the analyses.

Loss on Ignition

Theoretically, since all ash materials had undergone furnace firing temperatures higher than 1000°C, all carbon and organic matter in the coal should have been combusted. However, not all power plant boilers are operated with such efficiency. Also, if the ash had been ponded or stockpiled for some time, it could have been contaminated with various foreign materials. Therefore, it is customary to determine the loss on ignition of ash materials. This is determined by the weight loss on heating the ash material from 110°C to 600°C, and is usually expressed as a percentage of the oven-dried weight.

About 20 grams of oven-dried specimen were ground up in a grinder (Brinkman Retsch Co.), with a 0.5 μ m sieve. A sample splitter was used in deriving the 20-g sample out of a sample of about 2 kgs. Next, approximately one gram of the ground specimens was ignited in uncovered porcelain crucibles at 600°C. A muffle furnace (Thermolyne 2000) capable of generating a maximum temperature of 1,100°C was used in the test.

Microscopic Examination

This was performed by use of the StereoZoom microscope manufactured by Bausch & Lomb Inc. The microscope was also equipped with a 3-1/4 in. x 4-1/4 in. camera. Photomicrographs were taken at a magnification of 30, using Polaroid type 107 film (black and white). All bottom ashes were subjected to microscopic examination in order to characterize particle shape, angularity, and surface texture of ash materials. For comparison purposes, standard Ottawa sand was also microscopically examined.

X-Ray Diffraction

X-ray diffraction analyses were conducted by use of a Siemens D-500 diffractometer using copper radiation. All specimens were ground prior to analysis by the grinder previously described. The diffraction was performed over a range of 2θ angles from about 10 to 65 degrees, at a speed of 2 degrees/min. The standard X-ray diffraction patterns published by the Joint Committee on Powder Diffraction Standards (JCPDS) [143] were used in the identification of crystalline substances.

Grain Size Distribution

The gradations of bottom ash specimens were determined by the ASTM Designation C 136, which is designed for aggregates.

The dry sieve analysis was carried out using a Ro-Tap Testing Sieve Shaker (Tyler Co.). All sieves were U.S. Standard Sieves conforming to ASTM E 11 specifications [144]. Since all bottom ashes have less than 12 percent fines, the washing test, or ASTM C 117, was judged to be unnecessary.

Specific Gravity

The specific gravities of bottom ashes were determined using three different methods. The first two methods were standard ASTM tests, namely, C 128 and D 854 designed for aggregates and soils, respectively. The third method was performed by use of a gas pycnometer.

In the application of these two standard methods to bottom ashes, the difference existed in the techniques used to remove the entrapped air in the pycnometer. The former method eliminated air bubbles by agitating, rolling, and inverting the pycnometer, whereas boiling of the contents in the pycnometer was used in the latter method.

The gas pycnometer method was conducted in a two-chamber device [140]. The volume of gas in the sample chamber is inferred by a measurement of the pressure drop on opening the valve connecting the two chambers of known volume. By use of the Boyle's Law $P_1V_1 = P_2V_2$, the initial volume of the gas in the sample chamber can be calculated, from which the volume of the sample is derived.

The reason for determining the specific gravity by several different methods was to attempt to understand the differing structure of different bottom ashes which would cause variations among the results obtained from the several methods.

Aggregate Tests

Los Angeles Abrasion

The abrasion resistance of bottom ash was tested by the standard Los Angeles abrasion test, as described in ASTM C 131. The percent wears at 100 revolutions and 500 revolutions were both reported, to determine the uniformity of the sample under test. The gradings used in the test were selected to represent the most predominant size range in the materials as sampled. All specimens were prepared by washing and oven-drying.

Sulfate Soundness

The soundness of bottom ash specimens were determined by the sodium sulfate soundness test which was performed in accordance with ASTM Designation C 88. Due to the limited amounts of coarse fraction, only the fine aggregate test using the material passing the 3/8-in. sieve was performed. The weighted losses after five cycles of immersion and oven-drying were determined.

Geotechnical Property Tests

Maximum and Minimum Densities

The maximum density of selected bottom ashes was determined in a 4 in.-diameter mold by using a vertically vibrating table. The test was performed in accordance with the Dry Method specified in ASTM Designation D 4253. As-sampled gradation was used, except that the oversized fraction was scalped by screening through a 3/4 in. sieve.

The minimum density test was performed using a standard compaction mold (4 in. in diameter) following the procedures described in Method B (tube method) of ASTM Designation D 4254. The thin-walled tube has a 2.8 in. inside diameter, and the testing material was placed in the tube with a scoop. As in the maximum density test, oversized particles were scalped prior to testing. Maximum and minimum void ratios were calculated according to ASTM D 4254 method.

Permeability

The coefficient of permeability of bottom ashes was measured by falling head permeability tests. The permeameter was rigid-walled and had a 4 in. (10 cm) diameter. All specimens were about 8 in. (20 cm) high and were saturated for 24 hours before the test was performed. Ash materials were compacted at standard effort (ASTM D 698) and then placed in the permeameter at 95 percent maximum dry density using a

vibratory table. This was intended to determine the permeability of ash in its compacted condition, because bottom ash will always be well compacted for all highway applications.

Angle of Shearing Resistance

The angle of shearing resistance of bottom ash was determined by direct shear tests. The direct shear box had a diameter of 2.5 in. (64 mm) and a height of 1.5 in. (38 mm). Only materials finer than 3/8 in. (3.6 mm) were used in the test. The test was conducted on bottom ash at numerous relative densities, varying from very loose to very dense states. The normal stress used in the test ranged from about 5 psi (34 kPa) to 33 psi (240 kPa).

Compaction

The standard Proctor test, as described in the ASTM Designation D 698, was performed on selected bottom ashes to establish the moisture density relations in ash materials. Method C in the ASTM D 698 procedure, utilizing materials passing the 3/4 in. sieve, was adopted throughout the study. At each moisture content, fresh materials were used for the compaction test.

Degradation

The degradation of bottom ashes taking place under the drop hammer during the compaction test was studied by compacting bottom ash in accordance with the ASTM D 698 at the predetermined optimum moisture contents. Air-dried bottom ashes were initially sieved and then recombined into the previously established gradations. Following the compaction procedure, ash materials were carefully removed from the mold, oven-dried and subjected to sieve analysis. Extreme care was exercised to prevent particle breakdowns after compaction. Triplicate tests were performed on each ash and fresh materials were used for each replicate.

One-Dimensional Compression

One-dimensional compression tests were carried out in a consolidometer which has a diameter of 4 in. (102 mm) and ash specimens were 1.5 in. (38 mm) high. Initially, dry materials were placed in the consolidometer using a vibratory table at 90 percent of the maximum density determined by the standard compaction test. Two samples of each ash were tested, one in a dry condition and the other one in a saturated condition. The latter was saturated in the consolidometer under a seating pressure of 0.8 psi (5 kPa) and soaked for 24 hours to measure the swelling/collapse of the sample. The consolidometer was loaded incrementally by a electronically controlled hydraulic

loading system. Immediate measurements of deformation were made at 1 minute after the application of each load. Finally, the specimens were maintained under maximum stress until no further deformation was observed. A maximum stress of 150 psi (1000 kPa) was used in the test.

California Bearing Ratio (CBR)

Selected bottom ashes were subjected to the California Bearing Ratio test following an improved procedure proposed by Franco and Lee [145]. In this test, the ash materials were dried and pretreated for compaction per ASTM D 698. Water was added to the ash sample to prepare three specimens such that the moisture contents ranged around the optimum moisture content. Each specimen was then compacted according to Method D of ASTM D 698. The compacted ash in the mold was trimmed level with the top surface and the specimen was weighed to determine wet density and finally dry density.

The CBR of each ash tested was obtained for the as-compacted and the soaked condition. For the dry condition, the penetration test was performed immediately after the compaction. For the soaked condition, the soaking procedure of ASTM D 1883 was followed. After the percent swell had been determined, the penetration test was performed on the soaked ash. The surcharges used during the soaking period and the penetration were both 10 lbs. The correction of load-

penetration curves was carried out following the correction procedure of ASTM D 1883.

Stabilization

Three bottom ashes were selected for this phase of the experimental program because they were stored separately from fly ash at their source power plants. Bottom ashes from Gibson, Schahfer Unit 14, and Schahfer Unit 17 were used as the aggregate portion of two categories of mixtures.

The first category of mixtures was prepared using bottom and fly ashes from the same source. The bottom ash-fly ash proportions by weight considered in the mixtures were 90-10, 80-20, 70-30, and 60-40. The standard Proctor compaction test (ASTM D 698) was performed on the mixtures as well as fly ash alone to establish the moisture-density relations in these materials. Bottom ashes were initially sieved and fractioned into various sizes and then recombined into the gradations established earlier. After compaction, the materials were subjected to degradation analysis as previously described.

The second category of mixtures encompassed cement stabilized bottom ashes and bottom ash-fly ash combinations. The selection of bottom ash-fly ash proportions was based on the maximum dry density obtained from the first category of mixtures. The cement contents were selected arbitrarily at 6 and 10 percent by weight of the mixture. Accordingly, the fly ash contents were reduced in such a manner that the volume of

soil portion (cement + fly ash) in the mixture was the same as that producing the maximum dry density in the first category of mixtures. This is based on the assumption that cement and fly ash have comparable fineness. In other words, it is expected that the maximum dry density obtained from cement stabilized bottom ash-fly ash mixtures will be approximately the same as that obtained from untreated bottom ash-fly ash mixtures, if part of the fly ash of the untreated mixture is replaced by an equivalent volume of cement. The moisture-density relations of cement stabilized bottom ash-fly ash mixtures were determined in accordance with Method B of ASTM D 558 [146]. Two specimens were compacted at the optimum moisture content and moist cured for 7 days and then subjected to unconfined compression tests.

Compressive Strength

The standard method of test for compressive strength of soil-cement cylinders was followed as outlined in Method A of ASTM Designation D 1633 [147]. Bottom ash-cement and bottom ash-fly ash-cement mixtures were compacted at the predetermined optimum moisture content in a standard Proctor mold to achieve the maximum density. The specimens were cured in a moist room for a period of 7 days at 75°F. At the end of the moist-cure period, the specimens were immersed in water for 4 hours. Instead of capping, 4-in retaining cups (ECON-O-CAP) were placed on the top and bottom faces of the specimens

for compression testing. The compression load was applied at a rate of 0.05 in/min. The maximum load reached during the compression was recorded, and the unit compression strength was calculated by dividing the maximum load by the initial cross-sectional area of the specimens.

Leaching Tests

Extraction Procedure (EP) Toxicity

The EP toxicity tests were performed on selected bottom ashes in accordance with the EPA Method 1310, as specified in EPA SW-846: "Test Methods for Evaluating Solid Waste, Physical/Chemical Methods," Third Edition [117]. A sample size of 100 gm was used for all the ashes tested. Coarse particles were broken down so that they would pass the 3/8 in. sieve. Next, 1600 gm of deionized water was added to the ash and the ash-water mixture was agitated in a plexiglass container. The pH of the soil-water mixture was monitored by using a glass electrode pH meter. It was maintained at 5.0 ± 0.2 throughout the 24-hour extraction period, using acetic acid. At the end of the extraction, the water:ash (liquid:solid) ratio was adjusted to 20:1. Then the mixed solid and extraction liquid were separated by filtering the mixture through a filtration membrane having a nominal pore size of 0.45 micrometers. The solid was discarded and the liquid obtained from filtration was the EP Extract which was

subsequently analyzed for eight trace metals. Generally, 5 ml/L concentrated nitric acid (HNO_3) was added to the solution to preserve the extract.

Indiana Leaching Method

The Indiana leaching method test was conducted by the method as specified for EP toxicity testing, except with no addition of acetic acid. The pH of the extract was determined at the end of the 24-hour extraction period.

Leachate Analysis

The extract obtained from the EP toxicity test was analyzed by using the atomic absorption spectrophotometer equipped with a graphite tube atomizer. The analytical working range in the analysis for most elements was as low as 10^{-9} g/ml. Eight elements, namely, arsenic, barium, cadmium, chromium, lead, mercury, selenium, and silver, were analyzed using the appropriate test methods specified in EPA SW-846.

The extract produced from the Indiana leaching method test was analyzed for barium, boron, chloride, total cyanide, fluoride, pH, sodium, sulfate, total sulfide, and total dissolved solids. Of these, the analyses for boron, chloride, fluoride, sodium, sulfate, and total dissolved solids were conducted as specified in "Methods for Chemical Analysis of Water and Wastes," EPA 600/4-79-020 [148]; and total cyanide,

pH, and total sulfide were analyzed by methods specified in EPA SW-846.

The analyses for boron, total cyanide, fluoride, and total sulfide in the leachate were performed by the Environmental Laboratory Division, Indiana State Board of Health, Indianapolis, Indiana.

Radioactivity

For a chain of radioactive isotopes headed by a relatively long lived parent, the amount of each chain member will adjust until the sources and losses of each are in balance. When the only source is an original amount of a long-lived parent and the only losses are by the radioactive decay of each member of the chain, the equilibrium reached is one in which the activities of the long-lived parent and each of its shorter lived daughters are equal. Thus, the concentration of the long-lived parent can be determined by counting the decay of its short-lived daughters.

If one starts from pure radium as the "long-lived" parent, the time to attain 99% of the secular equilibrium of the radium daughters is approximately 27 days. Therefore, in this study, bottom ash samples were sealed in plastic canisters for 30 days to allow the short-lived radium daughters to reach equilibrium with radium. The canister had a 7-cm diameter and a height of 1.5 cm. After the 30-day storage, detection of radium was accomplished by counting

gamma rays emitted by its short-lived daughters in secular equilibrium with radium. Counting was carried out with a sodium iodine (NaI) detector connected to a multichannel analyzer (CANBERRA, Series 85). The window of the analyzer was set to count gamma rays between 270 to 720 keV. This range covered the Pb-214 peaks and the Bi-214 peak, both are daughters of radium-226. All counting lasted for one hour.

A standard canister of fly ash obtained from the National Bureau of Standards (NBS) was tested to provide a scale of the activity. This standard material (ID No. INJNS 8991) is reported to have 203 pCi radium. The background of the detector was obtained by counting a blank canister. Also, for comparison purposes, a soil obtained from the Agronomy farm at Purdue University, West Lafayette, Indiana, was tested. The soil was a clay with a liquid limit of 40.5% and a plasticity index of 21.2%.

The radium activity in each bottom ash sample was determined using the following formula:

$$\text{Activity(pCi)} = \frac{\text{Net count(bottom ash)}}{\text{Net count(standard)}} \times \text{Activity of standard}$$

where Net count = gross count - background count, and

Activity of standard material = 203 pCi.

The activity determined by this formula was then divided by the weight of the bottom ash in the canister to obtain the radium specific activity of bottom ash in pCi/g.

$$\text{Specific Activity (pCi/g)} = \frac{\text{Activity (pCi)}}{\text{weight of sample (g)}}$$

RESULTS AND DISCUSSION

As described in the foregoing sections, the laboratory experimental program consisted of a series of physical, chemical, and engineering property tests as well as leaching tests and leachate analysis. In the following sections, the results of these tests will be presented and discussed.

Shape and Surface Texture

In order to characterize the particle shape and surface texture of bottom ashes, and to gain some insight to the behavior of ash materials during the following testing operations, a microscopic examination was conducted on bottom ashes. Figures 18 through 28 are photomicrographs of all the ash materials studied. For purpose of comparison, Figure 29 shows the shape and surface characteristics of a standard 20-30 Ottawa sand. These photomicrographs were taken at a magnification of 40 to permit observation of the features of a number of particles at one time. It can be seen from the photomicrographs that the shape and surface characteristics of the ashes show some variation from plant to plant due to differences in coal type, burning processes, and different collection and handling methods used.

Figure 18. Micrograph of Schahfer Unit 14 wet bottom ash

Figure 19. Micrograph of Schahfer Unit 17 ash

Figure 20. Micrograph of Mitchell ash

Figure 21. Micrograph of Gibson ash

Figure 22. Micrograph of Gallagher ash

Figure 23. Micrograph of Wabash ash

Figure 24. Micrograph of Brown ash

Figure 25. Micrograph of Culley ash

Figure 26. Micrograph of Richmond ash

Figure 27. Micrograph of Perry ash

Figure 28. Micrograph of Stout ash

Figure 29. Micrograph of standard Ottawa sand

The majority of wet bottom ash particles were angular to subangular in shape and had a smooth surface texture. Also present was a small amount of rod-shaped particles, one of which is shown in Figure 18. Most of the particles featured fractured faces, which made wet bottom ash much like crushed glass. Some of the larger particles exhibited somewhat porous surface textures. The surfaces of the particles were quite clean and free of dust.

In general, the dry bottom ashes had quite angular particles, and a highly porous surface texture was observed even in fine ash particles. Particles resembling wet bottom ash were occasionally found, especially in the smaller sizes. It was also observed that dry bottom ashes were both externally and internally porous, resulting in an irregular particle shape and rough, gritty surface texture. They were usually light grey to black in color. The surfaces of the bottom ash particles were essentially free of dust, but some fly ash particles were observed to be loosely held to the surfaces of larger particles.

