POSSIBLE APPLICATIONS FOR CIRCULATING FLUIDIZED BED COAL COMBUSTION BY-PRODUCTS FROM THE GUAYAMA AES POWER PLANT

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Table of Contents

Table of Contents 2

List of Tables 5

List of Figures 5

Acknowledgement 6

Chapter 1: Synopsis 7

Chapter 2: Definitions and Background Information 9

2.1. Introduction 9

2.2. Fly ash 9

2.2.1. Definition of fly ash 9

2.2.2. Chemical properties of fly ash 10

2.2.3. Physical properties of fly ash 11

2.3. Bottom ash 14

2.3.1. Definition of bottom ash 14

2.3.2. Chemical properties of bottom ash 14

2.3.3. Physical properties of bottom ash 15

2.4. Manufactured Aggregate 17

2.4.1. Definition of manufactured aggregate 17

2.4.2. Chemical properties of manufactured aggregate 17

2.4.3. Physical properties of the manufactured aggregate 18

2.5. Summary 20

Chapter 3: Utilizations of CCP's in Geotechnical and Structural Fields 21

3.1. Geotechnical and structural utilizations of fly ash 21

3.1.1. Asphalt pavements 21

3.1.2. Structural fill for embankments and retaining walls 22

3.1.3. Flowable fill 23

3.1.4. Masonry 23

3.1.5. Road 24

3.1.6. Soil stabilization 25

3.1.7. Other uses 26

3.1.7.1. Grout 26

    - 3.1.7.2. Glass 26
    - 3.1.7.3. Paint 27
- 3.2. Geotechnical and structural utilizations of bottom ash 27
    - 3.2.1. Asphalt pavement 27
    - 3.2.2. Structural fill for embankments and retaining walls 28
    - 3.2.3. Masonry 28
    - 3.2.4. Roads 28
- 3.3. Geotechnical and structural utilizations of manufactured aggregate 28
    - 3.3.1. Asphalt pavement 28
    - 3.3.2. Structural fill for embankments and retaining walls 29
    - 3.3.3. Roads 29
    - 3.3.4. Landfill cover 29

Chapter 4: Utilizations of CCP’s in Environmental Engineering Fields 30

- 4.1. Removal of heavy metals 30
- 4.2. Removal of sulfur dioxide, organics and dyes 31
- 4.3. Landfill liners and covers 33
- 4.4. Acid mine drainage treatment 34
- 4.5. Agricultural amendments 34
- 4.6. Waste stabilization/solidification 36
- 4.7. Artificial reefs and shoreline dikes 36
- 4.8. Agricultural and environmental uses of lime 39

Chapter 5: Recommended Applications of CCP’s in Geotechnical and Structural Fields 42

- 5.1. Recommendation 1: Fly ash for ground improvement 42
- 5.3. Recommendation 2: Road construction 43
- 5.4. Recommendation 3: Structural fill 43

Chapter 6: Recommended Applications of CCP’s in Environmental Fields 45

- 6.1. Alkaline characteristics of AES CCP’s 45
    - 6.1.1. Methodology 45
    - 6.1.2. Experimental results 46
- 6.2. Recommendation 1: Alkaline explosives remediation 47

6.3. Recommendation 2: Agricultural amendment 48
Chapter 7: Summary and Conclusions 50
References 51
Appendix A. Literature Review Summary Tables 66

List of Tables

Table 1. Chemical requirements for fly ash according to ASTM C 618. 10

Table 2. Chemical composition of AES fly ash[1]. 11

Table 3. Physical requirements for fly ash according to ASTM C 618. 12

Table 4. Typical gradation for AES fly ash in tabular form. 13

Table 5. Chemical composition of AES bottom ash[1]. 15

Table 6. Typical gradation for AES bottom ash in tabular form. 17

Table 7. Chemical description of manufactured aggregate[1]. 18

Table 8. Gradation for the AES manufactured aggregate (Kochyil & Little 2004). 19

Table 9. AASHTO M17 requirements for mineral filler use in asphalt paving mixtures. 21

List of Figures

Figure 1. Typical gradation curve of AES fly ash. 13

Figure 2. Typical gradation curve for the AES bottom ash. 16

Figure 3. Gradation curve for the AES manufactured aggregate (Kochyil & Little 2004). 19

Figure 4. Metals most commonly present at Superfund sites (US EPA, 1996)................ 31

Figure 5. Structures of higher-order explosives TNT, RDX and HMX. 32

Figure 6. Puerto Rican coral reef locations.. 37

Figure 7. An example of man-made artificial reef... 38

Figure 8. Schematic of shoreline erosion dike with FGD, fly ash and cement core (Rusch et al., 2002). 39

Figure 9. Schematic of a retaining wall with manufactured aggregate backfill. 44

Figure 10. Kinetics of pH evolvement in 20 g/L CCP solution....................................... 46

Figure 11. Effect of CCP concentration on pH strength... 47

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Chapter 1: Synopsis

This report summarizes the result of a literature review process carried on behalf of AES Puerto Rico, LP (AES) for the time period of June 1 to August 15 of 2005. The literature review was carried out with the main objective to gather information regarding potential uses and applications for coal combustion by-products (herein abbreviated CCP's) such as fly ash (FA), bottom ash (BA), and manufactured aggregate (MA). The project was carried out by 4 university students with the guidance from two professors.