Perry ash, produced from stoker-firing furnaces, showed distinctively different features from the other dry bottom ashes. It appeared to have an extremely porous structure, and appreciable quantities of popcorn-like particles were identified in this ash. Furthermore, the internal porosity of many of the large particles were so high that it caused weak planes in the particle structure. Hence crushing of these

larger particles can be accomplished with fingers. Perry ash was red to brown in color. Some particles in the Stout ash exhibited green to yellowish color, which is an indication of pyrite particles.

In summary, the ashes that resulted from burning pulverized coal in dry bottom furnaces were similar, in terms of the shape and surface texture. The ash produced from stoker-firing furnaces was extremely porous and had low resistance to breaking with the fingers. Wet bottom ash exhibited distinctly different shape and surface characteristics than dry bottom ash. Although only one wet bottom ash was examined in this study, the observation was consistent with that reported by other researchers [3,4,38].

Mineralogical Analysis

X-ray diffraction analysis is the most powerful and probably the only tool for direct identification and determination of constituent minerals. It is known that the chemical constituents of ash material may exist in either crystalline form or as a glass. Figures 30 and 31 show the typical X-ray diffraction patterns for dry and wet bottom ashes, respectively. The crystalline contents of dry bottom ash are characterized by the angles of 2θ of the peaks. In contrast, the X-ray diffraction pattern for wet bottom ash shows no pronounced peaks (Fig. 31). In other words, the chemical constituents of wet bottom ash simply exist as a

Figure 30. Typical X-ray diffraction pattern of dry bottom ash (Richmond)

Figure 31. Typical X-ray diffraction pattern of wet bottom ash (Schahfer Unit 14)

glass, which indeed is suggested by the physical appearance of this type of ash.

In addition, the glass is indicated by a broad band of intensity that shifts the background upward over a range of 2θ angles. The relative intensity of the peaks and the glass band can be used as a measure of the relative amount of crystalline substances and glass, respectively, present in the ash. Furthermore, the angle 2θ at which the maximum of the glass band occurs provides an indication of the basic structure of the glass. Table 23 tabulates the crystalline compounds present in each ash. Crystalline compounds such as quartz (SiO_2) and hematite (Fe_2O_3) are found in almost all dry bottom ashes. Mullite ($3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$) and magnetite (Fe_3O_4) are also frequently found in dry bottom ash. Pyrite (FeS_2) was identified in two ash samples, one in significant content (Stout) and the other one in a minute amount only (Mitchell).

Characteristics of the glass present in bottom ash vary considerably. Interpretation of the glass band for bottom ashes is summarized in Table 24 [140]. The X-ray diffraction patterns for all bottom ashes studied are reproduced in Appendix A.

Chemical Analysis

The chemical compositions of bottom ashes sampled at different times, determined on an oven-dry weight basis, are shown in Table 25. The principal ash constituents are silica

Table 23. Results of X-ray analysis on bottom ashes

Ash source	Quartz SiO_2	Hematite Fe_2O_3	Magnetite Fe_3O_4	Mullite $3\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$	Pyrite FeS_2	Anhydrite CaSO_4
Schahfer	-	-	-	-	-	-
Unit 14	X ^a	X	-	-	-	-
Unit 17	X	X	-	-	-	-
Gibson	X	X	X	X	-	-
Gallagher	X	X	-	-	-	-
Perry	X	X	-	X	-	-
Mitchell	X	-	X	-	X	-
Wabash	X	X	X	X	-	-
Richmond	X	X	X	X	-	-
Stout						
1st sample	X	X	-	-	X	-
2nd sample	X	X	-	X	-	X
Culley	X	X	-	-	-	X
Brown	-	X	-	X	-	-

^a X denotes presence of mineral

Table 24. Glass in bottom ash

Ash Source	Glass content	2 θ ^a (degrees)	Glass structure
Schahfer			
Unit 14	very high	27	silica
Unit 17	low	24	silica
Mitchell	low	24	silica
Gibson	high	24	silica
Gallagher	low	31	calcium aluminate
Wabash	low	23	silica
Brown	low	25	silica
Culley	trace	31	calcium aluminate
Richmond	high	24	silica
Perry	low	23	silica
Stout ^b #1	-	-	(little or no glass)
#2	high	24	silica

^a Angle of 2 θ for the maximum intensity of the glass band.

^b A second set of data are presented only if the glass of the two samples are determined to be different.

(SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). There are smaller quantities of calcium oxide (CaO), magnesium oxide (MgO), potassium oxide (K_2O), sodium oxide (Na_2O), and sulfur trioxide (SO_3), as well as minute traces of other elements. As can be seen from Table 25, the chemical compositions of each bottom ash show a reasonable degree of uniformity, except those ashes from Perry and Richmond. These stations were burning different sources of coal just prior to the dates of sampling, and this is reflected by greater variations in the chemical composition of the bottom ash. Stout ash also shows significant variation in chemical composition, due to the presence of pyrite particles in the first sample.

As expected, bottom ashes produced from western lignite coal (Schahfer Unit 14 and Mitchell) have higher calcium content than those produced from eastern bituminous coal. The first sample of Stout ash has an iron oxide content of as high as 42 percent. The significant amount of pyrite particles, as demonstrated by the X-ray diffraction analysis, accounts for the unusual high iron content in this sample. The high calcium contents (18% and 8%) are also accompanied by higher magnesium contents. However, the reported calcium content of fly ashes from the same sources were well over 30 percent [140]. In other words, calcium is partitioned preferably in fly ash rather than in bottom ash.

The loss on ignition values represent the unburned carbon content in the ash samples. Again, an extremely high value

Table 25. Chemical composition of Indiana bottom ashes

Ash source	Date sampled	Percent by weight								Loss on ignition
		SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	
Schahfer Unit 14	6-19-87	60.1	5.2	10.4	16.6	5.7	0.9	0.4	0.9	0.3
	5-12-88	53.4	6.0	13.5	18.5	5.7	1.2	0.3	1.0	0.1
Schahfer Unit 17	6-19-87	58.1	15.2	12.7	7.0	0.8	1.9	0.3	2.2	0.1
	5-12-88	52.1	23.2	13.2	4.8	0.9	1.4	0.2	1.5	0.8
Gibson	5-18-87	58.7	14.6	14.1	3.1	0.8	2.0	0.4	1.3	0.4
	5-17-88	53.6	20.8	14.8	2.6	1.0	1.9	0.5	1.1	1.0
Gallagher	5-26-87	41.2	28.4	11.2	12.6	0.7	1.6	0.3	1.0	0.9
	5-14-88	49.3	24.2	16.4	3.9	0.9	1.7	0.2	2.6	1.4
Perry ^a	5-19-87	48.9	22.2	13.0	0.8	0.7	2.2	0.3	0.6	7.2
	5-14-88	52.5	6.0	24.3	0.9	0.1	2.3	0.4	0.6	6.2
Mitchell	6-19-87	58.8	6.8	7.8	7.9	2.2	1.4	0.1	3.3	8.1
	5-12-88	51.3	6.5	14.2	8.5	3.0	0.9	0.3	1.0	8.0
Wabash	6-23-87	55.7	21.5	14.3	1.7	0.7	1.9	0.3	0.8	0.2
	4-26-88	51.7	23.0	16.0	1.7	0.9	1.9	0.3	0.6	1.0
Richmond ^a	8-17-87	48.3	33.3	11.9	1.3	0.4	0.9	0.2	1.7	2.2
	5- 5-88	41.6	20.9	18.6	1.3	0.6	1.1	0.1	1.9	14.1

^a Plants were burning different sources of coal prior to the dates of sampling

Table 25. (continued)

Ash source	Date sampled	Percent by weight								Loss on ignition
		SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	
Stout ^a	5-27-87	24.2	42.0	6.9	2.2	0.4	0.6	0.2	0.8	18.4
	6-20-88	54.9	20.2	16.7	1.6	0.9	1.9	0.8	1.8	0.3
Culley	8-21-87	35.6	30.1	11.7	14.6	0.8	1.4	0.3	1.0	0.0
	5-14-88	31.0	31.1	11.8	13.9	1.1	0.5	0.2	0.9	0.3
Brown	8-21-87	48.1	27.6	13.4	3.1	0.8	2.1	0.3	1.7	1.9
	5-17-88	38.5	38.0	12.6	3.8	0.7	1.3	0.2	3.3	1.1
Average		48.6	21.2	13.6	6.0	1.4	1.5	0.3	1.4	3.4
Typical range for ash ^b		20-60	5-35	10-35	1-20	0.3-4	1-4 ^c		0-12	-

^b From Selvig and Gibson [54] and Abernethy, et al. [55]^c Range for the sum of K₂O and Na₂O

was found for the first sample of Stout ash, due to the presence of pyrite particles in the sample. The same reason may also explain the rather high values reported on Mitchell ashes. Considering the stoker furnace used at Perry station, the relatively high loss on ignition values are expected for this type of ash.

For comparison purposes, the results of chemical analysis reported by other investigators [3,42,54,55] are shown at the bottom of Table 25. In general, Indiana bottom ashes are reasonably typical in chemical composition, except the high content of iron in Stout ash. The ranges in contents and associated averages for each constituent in Indiana bottom ashes are presented graphically in Figure 32.

Grain Size Distribution

The results of the gradation analyses obtained by dry sieving each of the bottom ashes sampled at different times are presented graphically in Figures 33 through 43. As can be seen in these figures, dry bottom ash and wet bottom boiler slag have quite different gradation characteristics. Dry bottom ashes (Figures 34 through 43) exhibit well-graded size distribution ranging from fine gravel to fine sand sizes, whereas the gradation of the wet bottom ash (Figure 33) is quite uniform with a majority of the sizes occurring in a narrow range between the No. 8 and No. 30 sieves. The coefficient of uniformity (C_u) for bottom ashes range from 8

Figure 32. Variation in chemical constituents of bottom ash

Figure 33. As-sampled gradations of Schahfer Unit 14 ash

Figure 34. As-sampled gradations of Schahfer Unit 17 ash

Figure 35. As-sampled gradations of Gibson ash

Figure 36. As-sampled gradations of Perry ash

Figure 37. As-sampled gradations of Gallagher ash

Figure 38. As-sampled gradations of Mitchell ash

Figure 39. As-sampled gradations of Wabash ash

Figure 40. As-sampled gradations of Stout ash

Figure 41. As-sampled gradations of Brown ash

Figure 42. As-sampled gradations of Culley ash

Figure 43. As-sampled gradations of Richmond ash

to 50, while that for wet bottom ash is about 3. Table 26 summarizes the coefficient of uniformity and the coefficient of curvature (C_c) for all the bottom ashes studied, along with the resulting classification based on the Unified Soil Classification System (USCS). Of the 11 bottom ashes studied, ten (10) are classified as sand and the other one as gravel. The wet bottom ash is found to be poorly graded because of its low coefficient of uniformity. Richmond ash is also classified as poorly graded, due to the low value of the coefficient of curvature. Classification of bottom ashes by the AASHTO system [149] is presented in Table 27. All bottom ashes fall in the A-1 group, with 7 ashes classified as A-1-a and the remaining four as A-1-b.

The fine portions passing the No. 200 sieve for dry bottom ashes range from 0 to 12 percent, with an average of 4.4 percent. The wet bottom ash is essentially free of fines. Attempts were made to perform the Atterburg limits tests on the fines passing the No. 200 sieve. However, it was not possible to establish either a liquid limit or a plastic limit for the bottom ashes. Therefore, the fines present in bottom ashes are non-plastic.

The gradation curves for bottom ashes sampled at different times provide an indication of the potential variability in the gradation. Generally, lesser variations are found in bottom ashes which were handled and stored separately from fly ash. For power plants where bottom and

Table 26. Unified soil classification of bottom ashes

Ash Source	C_u^a		C_c^b		USCS ^c Classification
	First sample	Second sample	First sample	Second sample	
Schahfer Unit 14 ^d	3.7	2.7	0.7	1.4	SP
Unit 17	13	13	2.2	1.1	SW
Mitchell	22	12	3.0	2.1	GW
Gibson	8	14	1.8	1.4	SW
Gallagher	33	38	1.3	2.0	SW
Wabash	8	54	1.6	1.8	SW
Brown	17	30	2.6	3.0	SW
Culley	18	38	1.5	1.0	SW
Richmond	32	30	0.8	0.7	SP
Perry	8	8	1.4	1.5	SW
Stout	10	26	2.2	2.0	SW

^a Coefficient of uniformity = C_{60}/C_{10} ^b Coefficient of curvature = $C_{30}^2/(C_{60} \cdot C_{10})$ ^c Unified Soil Classification System^d Wet bottom ash

Table 27. AASHTO classification of bottom ashes^a

Ash source	Percent passing			AASHTO Classification
	No. 10 ^b	No. 40 ^c	No. 200 ^d	
Schahfer				
Unit 14	90	7	0	A-1-b
Unit 17	56	20	3	A-1-b
Mitchell	19	8	1	A-1-a
Gibson	62	25	4	A-1-b
Gallagher	49	23	8	A-1-a
Wabash	45	17	6	A-1-a
Brown	48	19	5	A-1-a
Culley	41	17	5	A-1-a
Richmond	63	38	13	A-1-b
Perry	46	12	4	A-1-a
Stout	31	12	5	A-1-a

^a All values reported are the average from two samples^b 2.00 mm^c 0.425 mm^d 0.075 mm

fly ashes were mixed in the storage, the variations in the gradation tend to be higher. Figure 44 illustrates the range of gradation for the 11 bottom ashes, as well as for fly ashes from the same sources, which was determined in a previous study [140]. The fines in bottom ashes are, in fact, composed of coarse fly ash particles.

Comparing the gradations of bottom ash with the specification limits given by the Indiana Department of Transportation (Table 6) shows that most dry bottom ashes would satisfy the gradation specifications for either the 1 in. or 1/2 in. top size materials. The wet bottom ash, being too uniform and coarse, falls outside the gradation specifications for bases and subbases.

Specific Gravity

The specific gravity of bottom ash, as determined by the test methods applicable to aggregates and soils, are tabulated in Table 28. As can be seen from the Table, the specific gravity of bottom ashes ranges from 1.9 to 3.4, which is much wider than that for most soils (ranges from 2.5 to 2.8 [74]). It is known that the specific gravity of bottom ash is a function of its chemical composition. Thus, the high specific gravity for Stout ash is explained by its extremely high iron content, which in turn results from the large amount of pyrite particles present in the first sample from Stout. Also, the high specific gravity (3.2) found on Culley ashes are not

Figure 44. Range of gradations for bottom and fly ashes

Table 28. Apparent specific gravity of bottom ashes

Ash source	ASTM C 128 ^a		ASTM D 854 ^b	
	1st ^c	2nd ^d	1st ^c	2nd ^d
Schahfer				
Unit 14	2.81	2.81	2.82	2.81
Unit 17	2.47	2.49	2.57	2.57
Mitchell	2.35	2.44	2.44	2.47
Gibson	2.50	2.50	2.55	2.54
Gallagher	3.05	2.57	3.07	2.64
Wabash	2.45	2.41	2.56	2.48
Brown	2.70	2.95	2.74	2.97
Culley	3.20	3.20	3.21	3.23
Richmond	2.79	2.25	2.90	2.40
Perry	1.84	1.60	2.12	1.94
Stout	3.43	2.40	3.46	2.45

^a Standard test method for specific gravity and absorption of fine aggregate

^b Standard test method for specific gravity of soils

^c The first sample from the source

^d The second sample from the source

unreasonable, considering the high iron content in the ash (30 to 31%). On the other hand, the low specific gravity values recorded for Perry ashes (1.9 to 2.1) indicate an appreciable closed or inaccessible porosity in this ash.

It should be noted from Table 28 that, for most bottom ashes, the specific gravity values determined by test methods for soils (ASTM D 854) are greater than those determined by test method for aggregates (ASTM C 128). The two test methods were carried out in the same pycnometer apparatus, but differed only in the techniques used in removing the entrapped air. The ASTM C 128 method removed air bubbles by agitating, rolling, and inverting the pycnometer, while boiling of the contents in the pycnometer was used in the ASTM D 854 method. A comparison of the results indicates that boiling is more effective in removing the entrapped air than agitating.

Of greater importance is the implication that bottom ash possesses a complex structure in its pore system. This is further demonstrated by comparing the results from the previous two water pycnometer tests with the specific gravity measured by the gas pycnometer, as shown in Table 29. The values obtained from the gas pycnometer are always greater than those determined by the water pycnometer tests, because some pores or voids can be penetrated by gas but not by water. Therefore, the variations in the specific gravity values recorded by different methods seem to provide an indicator of the degree of complexity in the pore structure of bottom

Table 29. Specific gravity of the first ash sample using different methods

Ash Source	ASTM C 128 ^a	ASTM D 854 ^b	Gas pycnometer
Schahfer			
Unit 14	2.81	2.82	2.83
Unit 17	2.47	2.57	2.61
Mitchell	2.35	2.44	2.57
Gibson	2.50	2.55	2.74
Gallagher	3.05	3.07	3.10
Wabash	2.45	2.56	2.56
Brown	2.70	2.74	2.75
Culley	3.20	3.21	3.19
Richmond	2.79	2.90	2.89
Perry	1.84	2.12	2.32
Stout	3.43	3.46	3.50

^a Standard test method for specific gravity and absorption of fine aggregate

^b Standard test method for specific gravity of soils

ashes. For example, the three specific gravity values reported on Schahfer 14 ash, which was determined to be hard, dense, and with a glassy surface texture, agree very well. On the other hand, Perry ash, with an extremely porous texture and the presence of popcornlike particles, shows a significant variation among the three specific gravity measurements.

Generally, the more porous or vesicular an ash appears, the greater the variation in the specific gravity determined by different methods. It is also found that low specific gravities are always accompanied by greater variations in the measurements. Thus, it is reasonable to state that a low specific gravity represents a highly porous or vesicular texture, which is the characteristic of popcornlike particles. Since popcornlike particles are readily degradable under loading or compaction, bottom ash containing a large amount of these particles may be undesirable for engineering purposes. Indeed, the results from the specific gravity tests suggest that the specific gravity of bottom ash may be used as an indicator of the material quality, as proposed by Anderson, et. al. [33].

Soundness

Only fine aggregate test using material passing the 3/8-in. sieve was performed. The fraction of bottom ash coarser than the 3/8-in. sieve is assumed to have the same loss as the next smaller size for which test data are available. The

sodium sulfate soundness losses on bottom ashes after five cycles of soaking and drying are presented in Table 30.

The soundness loss for bottom ashes tested in the study varies from 1.3 to 10.8 percent. As expected, the wet bottom ash has the lowest sulfate soundness loss because of its glassy surface texture and its low porosity. Significant differences between the soundness losses of the coarse and fine fractions of wet bottom ash have been reported in the literature [33,38]. Due to the lack of coarse particles in the wet bottom ash studied, the comparison of the losses between the coarse and fine fractions is not possible. However, no noticeable difference on the soundness loss is observed in the size range tested. In fact, there is no evidence demonstrating the existence of residual stress in particles of the wet bottom ash studied. This residual stress, resulting from the quenching of the molten ash, has been identified by researchers [30,33,38] as the cause of the high soundness loss found on wet bottom ash.

The soundness losses for dry bottom ashes ranged from about 2 to 6 percent except for Perry ash produced from stoker furnaces. The presence of porous and popcornlike particles has caused a significant increase in the soundness loss of Perry ash (10.8 percent). On the basis of the specification limits given by Indiana Department of Transportation [53] all bottom ashes studied would be considered adequate for class A subbase material.

Table 30. Sulfate soundness of bottom ashes^a

Ash Source	sodium sulfate soundness loss (%) ^b
Schahfer	
Unit 14	1.3
Unit 17	2.8
Mitchell	5.5
Gibson	2.8
Gallagher	2.2
Wabash	3.0
Brown	6.7
Culley	3.9
Richmond	2.2
Perry	10.8
Stout	6.3
Crushed limestone ^c	12.9
Natural river aggregate ^c	10.3
INDOT specifications	
Class C subbase	16.0
Class A subbase	12.0

^a Fine aggregate test only

^b Weighted loss after 5 cycles of
soaking and drying

^c From Usmen [38]

The behavior of bottom ashes during the soundness test was carefully inspected to gain insight into the nature of disintegration occurring in ash particles. It was observed that appreciable drainage of the sulfate solution from the large pores of the coarser particles takes place prior to the placement of the specimens into oven for drying. This has greatly reduced the salt crystallization in ash particles during drying. Consequently, it was possible to identify some very porous particles which could be crushed with fingers after five cycles of the soaking and drying. It is likely that the test would predict the freeze-thaw durability of bottom ashes. However, the sulfate soundness test is not recommended to discriminate among bottom ashes for quality.

Los Angeles Abrasion

The percent wear values determined by the Los Angeles abrasion test on bottom ashes are summarized in Table 31. The gradings used for bottom ash samples, as shown in the Table, were selected to represent the particle sizes occurring in the largest quantities of the ashes. As can be seen from this Table, all ashes, but one, have Los Angeles abrasion values less than 50. Therefore, all of the bottom ashes studied, except one, would meet the ASTM D 1241 and AASHTO M 147 specifications for soil-aggregate base and subbase [50]. Some samples have abrasion values greater than 40 but less than 45. Thus, most bottom ashes would meet the specifications given by

Table 31. Results of the Los Angeles abrasion test

Material	Grading	% wear	ratio ^a 100/500
Schahfer			
Unit 14	- ^b	-	-
Unit 17	D	38	0.35
Mitchell	C	36	0.30
Gibson	D	34	0.39
Gallagher	D	37	0.31
Wabash	D	41	0.32
Brown	D	45	0.38
Culley	C	40	0.38
Richmond	- ^b	-	-
Perry	D	48	0.42
Stout	C	43	0.30
Crushed limestone ^c	B	16	
Indiana carbonate aggregate ^d		24-39	
ASTM D 1241 soil-aggregate subbase, base, and surface		50	
AASHTO M 147 aggregate base and subbase		50	
INDOT specifications			
Class C subbase		45	
Class A subbase		40	

^a The ratio of the loss after 100 revolutions to the loss after 500 revolutions

^b Denotes samples with less than 10 percent coarser than the No. 8 sieve

^c From Usmen [38]

^d From Aughenbaugh, et al. [158]

INDOT for class C subbase, and some ashes are able to meet the specifications for class A subbase [53]. However, it can also be noted from Table 31 that none of the bottom ashes show the abrasion resistant quality possessed by conventional aggregates [38].

The ratio of the loss after 100 revolutions to the loss after 500 revolutions provides an indication of the uniformity of the material hardness. A value of the ratio close to 0.2 represents an uniform hardness of the material tested. The ratios obtained from bottom ash samples range from 0.28 to 0.39, which indicates that more particle breakdowns occurred during the early stage of the test. This is understandable because the weaker and popcornlike particles readily break under the impact during the initial revolutions of the abrasion test.

A comparison between the sulfate soundness losses and abrasion values reveals that bottom ashes with high sulfate soundness losses also have high percentage wears under an abrasion test. Since the applicability of the sulfate soundness test on bottom ash material has been previously questioned, the Los Angeles abrasion test may provide a superior measure of the quality of bottom ash as an aggregate. However, a shortcoming of the Los Angeles abrasion test as applied to bottom ash is that the test is designed for four gradations, on the assumption that the materials tested will fall within one of the four gradation limits. With materials

like many bottom ashes, having high percent fines (finer than the No. 8 sieve), only a small portion of the sample may fall within the specified gradations. In this study, only 15 to 30 percent of any sample could be used in abrasion testing, so the results may not represent the abrasion potential of the entire sample.

Visual inspections on the fines (passing the No. 12 sieve) produced from bottom ashes were performed after the test. In contrast to the powdery fines produced from natural aggregates, the fines produced from bottom ashes were intermediate in size and appeared as small broken pieces of larger ash particles, having angular shape and porous texture. A similar observation was reported by Usmen [38] and Usmen et. al. [65] on selected West Virginia bottom ashes.

It was also reported that due to the lightweight nature of the porous and popcornlike particles, some ash particles might escape the abrasion process and could still be crushed with fingers after the abrasion test [38]. Practically, no such phenomenon was observed in this study.

Relative Density and Void Ratio

The maximum and minimum densities of selected bottom ashes, along with the corresponding minimum and maximum void ratios, are summarized in Table 32. The results show significant variations from plant to plant, primarily reflecting the specific gravity and the gradation of the

Table 32. Maximum and minimum void ratios and densities of selected bottom ashes

Material	Void ratio		Unit weight (pcf)	
	Maximum	Minimum	Maximum	Minimum
Schahfer				
Unit 14 ^a	0.82	0.48	118.3	96.3
Unit 17	1.23	0.68	95.5	72.0
Gibson	0.87	0.51	105.5	85.5
Perry ^b	2.92	1.53	52.3	33.8
Gallagher	0.99	0.55	106.7	82.9
Standard				
Ottawa sand ^c	0.80	0.50	110.0	92.0
Fine to coarse sand ^c	0.95	0.20	138.0	85.0
Silty sand and gravel ^c	0.85	0.14	146.0	89.0

^a Wet bottom ash

^b Stoker ash

^c From Hough [74]

ashes. The wet bottom ash (Schahfer Unit 14) has the highest densities, with a maximum of 118.5 pcf and a minimum of 96.3 pcf. Due to a highly porous nature, Perry ash has the lowest densities of 57.3 and 37.0 pcf as the maximum and minimum densities, respectively. Similarly, void ratios obtained from bottom ashes also show a wide range, varying from 0.48 to 1.31 for the minimum and 0.82 to 2.58 for the maximum.

When compared to the density and void ratio of natural soils with similar gradings (Table 32), the wet bottom ash has densities comparable to Ottawa sand; and most bottom ashes yielded much larger minimum void ratio than natural sands. However, the maximum void ratios for bottom ashes and natural sands are quite similar. In general, both the maximum and minimum densities for samples of bottom ash are somewhat lower than those for most sands. However, most bottom ashes would meet the ASTM specifications requiring the unit weight of slag for bituminous mixtures larger than 70 pcf. Current INDOT specifications on unit weight of steel furnace slag range from 70 to 75 pcf, depending on aggregate class.

Permeability

Table 33 gives the results of falling head permeability tests conducted on bottom ashes at a relative density of approximately 90 percent. The measured coefficients of permeability ranged from 0.003 to 0.10 cm/sec for selected bottom ashes. The wet bottom ash (Schahfer unit 14) displays

Table 33. Coefficients of permeability of bottom ashes

Material	Void ratio	Percent fines ^a	Coefficient of permeability k (cm/sec)	Hazen's C ^b
Schahfer				
Unit 14 ^c	0.51	0.3	0.101	0.57
Unit 17	0.73	3.5	0.034	0.85
Gibson	0.55	6.5	0.009	0.45
Perry ^d	1.44	5.9	0.014	0.12
Gallagher	0.59	10.1	0.003	0.53
Uniform coarse sand ^e			0.4	
Well-graded sand and gravel ^e			0.01	

^a Percent finer than the No. 200 sieve (0.075 mm)

^b $C = k/D_{10}^2$

^c Wet bottom ash

^d Stoker furnace

^e From Hough [74]

the largest value of coefficient of permeability due to its uniform size distribution and absence of fines. Generally, the coefficients of permeability of bottom ash fall in a medium permeability range (Table 33), and are comparable to those of granular soils with similar gradings.

It can also be noted from Table 33 that the percentages of fines have a predominant effect on the permeability of bottom ash. This can be expected because finer particles in a soil are known to have the most influence on the permeability. Based on Hazen's equation, a consistent relationship between the coefficient of permeability (k) and the effective grain size (D_{10}) exists in clean sands as

$$k = C D_{10}^2$$

The calculated C constant in Hazen's equation varies from 0.1 to 0.9 for bottom ash samples. Considering the wide range of coefficient for soils, the Hazen's equation may be used in estimating the coefficient of permeability for bottom ashes, when testing is not practicable.

Angle of Shearing Resistance

In order to determine the angle of shearing resistance ϕ' , a series of direct shear tests were conducted on dry bottom ashes at various relative densities. The normal stress varied from 5 to 34 psi. Figures 45 through 49 present the results of these tests on ash samples in different relative

Figure 45. Results of direct shear test on Perry ash

Figure 46. Results of direct shear test on Gallagher ash

Figure 47. Results of direct shear test on Gibson ash

Figure 48. Results of direct shear test on Schahfer 17 ash

Figure 49. Results of direct shear test on Schahfer 14 ash

densities. It is noted that a straight line fitted to the failure values yields a small strength intercept. The measured angles of shearing resistance along with the strength intercepts are summarized in Table 34. The values of ϕ' in this Table represent those corresponding to the peak strength, which is considerably higher than the value calculated from the ultimate strengths of compacted dense samples, which expand during shear. On the other hand, because loose samples did not exhibit this peak during shear, the values of ϕ' for bottom ashes in a loose condition were determined at a strain of 15 percent.

The angles of shearing resistance for bottom ash samples in a loose condition are quite large in magnitude, ranging from 35 to 45 degrees. These values are compared to the values obtained from conventional granular soils, as tabulated in Table 34. It is found that the angle of shearing resistance for the wet bottom ash falls within the same range as that for conventional soils. The values obtained from dry bottom ashes are higher than those from conventional soils. This can be attributed to the rough surface texture and angularity of the bottom ash particles, such that a higher degree of interlocking was developed in the shear process. However, it is generally believed that the angles of shearing resistance from direct shear tests are greater by 2 degrees than those from triaxial tests [73,150].

Table 34. Results of direct shear tests on bottom ashes

Material	Loose		Dense	
	Strength intercept (psi)	Values of ϕ' , deg	Strength intercept (psi)	Values of ϕ' , deg
Schahfer				
Unit 14 ^a	0.48	35.1	1.49	46.3
Unit 17	0.14	39.2	3.12	47.7
Gibson	0.20	44.8	1.66	55.0
Gallagher	0.49	41.3	2.00	51.6
Perry	0.49	41.5	3.00	50.6
Medium sand, angular ^b		32-34		44-46
Sand and gravel ^b		34		45
Well graded, angular sand ^c		39		45
Well graded rounded sand ^c		34		40

^a Wet bottom ash^b From Leonards [75]^c From Sowers [93]

Bottom ashes tested in a dense condition yielded angles of shearing resistance approximately 8 to 10 degrees larger than those in a loose condition. The strength intercepts are also larger in a dense state. This can be expected because the curvature of the Mohr envelope increases as a granular soil becomes denser [73]. It should be pointed out that because of the possibility of progressive failure in backfill or embankment, use of ϕ' corresponding to the peak value may not be warranted. Burmister suggested that only 50 to 75 percent of the increase of the value of ϕ over its value at a very loose state be used, depending on the amount of restraint against progressive failure [151].

If bottom ash is used as an embankment material, based on present test results, the stability of the embankment can be higher than that for natural granular soils. If it is used in highway subgrades or subbases, the bearing value may be higher than that encountered with a natural sand.

Moisture-Density Relations

The relationship between dry density and moisture content was determined by the standard Proctor compaction procedures for several bottom ash samples [15]. Samples were tested at a range of moisture contents from air-dried to essentially saturated. The resulting moisture-density relations are presented in Figures 50 through 53. The shapes of the moisture-density curves are typical of those for cohesionless

Figure 50. Moisture-density relations for Schahfer 14 ash

Figure 51. Moisture-density relations for Schahfer 17 ash

Figure 52. Moisture-density relations for Gibson ash

Figure 53. Moisture-density relations for Gallagher ash

materials [81,82]. The dry densities obtained are high when the soil is air-dried, and high when the soil is completely saturated, with somewhat lower densities occurring when the soil has intermediate water contents. As discussed earlier, the low densities obtained at intermediate water contents, frequently called "bulking", are due to capillary forces resisting rearrangements of the sand grains [73,151]. This bulking phenomenon is not present in air-dried samples and disappears in the saturated state.

The compaction curves show a slight decrease in density at the highest water contents. Field compaction data reported on free draining materials indicates that field compaction curves do not show such a decrease [79,152]. Field curves generally exhibit maximum dry density at either an air-dried condition or a "flushed" condition. This can be better illustrated by plotting the dry density versus the water content prior to compaction, as in Figures 50 through 53, because some loss of water occurred during compaction at high water contents.

Sometimes, the air-dried condition may not be practicable for field construction, but it is practicable to maintain the material in a flushed condition during the compaction process. If adequate measures have been taken to protect the underlying layers, close control of the water content will not be necessary, and the flushed condition can be achieved simply by applying an excess of water. Although the differences in

laboratory densities between the bulking water content and the flushed condition are only about 5 pcf, the differences are expected to be greater for field compaction. Therefore, it is necessary to maintain a high water content to achieve the greatest densification.

The maximum dry densities and optimum moisture contents determined by the compaction tests on bottom ashes are summarized in Table 35. Because of the wide variation in the specific gravities of ashes, a normalized density appears to be a better indicator of the degree of densification in the compacted materials than the dry density. The normalized density is obtained by dividing the dry density of the material by its specific gravity

$$\gamma_n = \frac{\gamma_d}{(G_s)(\gamma_w)} = \frac{V_s}{V} = 1 - \frac{V_v}{V}$$

where γ_n = normalized density

γ_d = compacted dry density

G_s = specific gravity of the solids

γ_w = density of water

V_s = volume of solids

V = total volume, and

V_v = volume of voids.