The activities carried out consisted in consulting literature databases, organization webpages, thesis, dissertations, specialized article databases, and other sources. The information was classified into different groups based on the general area of the application. The information gathered is summarized in the matrix tables in Appendix A.

The main objective of the study was to identify possible applications for circulating fluidized bed (CFB) coal combustion by-products (CCP's) from the Guayama facility of AES Puerto Rico, LP. This facility produces the following CCP's: FA, BA, and MA. The applications identified as part of this study were rated for possible detailed studies based on three criteria: utilization volume of CCP's, cost, and potential benefits.

This report also provides recommendations for carrying out feasibility studies for some selected applications which appear to have good potential for Puerto Rico.

This report is organized into 7 chapters and one appendix. Chapter 2 presents general definitions of CCP's and a general description of the CCP's generated at the Guayama plant of AES Puerto Rico, LP. The description of the Guayama CCP's was based on information of physical and chemical properties provided by AES Puerto Rico, LP.

Chapter 3 contains a summary of CCP recycling applications identified in the literature review related to the geotechnical/structural engineering field. The applications are presented in three subsections (FA, BA, and MA).

Chapter 4 presents a summary of the identified recycling applications in the broad field of environmental engineering. The applications are presented in three subsections (FA, BA, and MA).

Chapters 5 and 6 provide the recommended recycling applications for the CFB CCP’s of AES for the fields of geotechnical/structural engineering and environmental engineering, respectively. These recommendations took consideration of the specific characteristics related to the Guayama AES CFB CCP’s and the context of Puerto Rico.

Summary and conclusions are presented in Chapter 7. The detailed results from the literature review are presented in Appendix A.

Chapter 2: Definitions and Background Information

2.1. Introduction

The AES power plant facility in Guayama, Puerto Rico mainly produces two types of CCP's: fly ash (FA) and bottom ash (BA). By mixing these two products with water, the AES Guayama facility also produces a third by-product referred to as manufactured aggregate (MA). A general description of the three CCP's produced at the AES Guayama facility will be reviewed in this chapter. Physical and chemical characterization of the different CCP's produced at the Guayama power plant was not part of the scope of this study. However, an adequate and thorough characterization of the CCP's is very important to be able to determine the feasibility of their use for the different possible applications identified in this study.

The following subsections provide general descriptions of the three CCP's produced in the AES Guayama plant. The information presented is primarily based on information provided by AES, and complemented in a few instances with results from preliminary laboratory tests performed at UPRM during this project.

2.2. Fly ash

2.2.1. Definition of fly ash

Fly ash is the finely divided mineral that results from the combustion of pulverized coal produced during the steam generation process in the power plant. The fly ash particles solidify while suspended in the exhaust gases and are collected by electrostatic precipitations. The physical and chemical characteristics of fly ash can vary greatly and will mainly depend on the combustion method and coal properties used at a particular power plant. Fly ash is commonly used as a pozzolan, reacting in the presence of water with calcium hydroxide at ordinary temperatures to produce cementitious compounds. The pozzolanic properties of fly ash can be stabilized with cement or lime.

2.2.2. Chemical properties of fly ash

Fly ash consists primarily of silica, aluminum, iron, and calcium oxides. Other elements; such as magnesium, potassium, sodium, titanium and sulfur; are also present to a lesser degree. According to the American Society for Testing and Materials (ASTM) (ASTM Standard C 618), fly ash can be classified in 2 main types: Class C, and Class F. Class C, is a fly ash with high calcium content (>20% by weight), and Class F, a low calcium fly ash (<10% by weight). The principal factors that influence the classification of fly ash are the percentages of silica (SiO_2), alumina (Al_2O_3), and ferric oxide (Fe_2O_3.). Table 1 shows the chemical requirements specified in ASTM Standard C 618 (ASTM 2005) for the two main types of fly ash.

Table 1. Chemical requirements for fly ash according to ASTM C 618.