The specific gravity and the normalized density of the materials tested are also shown in Table 35. It is seen that,

Table 35. Moisture-density properties of bottom ashes

Material	Optimum moisture content (%)	Maximum dry density γ_d (pcf)	Specific gravity ^a G_s	Normalized maximum dry density γ_n^b
Schahfer				
Unit 14 ^c	12.9	112.2	2.81	0.639
Unit 17	21.5	95.4	2.57	0.594
Gibson	19.5	101.3	2.55	0.637
Gallagher	16.1	108.7	2.64	0.660
Perry ^d	40.8	63.0	2.12	0.476
Brown	20.8	102.1	2.74	0.597
Crushed LS aggregate ^e	8.9	130.6	2.72	0.769
Natural river aggregate ^e	10.5	123.2	2.66	0.742

^a As determined by ASTM Designation D 854

^b $\gamma_n = \gamma_d / (G_s)(\gamma_w)$, where γ_w is the density of water

^c Wet bottom ash

^d Stoker ash

^e From Usmen [38]

when compared to conventional materials, bottom ashes have lower normalized maximum dry densities which indicate high air voids in the bulk compacted volume. This can be attributed to the rough, gritty surface texture and irregular shape of the bottom ash particles.

Degradation

During the compaction process, fracturing and abrasion break down individual ash particles. The result is a compacted material that has a gradation different from that of the uncompacted material. The degradation of bottom ash samples occurring under standard Proctor compaction (ASTM D 698) at optimum moisture content is presented in Figures 54 through 58. It can be seen from Figure 54 that the wet bottom ash underwent essentially negligible degradation under compaction, due to the hard and dense nature of wet bottom ash particles. On the other hand, dry bottom ash samples exhibited substantial degradation upon compaction. As can be expected on the basis of the soundness and Los Angeles abrasion test results, Perry ash showed the most severe degradation upon compaction.

In order to quantify the degradation, the "index of crushing" and the increase in percent passing the No. 200 sieve are evaluated. The increase in percent passing the No. 200 sieve provides information on the amount of fines generated. The index of crushing, as developed by the British

Figure 55. Gradations of Schahfer 17 ash before and after compaction

Figure 56. Gradations of Gibson ash before and after compaction

Figure 57. Gradations of Perry ash before and after compaction

Figure 58. Gradations of Gallagher ash before and after compaction

Road Research Laboratory [153], evaluates the general breakdown in the aggregate over a size range of the 3/4 in. to the No. 100 sieves. It is a gradation index based on the summation of the weighted fractions of several size groups. Hale, et al. [154] have used the index of crushing successfully as a measure of shale degradation during compaction. It is obtained by calculating the weighted mean size of the aggregate sample before and after compaction and expressing the percent reduction between the two mean sizes based on the initial mean size. As the numerical value increases, the degree of crushing increases [155]. A sample calculation form for the index of crushing is shown in Appendix B.

Values of the index of crushing and the increase in percent of fines for bottom ashes and several conventional aggregates are shown in Table 36. The indices of crushing for bottom ashes are found to be higher than those of conventional aggregates. Again, this is attributed to the breakdown of the weak and porous particles present in the materials.

It has been reported that excessive amounts of plastic fines produced from aggregate degradation are responsible for the loss of base course support, the reduction of drainage, and the creation of frost-susceptible material [156,157]. It is interesting to note that the increases in percent fines for bottom ashes are less than those for conventional aggregates, with the exception of Perry ash. Besides, the fines produced

Table 36. Degradation of bottom ashes under compaction

Material	Percent fines			Index of crushing %
	Before compaction	After compaction	Increase	
Schahfer				
Unit 14 ^a	0.3	0.4	0.1	4.8
Unit 17	2.5	3.5	1.0	11.5
Gibson	6.1	6.5	0.4	10.0
Gallagher	9.4	10.1	0.7	5.1
Perry ^b	2.6	6.1	3.5	32.6
Crushed limestone aggregate ^c	3.0	6.0	3.0	4.9
Natural river aggregate ^c	1.0	3.0	2.0	6.5
Carbonate aggregate ^d	0.0	1.0-2.2	1.0-2.2	8-15

^a Wet bottom ash

^b Stoker ash

^c From Usmen [38]

^d From Aughenbaugh, et al. [158]

from bottom ashes are known to be non-plastic. Therefore, the detrimental effect of bottom ash degradation may not be as severe as that suggested by the index of crushing. Furthermore, aggregate degradation is not always detrimental. The limited breakdown during placement of the aggregate can be beneficial in producing the desired density [158].

Nevertheless, continued degradation allows further densification to occur in the aggregate mass as the particles are reduced in size and differential settlement can develop. Although this detrimental effect has not been identified positively as a principal cause of highway settlement, it appears that there should be further research efforts to study the densification effect upon degradation.

One-Dimensional Compression

One-dimensional compression tests were performed on bottom ashes in a dense condition. The samples were densified using a vibratory table. One bottom ash (Schahfer Unit 14) experienced a small swelling of 0.07 percent after the 24-hour soaking period and the swelling pressure was found to be only 6 psi. Due to the high permeability of bottom ash, the deformations took place almost immediately. All specimens were also maintained at the maximum stress for at least 24 hours to allow creep to develop. Only one of the bottom ashes produced measurable creep. A small amount of creep of 2 percent was observed on Perry ash.

The stress-strain relationships for several bottom ashes obtained from one-dimensional compression tests are presented graphically in Figures 59 and 60. In order to relate the compressibility of bottom ashes to more familiar soil materials, the stress-strain curve obtained from an uniform medium sand is also shown in the Figures 59 and 60 [89]. It can be seen that bottom ashes are slightly more compressible than the sand.

Two factors are believed to contribute to this finding. The first is the angularity and rough surface texture of bottom ash particles. Sands with angular particles are known to be more compressible than the well-rounded sands, because the sharp edges become overstressed during movement and reorientation of the particles and hence break to allow compression [88,89]. The second factor is the presence of weak and popcornlike particles. These particles break at a relatively low stress level resulting in increased deformations.

If bottom ash is used as a fill material the compression of the bottom ash layer is usually estimated by elastic theory. When vertical loads of large lateral extent are applied to the bottom ash layer, the compression behavior becomes one-dimensional and the parameter used in estimating settlement is the secant constrained modulus. The secant constrained modulus is the rate of change of vertical stress

Figure 59. One-dimensional compression curves for bottom ashes and a medium sand

Figure 60. One-dimensional compression curves for bottom ashes and a medium sand

with respect to the vertical strain under conditions of zero lateral strain, and can be expressed as

$$D = \frac{\Delta \sigma_v}{\Delta \epsilon_v} = \frac{\sigma_{v2} - \sigma_{v1}}{\epsilon_{v2} - \epsilon_{v1}}$$

where D = secant constrained modulus,

ϵ_{v1} = vertical strain at a stress level of σ_{v1} , and

ϵ_{v2} = vertical strain at a stress level of σ_{v2} .

Figure 61 shows the secant constrained modulus calculated from zero stress to various stress levels. A comparison is made between the constrained moduli for bottom ash and those for a uniform medium sand [89], and the results are shown in Table 37. It is found that the moduli for one ash (Schahfer Unit 14) are comparable to those of the well graded sand. The values for the other two ashes are somewhat lower than those for sand, especially at the high stress level. The crushing of angular particles at high stress may play an important part in this phenomenon [90].

California Bearing Ratio (CBR)

In this study, at least two samples were prepared for each moisture content and density condition and the CBR values obtained from these two samples averaged. Results of the test on selected bottom ashes are summarized in Table 38. As

Figure 61. Constrained modulus vs. vertical stress curves for bottom ashes and a medium sand

Table 37. Secant constrained modulus of bottom ashes

Materials	Constrained modulus (ksi)			
	Relative density, %	$\sigma_{v1}=6$ ksi $\sigma_{v2}=13$ ksi	$\sigma_{v1}=112$ ksi $\sigma_{v2}=146$ ksi	
Schahfer				
Unit 14 ^a	98	7.5		21.2
Unit 17	91	5.1		7.1
Gibson	85	3.8		12.0
Gallagher	90	4.4		10.6
Perry ^b	95	2.6		1.6
Uniform medium sand ^c (0.1 mm < d ^d < 0.6 mm)	89	7.8		25.9

^a Wet bottom ash^b Stoker ash^c From Schultze and Moussa [89]^d d = particle size

Table 38. CBR test results on selected bottom ashes

Ash source	Initial Moisture content ^a (%)	CBR			
		Unsoaked		Soaked	
		at 0.1 in.	at 0.2 in.	at 0.1 in.	at 0.2 in.
Schahfer Unit 14 ^b	0.2	36	40	46	53
	8.5	40	47	39	46
	10.6	44	51	38	47
	12.8	41	51	45	52
	14.1	45	52	41	47
Schahfer Unit 17	14.3	44	48	47	52
	18.1	46	52	46	48
	20.9	41	47	40	48
	22.3	50	59	47	50
	24.1	45	53	43	49
Gibson	0.4	59	70	58	70
	13.8	50	55	43	53
	17.4	54	67	51	63
	20.0	45	56	47	58
	22.4	50	60	45	54

^a Water content prior to compaction^b Wet bottom ash

suggested by Yoder and Witczak [48], granular soils often yield erratic results from the CBR test. The CBR values in this study have an average coefficient of variation of about 29 percent.

As can be seen from Table 38, soaking does not affect the CBR of bottom ashes, which is to be expected because of the granular nature of bottom ash [160]. An unusual finding is that, in all cases, the 0.1-in CBR value is less than the 0.2-in value. A similar phenomenon was also reported by Franco and Lee [145] on a set of sandy gravel base course materials which were classified as A-1-a and A-1-b by the AASHTO system. Note that of the 11 bottom ashes studied, 7 are classified as A-1-a and the remaining 4 as A-1-b. The CBR values for bottom ash range from 40 to 70. Compared to the typical values for a number of soils and base course materials, bottom ash falls in the categories of "good subbases" and "good gravel bases" on the basis of the CBR values [161].

Figures 62 through 64 show the moisture-density-CBR relations of bottom ashes. In general, the shapes of the CBR curves follow the same pattern as those of the compaction curve. Although the CBR curves have their peaks to the dry side of optimum moisture content, the CBR values at the wet side of the peak are higher than those at the dry side. As discussed previously in the Compaction section, this again suggests that it is advantageous to compact bottom ash in a flushed condition.

Figure 62. Moisture-density-CBR relations for Schahfer 14 ash

Figure 63. Moisture-density-CBR relations for Schahfer 17 ash

Figure 64. Moisture-density-CBR relations for Gibson ash

Mechanical Stabilization

Densification Behavior

The relationship between maximum dry density and the proportion of bottom ash and fly ash for selected ash sources are shown in Figures 65 through 68. In these figures, the maximum dry density obtained from various proportions of bottom ash-fly ash mixtures have been plotted versus the percentages of bottom ash and fly ash. The complete set of compaction curves for the bottom ash-fly ash mixtures from which the results were extracted are presented in Appendix C.

By referring to Figures 65 through 68 the effect of fly ash on the maximum density of bottom ash-fly ash mixtures is clearly illustrated. It is evident that the densities can be improved by combining bottom ash with fly ash. The addition of fly ash to bottom ash at first increases the maximum density as the fine-grained fly ash fills the voids in bottom ash skeleton. As the amount of fly ash increases, the density increases until the voids are filled with fly ash, and then decreases as the amount of fly ash is increased beyond this point. Thus, there is a definite optimum fly ash content at which the density of bottom ash-fly ash mixtures is highest. The highest density of bottom ash-fly ash mixtures is greater than that of either the bottom ash or the fly ash, and it is

Figure 65. Maximum density and optimum moisture for various proportions of Gibson bottom and fly ashes

Schahfer 17

Figure 66. Maximum density and optimum moisture for various proportions of Schahfer 17 bottom and fly ashes

Figure 67. Maximum density and optimum moisture for various proportions of Schahfer 17 bottom ash and Schahfer 14 fly ash

Figure 68. Maximum density and optimum moisture for various proportions of Schahfer 14 bottom and fly ashes

approximately 22 lb per cubic ft or 21 percent greater than their average.

Figure 69 shows the densification behavior of bottom ash-fly ash mixtures by plotting the normalized density of the mixtures versus the proportions of bottom ash and fly ash. Schahfer 17 ash mixtures have relatively lower normalized density because particles of this bottom ash are more porous and vesicular than those of Gibson bottom ash, as revealed by the greater difference between two specific gravity measurements (Table 28). Particles of Schahfer 14 ash (wet type) are practically poreless; however, the ash is uniformly graded. As a result, the normalized densities of this ash are slightly lower than those of Gibson ash, which is well-graded and has a relatively low vesicularity in surface texture.

In order to examine the densification mechanism of bottom ash-fly ash mixtures, the absolute volumes of bottom ash, fly ash, and voids in the mixtures were computed for a typical ash (Gibson). The results are illustrated in Figure 70. In this figure, the absolute volume of voids in the bottom ash-fly ash mixtures is indicated by curve ABC. The ordinates between curves ADE and FE and those between curves ABC and ADE represent the absolute volume of bottom ash and fly ash, respectively.

Based on the assumption that both bottom ash and fly ash had no change in their void characteristics when they are combined, lines AE and AC represented the absolute volumes of

Figure 69. Densification behavior of various bottom ash-fly ash mixtures

Figure 70. Absolute volumes of bottom ash, fly ash, and voids in Gibson ash mixtures

bottom ash and fly ash in various mixtures; and the absolute volume of the voids would be represented by the ordinates of line AC. However, the actual absolute volumes of bottom ash and fly ash have been computed to be larger than those assumed. The difference between the actual and assumed volume of bottom ash is represented by the ordinates between the lines AE and ADE; and that of fly ash is represented by the ordinates between lines AC and AGC, or the ordinates between AC and ABC minus the ordinates between AE and ADE.

It can be seen in Figure 70 that the addition of fly ash to bottom ash obviously reduces the particle interference and facilitates the rearrangement of bottom ash particles. Thus, a closer association can be achieved upon compaction by incorporating fly ash in bottom ash. The concurrent increase in the absolute volume of fly ash can be attributed to the voids of bottom ash being filled with fly ash.

The increases in the absolute volume of bottom ash are relatively greater in lean mixes due to the fact that since there is only a small amount of fly ash between bottom ash particles, there is a greater possibility of pushing the bottom ash particles together and decreasing the void space that is taken up by fly ash in the richer mixes.

Load-Deformation Characteristics

The load-deformation characteristics of the bottom ash-fly ash mixtures were investigated using CBR test. Two tests

were performed on each bottom ash-fly ash mixture compacted at optimum moisture content. One test was performed on as-compacted specimens and the other after a 4-day soaking.

Some of the bottom ash-fly ash mixtures showed a decrease in penetration resistance after increasing rapidly from zero load to a maximum at approximately 0.3 inch penetration, and then increased again at deeper penetrations. This type of penetration curve showed a shear failure and was accompanied by heaving of the material surrounding the piston. Considering this, the critical bearing value in this series of tests was taken as the ultimate penetration resistance at 0.5 inch penetration to avoid the inconsistencies that might arise if the bearing value at smaller penetration was used.

Figure 71 presents the results of the CBR tests from various bottom ash-fly ash mixtures. Qualitatively, the relationship between CBR value and the proportions of bottom ash and fly ash is similar to that between maximum density and ash proportions. The CBR value increases with small amounts of fly ash until maximum CBR is reached, and then it decreases as the fly ash content is increased beyond this value. However, it is noted that the maximum CBR is obtained with 10 to 15 percent fly ash, which is significantly less than the optimum of 25 percent as determined by the compaction tests. This can be attributed to the decrease in the amount of bottom ash (aggregate) resulting from the increase in fly ash content from 15 to 25 percent. By referring to Figure 70, it can be

Figure 71. CBR values and percent swelling of various proportions of Gibson bottom ash-fly ash mixtures

seen that the amount of bottom ash remains practically constant as the fly ash content is increased from 0 to about 15 percent. In this range, the bearing value increases as a result of the decrease in the volume of voids (or increase in density). Then, as the fly ash content increases from 15 percent, the increase in density is small (Figure 65) and the amount of bottom ash decreases rapidly, which in turn accounts for the decrease in CBR.

Similar tests conducted on conventional soil-aggregate mixtures indicated that the disagreement in the optimum soil contents for strength and density was only 0 to 3 percent [94,99]. Considering the irregular shape and porous, gritty surface texture of bottom ash particles, it is hypothesized that there are voids between bottom ash particles not readily accessible to fly ash (fines). At the optimum fly ash content for strength (10 to 15 percent in Figure 71), the easy-to-fill voids are essentially filled up with fly ash. Further increase in fly ash content increases the possibility of filling the hard-to-fill voids and slightly increases the density; concurrently, the amount of fly ash surrounding bottom ash particles also increases. As a result, the strength of the mixture in terms of CBR decreases. In other words, it is not possible to fill these hard-to-fill voids without destroying the grain-to-grain contacts between bottom ash particles. As the amount of fly ash is increased to the optimum for density, bottom ash floats in the matrix of

compacted fly ash and both strength and density of the mixture start to decrease.