Chemical		**Class**	
		F	**C**
$SiO_2 + Al_2O_3 + Fe_2O_3$	min %	70	50
SO_3	max%	5	5
Moisture Content	max%	3	3
Loss on Ignition	max%	6	6
Optional Chemical			
Available Alkalies	max %	1.5	1.5

No chemical analyses were completed as part of this study. However, results of chemical analyses for the fly ash from the Guayama AES power plant were provided by AES Puerto Rico, LP and are summarized in Table 2. The information provided in this table is based on chemical analyses carried out by SGS North America Inc. on January 19, 2005 from a sample obtained on December 16, 2004. Based on the results listed in Table 2, the AES fly ash complies with most of the chemical requirements for a Class C fly ash. However, the content of sulfur trioxide (SO_3) of 12.57% exceeds the 5% maximum percentage specified in ASTM Standard C 618.

Table 2. Chemical composition of AES fly ash[1].

Analysis of Fly ash	**Result**
Silica, SiO_2 (% by Weight)	39.41
Alumina, Al_2O_3 (% by Weight)	12.59
Ferric Oxide, Fe_2O_3 (% by Weight)	4.35
$SiO_2 + Al_2O_3 + Fe_2O_3$ (% by Weight)	**56.35**
Titania, TiO_2 (% by Weight)	0.51
Lime, CaO (% by Weight)	27.02
Magnesia, MgO (% by Weight)	1.27
Potassium Oxide, K_2O (% by Weight)	1.17
Sodium Oxide, Na_2O (% by Weight)	0.44
Sulfur Trioxide, SO_3 (% by Weight)	12.57
Phosphorus Pentoxide, P_2O_5 (% by Weight)	0.28
Strontium Oxide, SrO (% by Weight)	0.14
Barium Oxide, BaO (% by Weight)	0.23
Manganese Oxide, Mn_3O_4 (% by Weight)	0.02
Undetermined (% by Weight)	0
Alkalis as Na_2O, Dry Coal Basis (% by Weight)	1.12
Base to Acid Ratio	0.65
T250 Temperature (^oC)	2224

Note: (1) Data from SGS as provided by AES Puerto Rico, LP.

2.2.3. Physical properties of fly ash

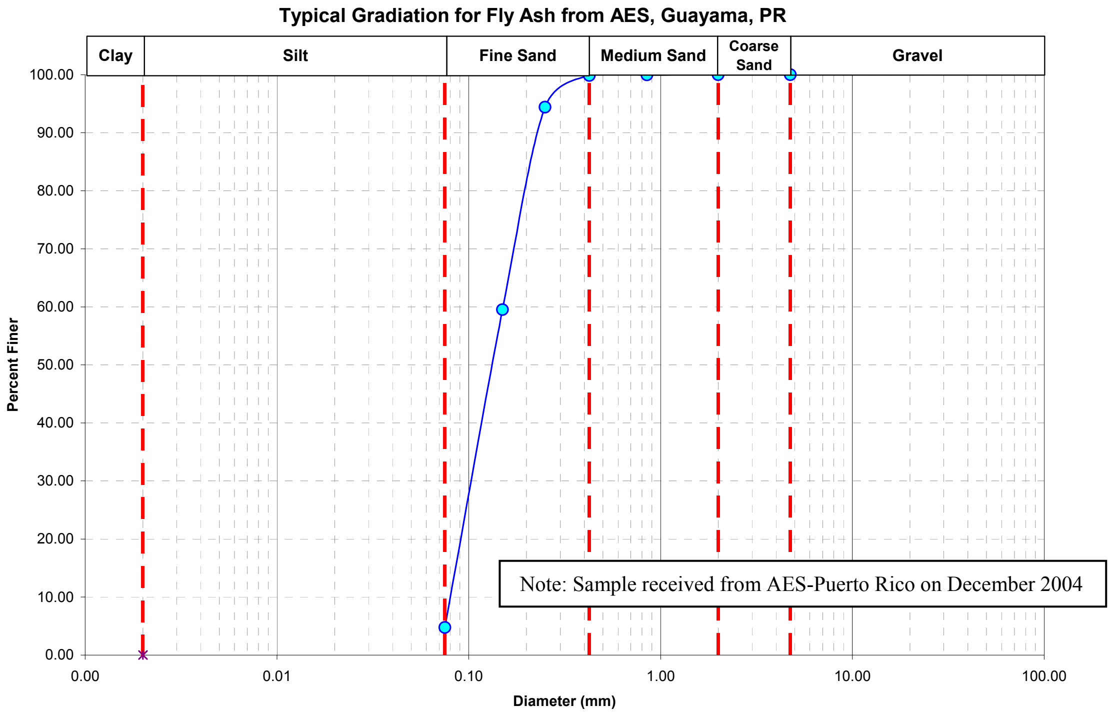
Typically, fly ash consists of spherical silt-sized particles finer than Portland cement and lime, i.e., particle sizes ranging between 10 and 100 microns. Fly ash is usually dark gray in color, but this depends on its chemical composition and mineral constituents (e.g., fly ash with high calcium content usually is cream colored, and fly ash from bituminous coal is gray colored due to its high carbon content). Approximately 80% of fly ash consists of tiny glass spheres. The other 20% is composed of quartz, mullite, hematite and magnetite. The specific gravity (equal to the density of the material divided by the density of water) of most fly ash is between 1.9 and 2.5 (Hausmann, 1990). Its dry density in a compacted state can vary between 70 and 115 lb/ft^3. The friction angle of fly ash is typically of the order of 30^o, but values between 20^o and 40^o