From the grain size distribution of bottom and fly ashes, it is possible to find the range of fly ash content that would satisfy the ASTM and AASHTO requirements for soil-aggregate materials (Table 5). These limits are shown in Figure 72. As can be seen in this figure, the proportions for maximum density are outside the specified limits while those for maximum strength lie close to the upper limits of the two specifications. Since the strengths of mixtures at the lean side of the optimum are only slightly smaller than the maximum strength, the specifications are considered applicable to bottom ash-fly ash mixtures.

Cement Stabilization

Because one of the fly ashes collected was found to be self-cementing (Class C fly ash), it was decided to evaluate the feasibility of stabilizing bottom ash using Class C fly ash as the sole stabilizing agent. In this phase of the study the strength development characteristics of the mixtures were investigated using the unconfined compressive test, instead of the CBR test.

The relationship between the 7-day compressive strength and fly ash content for various mixtures is presented in Figures 73 and 74. For the two bottom ashes tested, the maximum strength was attained at fly ash contents of 25 and 35

Figure 72. Maximum density and CBR values for various proportions of Gibson ash mixtures

Figure 73. Seven-day compressive strength for various proportions of Schahfer 17 bottom ash and Schahfer 14 fly ash

Figure 74. Seven-day compressive strength for various proportions of Schahfer 14 bottom and fly ashes

percent. And these contents agree with the optimum fly ash contents determined by compaction tests. This indicates that Class C fly ash in the mixtures functions both as a cementing agent to provide cementation and as a binder to densify the mixture. The maximum 7-day compressive strengths obtained from the two bottom ashes are approximately 1700 and 900 psi, which are well above the minimums often specified for cement stabilized base courses. Further increase in fly ash content results in a reduction in compressive strength. It is probable that at higher fly ash contents, more heat of hydration was generated accelerating hydration of the ash prior to compaction. Also, various degrees of cracking were noted on the surfaces of specimens containing more than 40 percent Class C fly ash.

Limited experience on Class C fly ash stabilized bases indicated that fly ash has a very short initial set time [102-104]. In some cases this initial set can occur within 10 minutes. The fast-setting characteristics of Class C fly ash is not within the scope of this study. However, it should be pointed out that, if Class C fly ash is to be used as a stabilizing agent, it is necessary to use a retarder to delay the time to initial set.

The unconfined compressive strengths obtained on cement treated bottom ash and bottom ash-fly ash after 7 days of moist curing are summarized in Table 39. In Figures 75 and 76, the data listed in Table 39 are presented graphically for

Table 39. Compressive strength of cement stabilized bottom ashes and bottom ash-fly ash mixtures^a

Mixture composition (percent by weight)	7-day compressive strength (psi)
<u>Gibson ash</u>	
75% BA ^b + 25% FA ^c	35
90% BA + 10% PC ^d	752
75% BA + 15% FA + 10% PC	1823
75% BA + 17.5% FA + 7.5 % PC	1297
75% BA + 20% FA + 5% PC	837
94% BA + 6% PC	265
75% BA + 19% FA + 6% PC	1106
75% BA + 22% FA + 3% PC	817
<u>Schahfer 17 ash</u>	
70% BA + 30% FA	19
90% BA + 10% PC	535
70% BA + 20% FA + 10% PC	1450
70% BA + 25% FA + 5% PC	733
94% BA + 6% PC	221
70% BA + 24% FA + 6% PC	861
70% BA + 27% FA + 3% PC	361

^a Strengths are the average of two tests

^b Denotes Bottom Ash

^c Denotes Fly Ash

^d Denotes Portland Cement, Type I

Figure 75. Compressive strength of cement stabilized Gibson ash mixtures

Figure 76. Compressive strength of cement stabilized Schahfer 17 ash mixtures

the two bottom ashes tested. It is seen that, in all cases, the addition of cement results in marked increases in compressive strength of bottom ash and bottom ash-fly ash specimens.

By referring to Figures 75 and 76, it is noted that the compressive strengths of cement treated bottom ash-fly ash mixtures are higher than those of cement treated bottom ash alone. This indicates that the addition of fly ash has a beneficial effect in the stabilization of bottom ash with cement. As a matter of fact, with the addition of an appropriate amount of fly ash, the cement content in bottom ash can be reduced by 50 percent and still has comparable compressive strength. For example, Gibson bottom ash treated with 10 percent cement has a compressive strength of 780 psi while a mixture containing 75 percent Gibson bottom ash, 20 percent fly ash, and only 5 percent cement has a strength of 840 psi.

The relatively lower strengths of cement-stabilized Schahfer 17 ash can be attributed to two factors: the low particle strength of this ash and the high air voids in the bulk compacted volume. Inspection of the failed specimens after compression tests revealed that a portion of the failures occurred by the breaking of bottom ash particles. It is known that Schahfer 17 bottom ash particles are more vesicular than Gibson ash particles. More vesicular particles are weaker in particle strength. Also, as depicted in Figure

69, the normalized density of Schahfer 17 ash mixtures are lower than those of Gibson ash mixtures. This indicates higher air voids in the compacted mixtures. Consequently, cement treated Schahfer 17 ash is weaker than cement treated Gibson ash. Nevertheless, the compressive strengths of bottom ash-fly ash mixtures stabilized with only 3 to 6 percent cement are considered adequate for use in base and subbase courses, according to the strength criteria cited in Table 15.

Leachate Properties

In order to evaluate the leaching potential of bottom ash, the Extraction Procedure (EP) toxicity test and an Indiana leaching method were conducted on bottom ash samples. Results of the EP leachate analyses on eight trace elements in bottom ash leachates are presented in Table 40, along with the National Primary Drinking Water Standards (NPDWS) and with the maximum contaminant levels specified by EPA. Note that the maximum contaminant levels for characterizing hazardous waste materials are such that they are one hundred (100) times the NPDWS. All concentrations of the regulated analytes in bottom ash leachates are well below the maximum contaminant levels in EP toxicity, in most cases one to three orders of magnitude lower. Therefore, bottom ashes could be characterized by the EP toxicity test as nonhazardous.

The Resource Conservation and Recovery Act also regulates the presence of six herbicides and pesticides in waste

Table 40. Results of the EP toxicity test on selected bottom ashes

Contaminant	Concentrations (mg/L)					Drinking water ^a
	Schahfer Unit 17	Gibson	Schahfer Unit 14	Perry	EPA allowable	
Mercury	0.0002	0.0001	<0.0001	0.0002	<0.2	<0.002
Silver	0.001	<0.001	<0.001	<0.001	<5.0	<0.05
Cadmium	0.0008	0.025	0.0007	0.0004	<1.0	<0.01
Chromium	0.0009	0.0005	0.0012	0.0009	<5.0	<0.05
Arsenic	0.020	0.010	0.005	0.008	<5.0	<0.05
Selenium	0.005	0.005	0.003	0.004	<1.0	<0.01
Barium	0.098	0.103	0.136	0.108	<100.0	<1.0
Lead	0.007	0.002	<0.001	0.005	<5.0	<0.05

^a Primary Drinking Water Standard [118]

materials by EP toxicity. Because these organic species will not be present in coal combustion wastes under normal conditions [162], the concentration of these species is not analyzed.

When compared with the drinking water standards, the only concentration in excess of the NPDWS is cadmium from one bottom ash leachate (Gibson). Although the EP toxicity test protocol was not designed for the analysis of drinking water quality, studies on fly ash and other solid waste disposal sites have indicated that laboratory leaching tests predict which metals will occur in greatest concentration in groundwater [163,164]. Also, the concentrations of most metals in groundwater in contact with the waste were lower in groundwater than in laboratory leaching tests [165]. Therefore, in addition to being useful in hazard classification of wastes, the EP toxicity test can also provide information about the leachate characteristics of ash materials.

The salt content of bottom ash leachates was tested by the Indiana leaching method which is conducted as specified for the EP toxicity test, except with no addition of acetic acid [18]. Results of the test are summarized in Table 41. In this Table, the concentrations of the regulated analytes are compared with the Secondary Drinking Water Standards and with the maximum allowable limits specified in the Indiana Administrative Code (329 IAC 2-9-3) for type IV restricted

Table 41. Results of the Indiana leaching method test on selected bottom ashes

Contaminant	Concentrations (mg/L)				Indiana Maximum Allowable	Secondary drinking water standard
	Schahfer unit 17	Gibson	Schahfer unit 14	Perry		
Barium	0.098	0.103	0.136	0.108	1	1
Boron	0.21	0.19	0.02	0.47	2	-
Copper	<0.1	<0.1	<0.1	0.1	0.25	1
Chlorides	<1	<1	<1	1	250	250
Cyanide, total	<0.005	<0.005	<0.005	<0.005	0.2	-
Fluoride	<0.1	<0.1	<0.1	<0.1	1.4	1.4-2.4
Iron	0.1	0.4	0.1	0.1	1.5	0.3
Sodium	0.8	1.0	<0.5	1.5	250	-
Sulfate	31	55	19	26	250	250
Sulfide	<0.1	<0.1	<0.1	<0.1	1	-
Zinc	0.1	0.3	<0.1	<0.1	2.5	5
Total Dissolved						
Solids	90	140	10	145	500	500
Calcium	19	24	2	30	-	-
Magnesium	0.7	2.0	0.2	0.1	-	-
Potassium	1.0	0.7	0.1	2.0	-	-
Standard units						
pH	8.9	8.4	7.8	7.7	6-9	6.5-8.5

waste site [18]. Again, in all cases, the concentrations of bottom ash leachates are far below the type IV criteria which are the most restrictive ones in the code.

All of the bottom ashes tested have leachates that are slightly alkaline in character. This agrees with the findings in a number of studies that the majority of conventional ashes have a pH above 7.0 [33,38,114,119]. Ash leachates exhibiting acidic nature are most likely because of the presence of the pyrite particles in the material.

It is also noted that the leachate from wet bottom ash (Schahfer Unit 14) has lower concentrations of trace metals and salts than the leachates from dry bottom ashes. However, the wet bottom ash shows an intermediate pH value among all bottom ashes tested. This implies that a correlation between the pH value and the leachate concentrations does not seem to exist.

Due to the nature of the transport system, it was not possible to sample bottom ashes that had not been exposed to some degree of leaching, if the ash was wet-disposed. Since stockpiling of ash is necessary before the material is reclaimed, the samples are judged to be representative of future field conditions. In this study, only Perry ash could be sampled directly from the hopper; and supposedly it would have the highest portion of leachable metals and salts. However, no significant difference in the concentrations of leachate was observed between Perry and other ashes.

Pyrites, produced from preparation of coal prior to firing, are known to characteristically exhibit the highest pollution potential [162,165]. This is because pyrites will react with oxygen and water to form ferrous iron and sulfuric acid. The resulting acidic environment tend to increase the rate of dissolution of heavy metals and possibly produce a contaminated leachate. If pyrites are indiscriminately mixed with ash, leachate generated from the mixture could pose a problem because of the low pH that increases the potential for unacceptable concentrations of trace metals in the leachate.

In this study, leachates from the two ash samples containing pyrites showed very low pH values. Leachate from Stout ash, which contains significant amount of pyrites, has a pH as low as 2.9, as determined by the Indiana leaching method. Although there is only trace amount of pyrites present in Mitchell ash, the pH of the leachate from this ash is 6.0. Because visual identification of pyrite particles in bottom ash is difficult, especially if pyrites are present in a limited amount, the pH measurement may be used to identify bottom ash-pyrite mixtures which are objectionable in terms of environmental concerns.

Radioactivity

Results of the radioactivity test on selected bottom ashes and a natural soil are summarized in Table 42. The measured radium specific activities of bottom ash ranged from

Table 42. Radium-226 radioactivity of bottom ash

Material	Gross count	Weight of sample (g)	Specific activity (pCi/g)
NBS standard ^a	23553	57.91	3.17
Background	15462		
Gibson	28091	80.0	3.96
Perry	21124	30.0	4.74
Schahfer 14	29909	90.0	4.03
Schahfer 17	23888	70.0	3.02
Lafayette soil ^b	18308	70.0	1.02
Global average of soil ^c			0.8
Average of fly ash from western coal ^d			2.6
Average of fly ash from eastern coal ^d			3.7

^a National Bureau of Standards ID No. INJNS 8991.

^b A clay soil obtained from the Agronomy Farm at Purdue University, West Lafayette, Indiana.

^c From National Council for Radiation Protection and Measurements [134].

^d From Electric Power Research Institute [137].

3.01 to 4.74 pCi/g, with an average of 3.94. None of the bottom ashes tested has exceeded the 5.0 pCi/g criterion set before 1978. However, the radium specific activity of a Lafayette subsoil was found to be only 1.02 pCi/g. Note that the global average concentration of radium in the soil is 0.8 pCi/g [134]. Therefore, it is concluded that bottom ashes have higher radium radioactivities than natural soil.

When compared to fly ash, the specific activity of bottom ash is slightly higher (Table 42). This is probably because the porous nature of bottom ash particles provides an environment easier for radon, as a gas, to escape, especially when bottom ash is loosely placed. It is expected that the radioactivity of ash material would be greatly reduced if the ash is well-compacted. Also, measurements made on uranium mill tailings revealed that the radon emanation was reduced, by covering the tailing with natural soil, about a factor of 2.7 in one meter [166]. An alternative method using a thin layer (6 to 9 mm) of asphalt emulsions was reported to reduce the radon flux from uranium mill tailings by 99% [167].

If bottom ash is used in highway fills, it is likely that the ash will be covered by natural soil. If it is used as a subbase or base material, the surface course will also function as a seal. Therefore, it is expected that the radium radioactivity in the field would be much less than those reported in Table 42.

ECONOMIC EVALUATION

The economic feasibility of using bottom ash is probably the most important consideration that will govern its widespread use in highway construction. The economic evaluation of the use of bottom ash focuses on two phases [168]:

1. An assessment of economic potential for Indiana bottom ash based largely on the quantities available and their location with respect to potential market areas.

2. A qualitative study of the cost factors that would determine the cost of bottom ash in place for development as a highway construction material.

Assessment of Economic Potential

It is apparent that small quantities of an ash source located many miles from the point of use would virtually eliminate the use of the material. In contrast, large quantities of ash located near market or aggregate shortage areas are assessed as having a high "economic potential". The following indicators can be used as evidence of economic potential of the ash sources [2,168]:

- Ash accumulated or annually produced in large quantities
- Proximity to potential market areas
- Location with respect to existing or projected aggregate shortages
- Location in areas with growing demand for aggregates

In 1986, there were 29 utility power plants in the state of Indiana which burned coal as the primary fuel [169,170]. Of the 29 power plants, 20 were operated by the five utility companies in the state, and 9 were smaller municipal or privately-owned operations. The locations of all existing coal fired power plants in Indiana are shown in Figure 77. As can be seen from this figure, coal burning power plants are not spread uniformly throughout the state. There is a high concentration in the extreme southern part. In contrast, northeastern Indiana is essentially without power plants.

In order to identify potential bottom ash sources in Indiana, a telephone survey was conducted for the 29 power plants. Table 43 summarizes the plant location, annual production, ash type produced, and current marketing status of the 29 ash sources.

A large 1,000 megawatt power plant may burn 3 million tons of coal per year. With a typical ash content of 10 percent for Illinois Basin bituminous coal, approximately 300,000 tons of ash would be produced each year. Such a plant would likely be of the dry bottom type, producing 60,000 tons of dry bottom ash and 240,000 tons of fly ash. The 16 larger

Figure 77. Location of coal-burning power plants in Indiana

Table 43. Potential bottom ash sources in Indiana

Utility & plant	Rated capacity ^a (megawatt)	Location	Bottom ash type	Annual production (10 ³ tons)	Market ^b
<u>Indiana and Michigan Elec. Co.</u>					
Tanners Creek	1100	Lawrenceburg	dry	80	N ^d
Breed	496	Fairbanks	dry	35	N
Rockport	1300	Rockport	dry	90	N
<u>Indianapolis Power & Light Co.</u>					
Stout	704	Indianapolis	d & w ^c	30	N
Perry	46	Indianapolis	dry	10	N
Prichard	366	Martinsville	dry	20	N
Petersburg	1707	Petersburg	dry	110	N
<u>Northern Indiana Public Service Co.</u>					
Michigan City	661	Michigan City	wet	100	Y ^e
Mitchell	529	Gary	dry	40	N
Bailly	615	Chesterton	wet	90	Y
Schahfer	1943	Wheatfield	d & w	180	Y
<u>Southern Indiana Gas & Electric Co.</u>					
Culley	415	Newburgh	dry	25	N
Warrick	162	Yankeetown	dry	10	N
Brown	530	West Franklin	dry	30	N

^a Fossil system capacity only^b Current ash marketing status^c Denotes dry and wet bottom ashes^d Y = Yes, ash is being marketed^e N = no

Table 43. (continued)

Utility & Plant	Rated Capacity ^a (megawatt)	Location	Bottom ash type	Annual production (10 ³ tons)	Market ^b
<u>Public Service Co. of Indiana, Inc.</u>					
Wabash River	753	Terre Haute	dry	50	N
Noblesville	90	Noblesville	dry	5	N
Edwardsport	160	Edwardsport	dry	12	N
Gallagher	560	New Albany	dry	40	N
Cayuga	995	Cayuga	dry	65	N
Gibson	2863	Gibson Co.	dry	200	Y
<u>Municipal System</u>					
Crawfordsville	24	Crawfordsville	dry	3	N
Jasper	15	Jasper	dry	1	N
Logansport	53	Logansport	dry	4	N
Peru	32	Peru	dry	3	N
Richmond	93	Richmond	dry	8	N
<u>Commonwealth Edison Co. of Indiana</u>					
State Line	614	Hammond	wet	100	Y
<u>Hoosier Energy Rural Elec. Coop.</u>					
Ratts	233	Petersburg	dry	15	N
Merom	980	Sullivan	dry	70	N
<u>Indiana-Kentucky Elec. Corp.</u>					
Clifty Creek	1304	Madison	dry	90	N

power plants with capacity greater than 500 megawatts represent more than 90 percent of the total bottom ash produced in Indiana. Many of the smaller plants produce only a few thousand tons of bottom ash per year, which is of questionable economic value because of its limited quantity.

As indicated by Witczak, et al. [171] and Miller and Collins [2], a shortage of natural aggregate supplies has been reported in certain areas. Figure 78 denotes the location of areas in Indiana in which aggregate shortages have been reported. These are areas where the greatest potential probably exists for using power plant ash. Comparing Figure 78 with the distribution of coal-burning power plants in Indiana (Figure 77), it is found that the areas short of aggregate supplies are well covered by coal-burning power plants, except northeastern Indiana. Therefore, bottom ash has a great economic potential for use as a highway construction material in these areas.

Population and economic growth are generally accompanied by increased construction activities. Since population shifts have been toward the big cities, all major cities in Indiana are expected to continue their growth. Areas that are expected to have the highest rate of population and economic growth in Indiana are the Lake region, Indianapolis, north vicinity of Louisville, Fort Wayne, Evansville, and Terre Haute. Again, almost all of these areas have power plants, with the exception of Fort Wayne.

Figure 78. Areas lacking aggregates in Indiana

It should be pointed out that all of the existing construction materials such as crushed stone and sand and gravel that are competitive with power plant bottom ash exist in finite quantities and can be considered exhaustible at some future time. Bottom ash, however, is a renewable material, because increasing amounts of coal will be burned by electric utility companies in the foreseeable future. Therefore, the available quantities of ash, instead of decreasing as do other competitive materials, will continue to grow and become more available.

Cost Factors Influencing Ash Utilization

The elements that combine to influence the cost of the material in place are: disposal costs, processing costs, conventional aggregate costs, and transportation costs. In many cases, the most costly of these factors will be transportation. It undoubtedly will be the controlling factor in determining the extent of use of bottom ash [2,29].

Disposal Costs

The cost of disposing of bottom ash is an important input in the determination of the economic feasibility of bottom ash utilization. If ash material can be recovered prior to disposal, the cost associated with the disposal of ash would be reduced. However, the demand for highway aggregate is

seasonal in many regions. This requires stockpiling in order to meet peak requirements. Disposal costs will not usually be significantly reduced and any savings due to reduced disposal costs may be marginal.

Through a telephone survey, it is found that many power plants are willing to make their ash available for utilization free of charge. For power plants that are dry-disposing of their ashes, it is possible that the cost of ash would be negative because hauling of the ash to landfill is a direct expense to these power plants. For the time being, it seems to be reasonable to assume that bottom ashes are available at power plants free of charge.

Processing Costs

In most cases, the cost of processing a material is directly proportional to the number of processing steps required. For bottom ash, the cost of processing will essentially involve some form of size control and stockpiling operation. Based on the particle size distribution obtained from bottom ash, it seems that sizing for dry bottom ash may not be necessary. On the other hand, it is likely that wet bottom boiler slag will need to be sized prior to use, or blended with other waste material to develop as a highway material. Currently, no meaningful estimate of costs for any of these processing is available.

Conventional Aggregate Costs

Processing costs for synthetic aggregates are meaningful when compared with the cost of the conventional aggregate materials. Obviously, the cost of conventional aggregates will vary from one location to another, depending on the availability of these materials. Another factor which is difficult to define when attempting to compare the costs of competitive construction products is the pricing strategy of conventional material producers. If a conventional material producer fears inroads into his market from a competitive product, that producer may very well reduce his normal price substantially in an effort to boost the sales of this product.

In the Catalog of U.P.A. Prices for Roads, Bridges and Traffic Items published by Indiana Department of Highways in 1987 [172], the average prices of all of the competitive unit prices bid on all the highway construction of 1986 in Indiana are available. According to this catalog, the prices of conventional highway construction materials, for which bottom ash can be a substitute, are often dependent upon the amount of material involved in the bid. In general, the larger the amount of material involved, the lower the unit price for the material. For example, the unit price for less than 2,000 cubic yards of B-borrow material is \$12.37 per cubic yard; and it is only \$2.40 for more than 100,000 cubic yards of B-borrow material. Table 44 summarizes the average bid prices for borrow and subbase materials listed in the catalog.

Table 44. Average bid prices for borrow and subbase materials in Indiana (172)

Uses	Unit	Amount	Average price
Borrow	cys ^a	5000- 9999	5.84
		10000-24999	5.67
		25000-49999	7.18
		50000-99999	2.29
B-Borrow	cys	5000- 9999	10.64
		10000-24999	2.93
		25000-49999	8.75
		50000-99999	5.52
B-Borrow for structural backfill	cys		9.52
Subbase	cys		16.92

^a cubic yards

Note: The number of bids and other factors may bias the average prices shown.

Transportation Costs

On a national average it has been reported that transportation accounts for 50 percent or more of the delivered cost of construction materials [168]. If long hauls are involved, the cost of transportation will dictate the overall economic value of a material. It is believed that transportation costs are the single factor most responsible for limiting the use of various waste materials.

A telephone survey conducted on truck carriers in major cities of Indiana indicates that the cost for trucking varies with the road conditions during hauling, the distance of the haul, and the amount of material to be hauled. A good rule of thumb would be to figure on a rate of \$1.60 per ton for the first ten miles and \$0.08 to \$0.10 per ton for every mile thereafter. However, a rate would still be quoted on the basis of the origin and destination of the haul.

Assessment of Economical Potential

If bottom ash can be obtained from power plants free of charge, which is likely the case for most power plants, it is possible to convert the cost for conventional materials into transportation cost for bottom ash. It was found that bottom ash can be transported up to 31 and 83 miles from the power plants for B-borrow and subbase uses, respectively, before the

total cost of bottom ash in place begins to exceed that of conventional materials.

Using the locations of power plant as the centers and the distances determined above as the radii, the areas that bottom ash can be used economically in fills are illustrated in Figure 79. It can be seen that, in approximately 80 percent of the area of Indiana, use of bottom ash in highway fills may be economical. If bottom ash is to be used in subbase, it is found that bottom ash would be cost effective throughout the state due to the relative high cost of conventional subbase material.

Area showing economic potential

Figure 79. Areas showing economic potential for use of bottom ash in highway fills

RECOMMENDATIONS FOR IMPLEMENTATION

Ash Selection Guidelines

The selection of bottom ash for highway construction is complicated by two important considerations: (1) the non-uniformity of the material and (2) the applicability of the standard test methods and material specifications to bottom ash.

The information presented in the literature review and the results of the experimental program have shown that the physical, chemical, and engineering properties of bottom ash vary considerably, depending upon source and type of coal, boiler type, coal burning methods, and ash collection and handling practices. Properties of bottom ash vary not only from one power plant to another, but also from day to day production within a single plant.

Existing test methods and material specifications have been developed based on experience with conventional materials only. Because bottom ashes possess some special characteristics that are different from those of conventional materials, the applicability of the standard testing procedures and specifications to the evaluation of bottom ash material is imperfect.

Source Selection

Current disposal practices suggest that power plant bottom ash is still considered by many power-generating companies as a waste product. If more extensive utilization of the material is expected, bottom ash must be regarded as an useful resource by utility companies. It is strongly desired that power plants exercise closer controls over the production, collection and stockpiling of the material to provide a product of greater uniformity. It is believed that in order to boost the sale and use of the material, ash suppliers must be able to provide specific information on the physical and chemical properties of their materials. The non-uniformity of bottom ash is also of great concern to potential users of the material. If ash suppliers are able to document the level of non-uniformity and reduce the variation of production to within acceptable limits, bottom ash can become more attractive to potential users such as state and county transportation agencies.

Based on the results of laboratory evaluations of selected Indiana bottom ashes, the majority of the bottom ashes studied are suitable for various uses in highway construction. However, in selecting bottom ash sources for large-volume uses in highways, the following considerations must be taken into account:

1. In highway projects that involve large-volume utilizations of bottom ash, it is important to have

sufficient supplies of the material from a single source to complete the project. Any changes in source of coal or coal burning methods at the plant are strongly discouraged because they could result in unnecessary delays during the construction project.

2. In general, dry bottom ash tends to be more versatile in application to highway constructions. This is because the gradation of dry bottom ash is typically well-graded. On the other hand, wet bottom ash is usually blended with other conventional materials to achieve the acceptable gradation requirements for highway uses. Of the dry type, bottom ash produced from a stoker furnace tends to have low specific gravity and high content of popcornlike particles, both lead to poor material durability. Therefore, it is recommended that stoker ashes not be used, except where field and laboratory data indicate that they will perform satisfactorily.
3. It is critical that the costs of using bottom ash, including costs of the material, processing, and transportation, be less than those of using a conventional construction material. In this context, dry bottom ash seems to be more competitive because it is produced in larger

quantities and utilization of dry bottom ash has not been developed. Wet bottom ash has received wide acceptance for applications such as blasting sand, roofing granules, and ice-control material for highways. As such, wet bottom ash is likely to be more costly than dry bottom ash.

4. At the present time, stockpiling operations in power plants are not designed to preserve material quality but to facilitate handling and disposal. Ponding of ash is particularly vulnerable to segregation because coarse particles readily settle out. Segregation may also occur in dry stockpiles, especially when the ash is end dumped by truck over the edge of a large pile. It is recommended that bottom ashes be used only if they are stockpiled or stored separately from fly ash. Considerable testing is required when an existing stockpile is evaluated for potential highway use.
5. Co-disposal of iron pyrite from the coal cleaning operation with bottom ash is a common practice in many power plants. In these cases, the disposal operations should be modified to keep the pyrite from the ash, since pyrite exhibits extremely high pollution potential and it degrades readily in service.

Acceptance Criteria

On the basis of the laboratory test results presented earlier, the properties of most bottom ashes will meet the specifications set for conventional natural materials. Many of the criteria for acceptance of a conventional material may be applied to bottom ash material as well. However, because of the unique properties of bottom ash, it is possible that satisfactory performance can be achieved with bottom ash at a saving in cost even though the gradation or other existing specifications are not met. The acceptance criteria described below are intended to open the way to more extensive utilization of bottom ash in highway construction; as more field data and experience are accumulated, more detailed material and construction specifications can be developed.

1. The gradations of bottom ash range from fine gravel to fine sand in size and will generally meet the gradation specifications for bases and subbases. Dry bottom ash is typically well-graded and can often be used as received from the source or with minimal scalping effort. Wet bottom ash, on the other hand, tends to be more uniform and is usually blended with other conventional materials. It is recommended that the acceptance criteria for bottom ash gradation be the same as for conventional materials. However, in order to prevent possible

moisture accumulation, the portion finer than the No. 200 sieve should not exceed 8 percent.

2. As discussed in previous sections, the specific gravity of bottom ash may be used as an indicator of the material's quality. The apparent specific gravity ranges from 1.9 to 3.2 and 2.5 to 2.9 for dry and wet bottom ashes, respectively. An apparent specific gravity value of 2.3 or greater is recommended for potential dry bottom ash utilization. This criterion would eliminate most bottom ashes produced from a stoker furnace and those ashes with large amounts of weak particles. For wet bottom ash, a specific gravity greater than 2.5 is recommended.
3. Most specifications for material include a provision for soundness. In view of the serious criticism on the applicability of the sodium soundness test in evaluating bottom ash material, the sodium soundness test is recommended as a secondary screening test. A sodium soundness loss of 10 percent can be used as the acceptance criterion for use of bottom ash in subbase and base courses. For application in fills, a 12 percent loss is recommended and most bottom ashes can meet the limit.

4. The Los Angeles abrasion test is also widely used in evaluation of aggregates. The applicability of this test on bottom ash has been similarly criticized. However, it is possible to modify the test to include the fine portions of bottom ash material. This will require detailed studies, both in the laboratory and in the field. At the present time, it is recommended that a Los Angeles abrasion loss of 45 or less be accepted for subbase and base applications, and a value of 50 for use in fills..
5. When an existing stockpile of bottom ash is to be reclaimed for utilization, it is difficult to know if the ash has been contaminated with pyrite. Since pyrite solution is quite acidic, it is suggested that a pH of 6 or higher, determined by testing representative samples after considerable shaking, be accepted for existing stockpiles.

Environmental Concerns

The environmental concerns center around possible leaching of heavy metals from embankment constructed from ash material. Although the laboratory leaching test results obtained in this study and the groundwater monitoring data found in the literature suggest that bottom ash is a non-hazardous material, it is recommended that groundwater

monitoring programs be planned for the initial prototype highway projects involving ash materials.

If bottom ash is used as an embankment or backfill material, it is necessary to cover the bottom ash with natural soil, because the dark gray color of ash can make it an unattractive feature on the landscape. The covering layer should be dimensioned with respect to vegetation growth, and the species of vegetation that will occur on the finished surface. In all cases, the covering soil layer should have a thickness of at least one foot to ensure satisfactory performance of the covering layer. Also, the covering layer should consist of soil resistant to erosion.

Vegetation growth on the finished surface is important not only to prevent erosion, but also as a measure to reduce leachate production by increased evaporation.

SUMMARY AND CONCLUSIONS

This study evaluated the suitability of bottom ashes as substitutes for conventional geotechnical materials in highway construction. Eleven bottom ashes were extensively studied in the laboratory so as to provide a store of information on the properties of bottom ashes available in Indiana. An extensive review of literature has been presented on the current status of knowledge of bottom ash properties, with emphasis on potential application of the material in highway embankment and pavement construction. Also, previous laboratory and field experience with bottom ash utilization have been reviewed and documented. Based on the results of detailed laboratory evaluation and the literature review, the following conclusions are drawn:

1. There are two basic types of bottom ash: dry bottom ash and wet bottom ash. The two types of bottom ash have different physical and chemical characteristics and, consequently, different engineering properties.
2. The chemical, physical, and engineering properties of bottom ashes vary considerably, depending on the type and source of coal, coal burning methods, the

boiler type, and ash collection and handling practices. The non-uniformity of bottom ash is of great concern to potential users of the material. Closer controls over the production, collection, and stockpiling of the material must be exercised by power plants in order to provide a more uniform product.

3. Bottom ash material exhibits some special characteristics that are distinctly different from those of conventional materials. Of greatest importance are the complex pore structure and gritty surface texture of bottom ash particles, which affect the specific gravity, particle strength, permeability, moisture-density relations, and compressibility of bottom ash.
4. Of the dry type, bottom ash produced from stoker furnaces tends to have low specific gravity, excessive loss upon abrasion, weak particle strength, and considerable compressibility.
5. In general, bottom ash is similar to conventional materials with comparable gradings as far as soundness, abrasion resistance, and permeability are concerned. The angles of shearing resistance of bottom ashes are higher than that of conventional materials, whereas the compacted densities are generally lower for bottom ashes.

The void ratios and compressibility of bottom ash are slightly greater than those of conventional materials. In most cases, bottom ash would meet specification requirements set for conventional materials.

6. The densities attained by bottom ash-fly ash mixes are considerably higher than that attained by bottom ash alone and there is a definite optimum fly ash content at which the maximum density is attained. Due to the porous and gritty texture of bottom ash, the fly ash content at which the maximum bearing value occurs is less than that indicated by the maximum density.
7. Bottom ash can be an excellent base course material when suitably stabilized. Portland cement and Class C fly ash prove to be effective stabilizing agents. The addition of appropriate amount of fly ash to bottom ash reduces the cement requirement significantly.
8. It appears that bottom ashes show very good promise for use in highway construction. Potential large-volume highway applications include embankments, backfills, unstabilized subgrades and subbases, and stabilized bases.
9. Based on the EP toxicity tests, bottom ashes evaluated in this study can be classified as non-

hazardous according to the current EPA regulations governing characterization of solid waste.

10. Results of the Indiana leaching method test show that the effects of bottom ash on the quality of groundwater are minimal. The quality of leachates generated from bottom ashes would meet the most restrictive type of waste facility specified by Indiana state regulations.
11. Evaluations on the available quantities of bottom ashes and their locations with respect to potential market areas indicate that bottom ash possesses great economic potential for utilization in Indiana. Also, based on the availability of ash and current market price, use of dry bottom ash can be more cost effective than that of wet bottom ash.
12. Due to the unique characteristics of bottom ash, appropriate material specifications and effective construction techniques need to be developed to justify generalized acceptance of the material for highway applications.

Based on the results of laboratory evaluations of selected Indiana bottom ashes, it appears that the majority of the bottom ashes are suitable for various uses in highway construction. It is obvious that the utilization of such an extensively produced by-products of the power industry as an economic highway material should be encouraged in the future.

SUGGESTIONS FOR FURTHER STUDY

Based on laboratory investigations, it has been shown that bottom ash appears to be suitable for various uses in highway construction. The ultimate indicator of a material's quality is its ability to perform under actual service conditions. It is suggested that further research needs be focused on correlating the laboratory test results to the field performance of bottom ashes. A prototype test section designed and instrumented with in-situ measures should serve this purpose.

Further research is also needed in the following areas:

1. Resilient modulus, a material property used in pavement stress analysis, needs to be evaluated for bottom ashes in order to provide a basis for modern pavement design.
2. Since bottom ashes are generally grey to black in color, it seems logical to use the material in bituminous mixtures. Properties of ash-bituminous mixtures need to be examined.
3. It has been shown that stabilized bottom ash is suitable as a base material in terms of the strength development characteristics. Further research is necessary to evaluate the durability of stabilized bottom ashes.

4. The validity of the recommended modifications for standard tests need to be verified. The selection criteria established in this study would also need to be modified as performance data become available.
5. The bottom ashes considered in this study were produced from eastern bituminous coal. Further studies on the characteristics of bottom ashes produced from western lignite and subbituminous coals are needed.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. American Coal Ash Association, Inc., Ash Production and Utilization, Washington, D.C.
2. Miller, R. H. and Collins, R. J., Waste Materials as Potential Replacements for Highway Aggregates, National Cooperative Highway Research Program Report 166, Transportation Research Board, Washington, D.C., 1976.
3. Seals, R. K., Moulton, L. K., and Ruth, B. E., "Bottom Ash: An Engineering Material," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. 98, No. SM4, April, 1972, pp. 311-325.
4. Majidzadeh, K., El-Mitiny, R. N., and Bokowski, G., Power Plant Bottom Ash in Black Base and Bituminous Surfacing, Volume 2, User's Manual, Federal Highway Administration, Report No. FHWA-RD-78-148, Washington, D.C., June 1977.
5. Surface Transportation and Uniform Relocation Assistance Act of 1987, Public Law 100-17, United States Congress, Washington, D.C., April 2, 1987.
6. Federal Highway Administration, "Use of Coal Ash in Embankments and Bases," FHWA Technical Advisory T 5080.9, Washington, D.C., May 16, 1988.
7. U. S. Department of Energy, Federal Energy Regulatory Commission, 1981 Form 67, Washington, D.C.
8. American Society for Testing and Materials, "Standard Method for Sieve Analysis of Fine and Coarse Aggregates," ASTM Designation C 136, Philadelphia, Pa.
9. American Society for Testing and Materials, "Standard Test Method for Specific Gravity and Absorption of Fine Aggregate," ASTM Designation C 128, Philadelphia, Pa.
10. American Society for Testing and Materials, "Standard Test Method for Specific Gravity of Soils," ASTM Designation D 854, Philadelphia, Pa.

11. American Society for Testing and Materials, "Standard Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate," ASTM Designation C 88, Philadelphia, Pa.
12. American Society for Testing and Materials, "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine," ASTM Designation C 131, Philadelphia, Pa.
13. American Society for Testing and Materials, "Standard Test Method for Maximum Index Density of Soils Using a Vibratory Table," ASTM Designation D 4253, Philadelphia, Pa.
14. American Society for Testing and Materials, "Standard Test Method for Minimum Index Density of Soils and Calculation of Relative Density," ASTM Designation D 4254, Philadelphia, Pa.
15. American Society for Testing and Materials, "Standard Test Method for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 5.5-lb Rammer and 12-in. Drop," ASTM Designation D 698, Philadelphia, Pa.
16. American Society for Testing and Materials, "Standard Test Method for Bearing Ratio of Laboratory-Compacted Soils," ASTM Designation D 1883, Philadelphia, Pa.
17. U. S. Environmental Protection Agency, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, 2nd ed., Report SW-846, Washington, D.C., 1985.
18. Indiana Register, Vol. 12, No. 5, February 1, 1989.
19. Energy Information Administration, Annual Energy Review 1987, DOE/EIA-0384(87), U. S. Department of Energy, Washington, D.C.
20. Energy Information Administration, Monthly Energy Review, Dec. 1988, DOE/EIA-2035(88/12), U. S. Department of Energy, Washington, D.C.
21. Valley Forge Laboratories, Technical Background Document in Support of Development of Federal Procurement Guidelines for Use of Power Plant Ash in Transportation Construction Products, Report submitted to the U. S. Environmental Protection Agency, May 1984.

22. Energy Information Administration, Electric Power Annual 1986, DOE/EIA-0348(86), U. S. Department of Energy, Washington, D.C.
23. American Society for Testing and Materials, "Standard Classification of Coals by Rank," ASTM designation D 388, Philadelphia, Pennsylvania.
24. Bobcock & Wilcox Company, Steam: Its Generation and Use, Bobcock & Wilcox, New York, 1978.
25. Singer, J. G., editor, Fossil Power Systems, Combustion Engineering, Inc., Windsor, CT, 1981.
26. GAI Consultants, Inc., Fly Ash Design Manual for Road and Site Applications, Vol. 1, Dry or Conditioned Placement, Electric Power Research Institute, Report CS-4419, Palo Alto, Ca., February 1986.
27. Baker, W. T., editor, Workshop Proceedings: Research and Development Needs for Use of Fly Ash in Cement and Concrete, March 3-5, 1982, Electric Power Research Institute, Report CS-2616-SR.
28. Loftus, W. E., Proceedings of the American Power Conference, Vol. 38, Illinois Institute of Technology, Technology Center, Chicago, Ill., 1976.
29. Usmen, M. A., Head, W. J., and Moulton, L. K., "Use of Coal-Associated Wastes in Low-Volume Roads," Transportation Research Record 898, 1983, pp. 268-277.
30. Anderson, D. A., "Utilization of Bottom Ash in Highway Construction," Proceedings, International Conference on the Use of By-Products and Waste in Civil Engineering, Vol. 2, Paris, France, November 28-30, 1978, pp. 327-332.
31. Engineering News Record, "Billions at Stake in Coal Waste Fight," January 10, 1980, pp. 26-27.
32. Sikes, P. G. and Kolbeck, H. J., "Disposal and Uses of Power Plant Ash in Urban Area," Journal of the Power Division, ASCE, Vol. 99, No. PO1, May 1973, pp. 217-234.
33. Anderson, D. A., Usmen, M., and Moulton, L. K., "Use of Power Plant Aggregate in Bituminous Construction," Transportation Research Record 595, 1976, pp. 18-24.
34. Tyson, S. S., "Recent Progress in Coal Ash Utilization and the Effect of Environmental Issues and Regulations," in Disposal and Utilization of Electric Utility Wastes, M. A. Usmen, editor, ASCE, 1988, pp. 1-11.

35. Golden, D. M., "EPRI Ash Utilization Research," Proceedings, Eighth International Ash Utilization Symposium, Vol. 1, Electric Power Research Institute, Report CS-5362, Palo Alto, Ca., October 1987.
36. Moulton, L. K., Seals, R. K., and Anderson, D. A., "Utilization of Ash from Coal-Burning Power Plants in Highway Construction," Highway Research Record 430, 1973, pp. 26-39.
37. Moulton, L. K., "Bottom Ash and Boiler Slag," Proceedings of Third International Ash Utilization Symposium, Pittsburgh, PA, March 1973, Bureau of Mines, Information Circular 8640, pp. 148-169.
38. Usmen, M. A., A Critical Review of the Applicability of Conventional Test Methods and Materials Specifications to the Use of Coal-Associated Wastes in Pavement Construction, Ph.D. Dissertation, West Virginia University, Morgantown, WV, 1977.
39. Meyers, J. F., Pichumani, R., and Kapples, B. S., Fly Ash - A Highway Material, Federal Highway Administration, Report No. FHWA-IP-76-16, Washington, D.C., 1976.
40. Manz, O. E., "Lignite Production and Utilization," Proceedings, Fourth International Ash Utilization Symposium, St. Louis, Mo., March 1976, DOE/MERC/SP-76/4, pp. 39-57.
41. Dolar-Mantuani, L., "Soundness and Deleterious Substances," in Significance of Tests and Properties of Concrete-Making Materials, Chapter 42, American Society for Testing and Materials, STP 169B, Philadelphia, Pa., 1978.
42. McLaughlin, J. F., Woods, K. B., Mielenz, R. C., and Rockwood, N. C., "Distribution, Production, and Engineering Characteristics of Aggregates," in Highway Engineering Handbook, Section 16, Woods, K. B., editor, McGraw-Hill Book Co., New York, 1960.
43. Srinivasan, V., Beckwith, G. H., and Burke, H. H., "Geotechnical Investigations of Power Plant Wastes," ASCE Specialty Conference on Geotechnical Practice for Disposal of Solid Waste Materials, Ann Arbor, Mich., 1977, pp. 169-187.

44. Rose, J., Lowe, J. A., and Floyd, R. K., "Compositions and Properties of Kentucky Power Plant Ash," Proceedings, Fifth International Ash Utilization Symposium, Atlanta, Ga., February 1979, DOE/METC/SP-79/10(Pt. 1), pp. 220-244.
45. Gallaway, B. M. and Hargett, E. R., "Blending Lightweight Aggregates with Natural Aggregates for the Production of Bituminous Concrete," Highway Research Record 273, 1969, pp. 42-52.
46. Horvath, J. S., Discussion of "Pulverized Coal Ash as Structural Fill," by G. A. Leonards, Journal of the Geotechnical Engineering, ASCE, Vol. 109, No. 10, October 1983, p. 1360.
47. Krebs, R. D. and Walker, R. D., Highway Materials, McGraw-Hill Book Co., New York, 1971.
48. Yoder, E. J. and Witczak, Principles of Pavement Design, 2nd edition, Chapman & Hall, New York, 1975.
49. American Society for Testing and Materials, "Standard Specification for Graded Aggregate Material for Bases or Subbase for Highways or Airports," ASTM Designation D 2940, Philadelphia, Pa.
50. American Association of State Highway and Transportation Officials, "Standard Specification for Materials for Aggregate and Soil-Aggregate Subbase, Base and Surface Courses, AASHTO Designation M 147.
51. American Society for Testing and Materials, "Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses," ASTM Designation D 1241, Philadelphia, Pa.
52. McLaughlin, J. F., Woods, K. B., Mielenz, R. C., and Rockwood, N. C., Distribution, Production, and Engineering Characteristics of Aggregates, Section 16 in Highway Engineering Handbook, K. B. Woods, et al., editors, McGraw-Hill, New York, 1960.
53. Indiana Department of Highways, Standard Specifications, 1988.
54. Selvig, W. A. and Gibson, F. H., Analyses of Ash from United States Coals, Bulletin 567, Bureau of Mines, 1956.
55. Abernethy, R. F., Peterson, M. J., and Gibson, F. H., Major Ash Constituents in U.S. Coals, Report of Investigation 7240, Bureau of Mines, 1969.

56. GAI Consultants, Inc., Fly Ash Design Manual for Road and Site Applications, Volume 1: Dry or Conditioned Placement, Report No. CS-4419, Electric Power Research Institute, Palo Alto, CA, February 1986.
57. Los Alamos Scientific Laboratory, Environmental Contamination from Trace Elements in Coal Preparation Wastes, National Technical Information Service, Springfield, VA, August 1976, PB 267 339.
58. McCarthy, G. J., et al., "Correlations of Chemistry and Mineralogy of Western US Fly Ash," Material Research Society Proceedings, Vol. 86, Pittsburgh, Pa., 1987, pp. 109-112.
59. McCarthy, G. J., Johansen, D. M., Steinwand, S. J., and Thedchanamoorthy, A., "X-Ray Diffraction Analysis of Fly Ash," Advances in X-Ray Analysis, Vol. 31, 1988, pp. 331-342.
60. Watt, J. D. and Thorne, D. J., "Composition and Pozzolan Properties of Pulverized Fuel Ashes. I. Composition of Fly Ashes from Some British Power Stations and Properties of their Component Particles," Journal of the Applied Chemistry Vol. 15, December 1965, pp. 585-594.
61. Barber, E. G., "The Utilization of Pulverized-Fuel Ash," Journal of the Institute of Fuel, Vol. 43, No. 348, January 1970, pp. 4-9.
62. Yoder, E. J., et al., Pavement Design, Construction, and Reconstruction, Section 16 in Handbook of Highway Engineering, R. F. Baker, editor, Van Nostrand Reinhold Co., New York, 1975.
63. Woolf, D. O., "An Improved Sulfate Soundness Test for Aggregates," Bulletin 213, American Society for Testing and Materials, April 1956, p. 77.
64. Meininger, R. C., "Abrasion Resistance, Strength, Roughness, and Related Properties," Chapter 38 in Significance of Tests and Properties of Concrete and Concrete-Making Materials, ASTM STP 169B, 1978.
65. Usmen, M., Anderson, D. A., and Moulton, L. K., "Applicability of Conventional Test Methods and Material Specifications to Coal-Associated Waste Aggregates," Transportation Research Record 691, 1978, pp. 49-57.

66. Shelburne, T. E., "Crushing Resistance of Surface Treatment Aggregates," Engineering Bulletin of Purdue University, Research Series 76, Vol. 24, No. 5, 1940.
67. Majidzadeh, K., Bokowski, G, and El-Mitiny, R., "Material Characteristics of Power Plant Bottom Ashes and their Performance in Bituminous Mixtures: A Laboratory Investigation," Proceedings of the Fifth International Ash Utilization Symposium, Atlanta, Georgia, METC/SP-79/10 Vol. 2, pp. 787-804.
68. American Society for Testing and Materials, "Standard Test Method for Materials Finer Than 75- μ m Sieve in Mineral Aggregates by Washing," ASTM Designation C 117.
69. American Association of State Highway and Transportation Officials, "Standard Test Method for Amount of Material Finer Than 0.075 mm Sieve in Aggregate," AASHTO Designation T 11.
70. Powers, T. C., The Properties of Fresh Concrete, John Wiley & Sons, New York, 1968.
71. American Society for Testing and Materials, "Standard Specification for Coarse Aggregate for Bituminous Paving Mixtures," ASTM Designation D 692, Philadelphia, Pa.
72. Spangler, M. G., Engineering Characteristics of Soils and Soil Testing, Section 8 in Highway Engineering Handbook, K. B. Woods, et al., editors, McGraw-Hill, New York, 1960.
73. Lambe, T. W. and Whitman, R. V., Soil Mechanics, John Wiley and Sons, Inc., New York, 1969.
74. Hough, B. K., Basic Soils Engineering, 2nd Ed., The Ronald Press Co., New York, 1969.
75. Leonards, G. A., "Engineering Properties of Soil," in Foundation Engineering, G. A. Leonards, ed., McGraw-Hill Book Co., New York, 1962.
76. Terzaghi, K. and Peck, R. B., Soil Mechanics in Engineering Practice, 2nd edition, John Wiley and Sons, Inc., New York, 1967.
77. Hazen, A., Discussion of "Dams on Sand Foundations," by A. C. Koenig, Transactions, ASCE, Vol. 73, 1911, pp. 199-203.

78. Holtz, R. D. and Kovacs, W. D., An Introduction to Geotechnical Engineering, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981.
79. Highway Research Board, "Compaction of Embankments, Subgrades, and Bases," HRB Bulletin 58, 1952.
80. Foster, C. R., "Field Problems: Compaction," in Foundation Engineering, G. A. Leonards, editor, McGraw-Hill, New York, 1962.
81. Hilf, J. W., "Compacted Fill", Chapter 7 in Foundation Engineering Handbook, Winterkorn, H. F. and Fang, H. Y., editors, Van Nostrand Reinhold Company, New York, 1976.
82. Mitchell, J. K., Fundamentals of Soil Behavior, John Wiley & Sons, Inc., New York, 1976.
83. Wahls, H. E., Fisher, C. P., and Langfelder, L. J., The Compaction of Soil and Rock Materials for Highway Purposes, Department of Civil Engineering, North Carolina State University, Raleigh, August 1966.
84. Lee, P. Y. and Suedkamp, R. J., "Characteristics of Irregularly Shaped Compaction Curves of Soils," Highway Research Record 381, 1972, pp. 1-9.
85. Johnson, A. W. and Sallberg, J. R., Factors Influencing Compaction Test Results, Highway Research Board, Bulletin 319, 1962.
86. Spencer, W. T., Allen, H., and Smith, P. C., "Report on Pavement Research in Indiana," Highway Research Board, Bulletin 116, 1956, pp. 1-56.
87. Usmen, M., "Properties and Engineering Behavior of Coal Wastes Used in Road Construction," Proceedings of the International Conference on the Use of By-Products and Waste in Civil Engineering, Vol. 2, November 28-30, 1978, Paris, France, pp. 487-492.
88. Roberts, J. E. and DeSouza, J. M., "The Compressibility of Sands," Proceedings of the American Society for Testing and Materials, Vol. 58, 1958, pp. 1269-1277.
89. Schultze, E. and Moussa, A., "Factors Affecting the Compressibility of Sand," Proceedings of the Fifth International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, 1961, pp. 335-340.

90. Hendron, A. J. Jr., The Behavior of Sand in One-Dimensional Compression, Ph.D. Dissertation, University of Illinois, Urbana, 1963.
91. Lee, K. L. and Farhoomand, I., "Compressibility and Crushing of Granular Soil in Anisotropic Triaxial Compression," Canadian Geotechnical Journal, Vol. IV, no. 1, 1967, pp. 68-99.
92. Ritter, L. J., "Mechanical Soil Stabilization," Public Works, Vol. 85, No. 3, 1954, pp. 90-95.
93. Sowers, G. F., Introductory Soil Mechanics and Foundations: Geotechnical Engineering, 4th edition, Macmillan Co., New York, 1979.
94. Yoder, E. J. and Woods, K. B., "Compaction and Strength Characteristics of Soil Aggregate Mixtures," Proceedings, Highway Research Board, Vol. 26, 1946, pp. 511-520.
95. Spangler, M. G. and Handy, R. L., Soil Engineering, 3rd edition, Intext Educational Publishers, New York, 1973.
96. Miller, E. A. and Sowers, G. F., "The Strength Characteristics of Soil-Aggregate Mixtures," Bulletin 183, Highway Research Board, 1957, pp. 16-23.
97. Fuller, W. B. and Thompson, S. E., "Law of Proportioning Concrete," Transactions, ASCE, Vol. 59, 1907, pp. 67-143.
98. Deklotz, L. A., "Effect of Varying the Quantity and Quality of the Soil Portion of Highway Aggregates on their Stability," Proceedings, Highway Research Board, Vol. 20, 1940, pp. 787-797.
99. Yoder, E. J., Compaction and Strength Characteristics of Granular Base Courses, Unpublished M.S. Thesis, Purdue University, West Lafayette, Indiana, 1946.
100. Ingles, O. G. and Metcalf, J. B., Soil Stabilization, John Wiley & Sons, New York, 1973.
101. Johnson, A. W. et. al., Soil Stabilization, Section 21 in Highway Engineering Handbook, K. B. Woods, editor, McGraw-Hill Co., New York, 1960.
102. Ferguson, E. G., "Aggregate Bases Constructed with Self-Cementing Fly Ash," Proceedings, Eighth International Ash Utilization Symposium, Vol. 1, EPRI CS-5362, Electric Power Research Institute, Palo Alto, California, 1987, Paper No. 25.

103. Ferguson, E. G., "Recycling Pavements with Self-Cementing Fly Ash," Proceedings, Eighth International Ash Utilization Symposium, Vol. 2, EPRI CS-5362, Electric Power Research Institute, Palo Alto, California, 1987, Paper No. 53.
104. Electric Power Research Institute, Use of Coal Ash in Highway Construction: Kansas Demonstration Project, EPRI GS-6460, Palo Alto, California, 1989.
105. Highway Research Board, Soil Stabilization with Portland Cement, Bulletin 292, Washington, D.C., 1961.
106. Lambe, T. W., Soil Stabilization, Chapter 4 in Foundation Engineering, G. A. Leonards, editor, McGraw-Hill Co., New York, 1962.
107. Chapman, B. R. and Youdale, G. P., "Bottom Ash - From Industrial Waste to Pavement Material," Proceedings, Australian Road Research Board, Volume 11, 1982, pp. 90-104.
108. Electric Power Research Institute, Use of Coal Ash in Highway Construction: Georgia Demonstration Project, EPRI CS-5225, Palo Alto, California, 1987.
109. U. S. Congress, Resource Conservation and Recovery Act, Public Law 94-580, Section 3001 (b) (3), Washington, D.C., October 21, 1976.
110. Federal Register, "Hazardous Waste and Consolidated Permit Regulations," Vol. 45, No. 98, May 19, 1980, pp. 33063-33285.
111. U. S. Congress, Public Law 94-580, Amendments to the Resource Conservation and Recovery Act, Section 6921, Washington, D.C., 1980.
112. Electric Power Research Institute, Solid-Waste Environmental Studies: Description, Status, and Available Results, Report No. EPRI EA-5322-SR, Electric Power Research Institute, Palo Alto, CA, August 1987.
113. Gidley, J. S. and Sack, W. A., "Environmental Aspects of Waste Utilization in Construction," Journal of Environmental Engineering, ASCE, Vol. 110, No. 6, December, 1984, pp. 1117-1133.
114. Lundgren, T. and Elander, P., Environmental Control in Disposal and Utilization of Combustion Residues, Report No. 28E, Swedish Geotechnical Institute, Linköping, 1987.

115. Federal Register, Vol. 45, No. 98, May 19, 1980, pp. 33063-33285.
116. Daniels, S. L., "Development of Realistic Tests for Effects and Exposures of Solid Wastes," Hazardous Solid Waste Testing: First Conference, R. A. Conway, et al., editors, ASTM STP 760, January 1981, pp. 345-368.
117. Environmental Protection Agency, Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, 2nd ed., Report SW-846, EPA, 1985.
118. Environmental Protection Agency, National Interim Primary Drinking Water Regulations, 1976
119. Western Research Institute, Evaluation of the Toxicity Characteristic Leaching Procedure on Utility Wastes, Report No. EPRI CS-5355, Electric Power Research Institute, Palo Alto, CA, August 1987.
120. Perrket, C. L. and Webster, W. C., "Literature Review of Batch Laboratory Leaching and Extraction Procedures," Hazardous Waste Testing: First Conference, ASTM STP 760, R. A. Conway and B. C. Malloy, Eds., 1981, pp. 7-27.
121. U. S. Congress, Amendments to the Resource Conservation and Recovery Act, Section 3001 (g), Washington D.C., 1984.
122. Environmental Protection Agency, "Tentative Changes to and Classification of the Draft TCLP Protocol," EPA Draft, July 17, 1985.
123. Federal Register, Vol. 51, January 14, 1986, p. 1750.
124. Federal Register, Vol. 51, June 13, 1986, p. 21685.
125. Federal Register, Vol. 51, November 7, 1986, p. 40643.
126. Niece, J. E. and DiGioia, A. M., "Fly Ash Disposal and Groundwater Quality," in Water Quality Issues at Fossil Fuel Plants, W. G. Dinchak and M. J. Mathis, editors, ASCE, 1982, pp. 36-43.
127. Illinois State Geological Survey and Illinois Natural History Survey, Chemical and Biological Characterization of Leachates from Coal Solid Wastes, Springfield, Illinois, November 1980.

128. Envirosphere Company, "Report on the Groundwater Data Base Assembled by the Utility Solid Waste Activities Group," Appendix C of Report and Technical Studies on the Disposal and Utilization of Fossil-Fuel Combustion By-Products, Submitted to the U.S. Environmental Protection Agency, October, 1982.
129. Williams, R. J. and Okorn, D. W., "Regulatory and Environmental Issues of the Chisman Creek Superfund Site," Disposal and Utilization of Electric Utility Wastes, M. A. Usmen, editor, ASCE, 1988, pp. 66-81.
130. Nuclear Energy Agency, "Metrology and Monitering of Radon, Thoron, and their Daughter Products," Report by a Group of Experts, OECD, Paris, 1985.
131. Lederer, C. M. and Shirley, V. S., editors, Table of Isotopes, 7th edition, John Wiley & Sons, New York, 1978.
132. Walker, F. W., Miller, D. G., and Porstendorfer J., "Measurements of the Unattached Fraction of Radon Daughters in Houses," The Science of the Total Environment, Vol. 45, p. 261.
133. Robkin, M. A., Terminology for Describing Radon Concentrations and Exposures, Chapter 2 in Indoor Radon and Its Hazards, Bodansky, D. et. al., editors, University of Washington Press, Seattle, Washington, 1987.
134. National Council for Raidation Protection and Measurements, "Environmental Radiation Measurements," NCRP Report No. 78, Bethesda, Maryland, 1976.
135. Bodansky, D, "Overview of the Indoor Radon Problem," Chapter 1 in Indoor Radon and Its Hazards, Bodansky, D. et. al., editors, University of Washington Press, Seattle, Washington, 1987.
136. Schwieger, R. G., "Plants Show Progress in Pollution Control," Power, April, 1970, pp. 27-32.
137. Electric Power Research Institute, Physical-Chemical Characteristics of Utility Solid Wastes, Report No. EPRI EA-3236, September 1983.
138. Thompson, C. M. and Jones, B. F., Determination, of Hazardousness of Reuse Products Utilizing Low Rank Western Coal Fly Ash/Bottom Ash, DOE/FC/10229-1, Dpeartment of Energy, August 1981.

139. Rohrman, F. A., "Analyzing the Effect of Fly Ash on Water Pollution," *Power*, August 1971, pp. 76-77.
140. Diamond, S., Selection and Use of Fly Ash for Highway Concrete, Joint Highway Research Project, Report 85-8, Purdue University, West Lafayette, Indiana, 1985.
141. American Society for testing and Materials, "Standard Specification for Fly Ash and Raw Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete," ASTM Designation C 618.
142. American Society for Testing and Materials, "Standard Methods of Sampling and Testing Fly Ash or Natural Pozzolans for Use as a Mineral Admixture in Portland Cement Concrete," ASTM Designation C 311.
143. Joint Committee on Powder Diffraction Standards, Mineral Powder Diffraction File, JCPDS International Center for Diffraction Data, Swarthmore, Pa., 1980.
144. American Society for Testing and Materials, "Standard Specification for Wire-Cloth Sieves for Testing Purposes," ASTM Designation E 11.
145. Franco, C. A. and Lee, K. W., "An Improved California Bearing Ratio Test Procedure," *Transportation Research Record* 1119, 1987, pp. 91-97.
146. Environmental Protection Agency, Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020.
147. American Society for Testing and Materials, "Standard Test Methods for Moisture-Density Relations of Soil-Cement Mixtures," ASTM Designation D 558.
148. American Society for Testing and Materials, "Standard Test Method for Compressive Strength of Molded Soil-Cement Cylinders," ASTM Designation D 1633.
149. American Association of State Highway and Transportation Officials, "The Classification of Soils and Soil-Aggregate Mixtures for Highway Construction Purposes," AASHTO Designation M 145.
150. Taylor, D. W., "A comparison of Results of Direct Shear and Cylindrical Compression Tests, Proceedings, ASTM, Vol. 39, 1939.
151. Burmister, D. M., "The Importance and Practical Use of Relative Density in Soil Mechanics," Proceedings, ASTM, Vol. 48, 1948.

152. Turnbull, W. J. and Foster C. R., "Compaction of a Graded Crushed-Stone Base Course," Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, Vol. II, London, August 12-14, 1957, pp. 181-188.
153. Shergold, F. A., A Study of the Crushing and Wear of Surface-Dressing Chippings under Rolling and Light Traffic, Research Note No. RN/2298/FAS.B.P. 397, Road Research Laboratory, London, 1954.
154. Hale, B. C., Lovell, C. W., and Wood, L. E., "Development of a Laboratory Compaction-Degradation Test for Shales," Transportation Research Record 790, July 1981, pp. 33-41.
155. Aughenbaugh, N. B., Johnson, R. B., and Yoder, E. J., "Factors Influencing the Breakdown of Carbonate Aggregates during Field Compaction," Transactions, American Institute of Mining Metallurgical and Petroleum Engineers, Vol. 223, December 1962, pp. 402-406.
156. Ekse, M. and Morris, H. C., "A Test for Production of Plastic Fines in the Process of Degradation of Mineral Aggregates," STP 277, ASTM, 1959, pp. 122-126.
157. Erickson, L. F., "Degradation of Aggregates Used in Base Courses and Bituminous Surfacing," Circular 416, Highway Research Board, March 1960, pp. 1-9.
158. Aughenbaugh, N. B., Johnson, R. B., and Yoder, E. J., Degradation of Base Course Aggregates, School of Civil Engineering Report, Purdue University, West Lafayette, Indiana, May 1963.
159. West, T. R., Johnson, R. B., and Smith, N. M., Tests for Evaluating Degradation of Base Course Aggregates, NCHRP Report 98, Highway Research Board, 1970.
160. Jervis, W. H. and Eustis, J. B., "Accepted Procedure for the CBR Test," Transactions, ASCE, Vol. 115, 1950, pp. 472-484.
161. Porter, O. J., "Development of the Original Method for Highway Design," Transactions, ASCE, Vol. 115, 1950, pp. 461-467.
162. Radian Corporation, Characterization of Utility Low-Volume Wastes, EPRI CS-3737, Electric Power Research Institute, Palo Alto, Ca, May 1985.

163. Dodd, D. J. R., Golomb, A., Chan, H. T., and Chartier, D., "A Comparative Field and Laboratory Study of Fly Ash Leaching Characteristics," Hazardous Solid Waste Testing: First Conference, R. A. Conway, et al., editors, ASTM STP 760, Jan. 1981, pp. 164-185.
164. Rinaldo-Lee, M. B., Kunes, T. P., and Nichols, D. G., "A Comparison of Groundwater Quality at Selected Landfills to Leaching Test Results," Hazardous Solid Waste Testing: First Conference, R. A. Conway, et al., editors, ASTM STP 760, Jan. 1981, pp. 201-216.
165. Frascino, P. J. and Vail, D. L., "Utility Ash Disposal: State of the Art," Proceedings, 4th International Ash Utilization Symposium, St. Louis, Mo., March 24-25, 1976, MERC/SP-76/4, pp. 345-368.
166. Nevissi, A. E. and Bodansky, D., "Radon Sources and Levels in the Outside Environment," Chapter 4 in Indoor Radon and Its Hazards, Bodansky, D. et. al., editors, University of Washington Press, Seattle, Washington, 1987.
167. Hartley, J. A. et. al., "Uranium Mill Tailing Stabilization," Waste Management 80, R. G. Post, editor, University of Arizona, Tucson, 1980, pp. 193-204.
168. Collins, R. J. and Miller, R. H., Availability of Mining Wastes and Their Potential for Use as Highway Material, Federal Highway Administration, Report FHWA-RD-76-106, Vol. 1, May 1976.
169. Electrical World, Directory of Electric Utilities, 97th Edition, McGraw-Hill, Inc., New York, 1989.
170. Keystone Coal Industry Manual, McGraw-Hill, New York, 1987.
171. Witczak, M. W., Lovell, C. W., and Yoder, E. J., "A Generalized Investigation of the Potential Availability of Aggregate by Regional Geomorphic Units within the Conterminous Forty-Eight States," Highway Research Record No. 353, 1971, PP. 31-42.
172. Indiana Department of Highways, 1987 Catalog of U.P.A. Prices for Roads, Bridges, and Traffic, Indianapolis, Indiana, 1987.

APPENDICES

Appendix A

X-Ray Diffraction Patterns of Bottom Ashes

Figure A-1. X-ray diffraction pattern of Schaffer Unit 17 ash

Figure A-2. X-ray diffraction pattern of Mitchell ash

Figure A-3. X-ray diffraction pattern of Gibson ash

Figure A-4. X-ray diffraction pattern of Gallagher ash

Figure A-5. X-ray diffraction pattern of Wabash ash

Figure A-6. X-ray diffraction pattern of Perry ash

Figure A-7. X-ray diffraction pattern of Stout ash (first sample)

Figure A-8. X-ray diffraction pattern of Stout ash (second sample)

Figure A-9. X-ray diffraction pattern of Culley ash

Figure A-10. X-ray diffraction pattern of Brown ash

Appendix BSample Form for Calculation of the Index of Crushing

Table B-1. Sample form for calculation of the index of crushing from sieve analysis^a

	A	B	C	D	E
Standard sieve sizes	Mean diameter of sieves (in.)	Initial % retained	Initial Weighted % (columns) AxB	Final % retained	Final Weighted % (columns) AxD
3/4-1/2	0.625				
1/2-3/8	0.438				
3/8-#4	0.281				
#4-#12	0.127				
#12-#40	0.041				
#40-#100	0.011				
#100-Pan	0.003				
			ΣC		ΣE

$$\text{index of crushing} = 100 \times (\Sigma C - \Sigma E) / \Sigma C$$

^a From Shergold [153]

Appendix C

Moisture-Density Curves for Various Ash Mixtures

Figure C-1. Moisture-density curves for various proportions of Gibson bottom ash-fly ash mixtures

Figure C-2. Moisture-density curves for various proportions of Schahfer 17 bottom ash-fly ash mixtures

Figure C-3. Moisture-density curves for fly ashes

COVER DESIGN BY ALDO GIORGINI