have been reported (Hausmann, 1990). Table 3 shows the physical requirements specified in ASTM Standard C 618 for the two main types of fly ash.

Table 3. Physical requirements for fly ash according to ASTM C 618.

Physical		**Class**	
		F	**C**
Fineness (+ 325 Mesh)	max %	34	34
Strength Activity/Cement	min %	75	75
Water Requirement	max %	105	105
Autoclave Expansion	max %	0.8	0.8
Uniformity Requirements:			
- Density Maximum Variation	max %	5	5
- Fineness Points Variation	max %	5	5
Other Physical characteristics:			
Multiple factor		255	-
Drying Shrinkage	max %	0.03	0.03
Uniformity Requirements:			
- A.E. Admixture Demand	max %	20	20
Control of ASR:			
- Expansion, % of low alkali cement	max %	100	100
Sulfate Resistance:			
- Moderate exposure, 6 months	max %	0.10	0.10
- High exposure, 6 months	max %	0.05	0.05

While determination of physical properties of the AES fly ash were not required as part of this study, the specific gravity and the grain size distribution were determined from a 55-gallon drum sample received from AES, in December 2004. Following procedures in general accordance with the ASTM standards, the specific gravity for the AES fly ash was determined to be 2.55. The particle size distribution, or gradation curve, was obtained from a representative sample by mixing sub-samples following the AASHTO Standard T-248. A gradation test was carried out following ASTM Standard C-136, and the resulting gradation curve is shown in Figure 1. The gradation results are presented in tabular form in Table 4. Hydrometer tests were attempted to define the gradation for size fractions below sieve No. 200. However, during hydrometer testing the fly ash reacted with water impeding the completion of the test. Use of an alternative method is recommended for determination of the particle sizes below 0.075 mm.



Note: Sample received from AES-Puerto Rico on December 2004

Figure 1. Typical gradation curve of AES fly ash.

Table 4. Typical gradation for AES fly ash in tabular form.

Sieve Identification	Sieve size (mm)	Total % passing
#4	4.750	100.00
#10	2.000	100.00
#20	0.850	99.97
#40	0.425	99.87
#60	0.250	94.42
#100	0.150	59.52
#200	0.075	4.73
P-200	0	0.00

From the above results it can be seen that the AES fly ash has a gradation similar to fine sand. A detailed evaluation of the physical, mineralogical, and mechanical properties of the AES fly ash is recommended in order to better determine the suitability of this CCP for the different applications identified in this review.

2.3. Bottom ash

2.3.1. Definition of bottom ash

Bottom ash is a CCP consisting of coarse grained particles that fall to the bottom of the furnace as a result of the coal combustion procedures. It is usually the smaller portion of the total ash produced during the coal combustion process. Bottom ash may be vitrified or clinkered, but is friable. Similar to fly ash, the physical and chemical characteristics of bottom ash will mainly depend on the combustion method and coal properties used at a given power plant. The typical chemical and physical properties of bottom ash, as well as the specific information available for the AES bottom ash, are described below.

2.3.2. Chemical properties of bottom ash

The chemical composition of bottom ash is similar to fly ash. However, bottom ash is more inert than fly ash, and as a result, bottom ash particles have a greater tendency to fuse together. Due to this increase in fusing, bottom ash displays less pozzolanic properties than fly ash. Bottom ash is composed principally of silica (SiO_2), alumina (Al_2O_3), and iron with smaller percentages of calcium, magnesium, sulfates and other compounds.

Results of chemical analyses for the bottom ash from the AES power plant in Guayama were supplied by AES and are summarized in Table 5. The information provided in this table is based on chemical analyses carried out by SGS North America Inc. on January 19, 2005 from a sample obtained on December 16, 2004. Based on the results listed in Table 5, the main components of the AES bottom ash are silica+alumina+ferric oxide ($SiO_2 + Al_2O_3 + Fe_2O_3$), lime (CaO), and sulfur trioxide (SO_3), representing 47%, 36%, and 12.8% by weight, respectively.

Table 5. Chemical composition of AES bottom ash[1].

Analysis of Fly ash	Result
Silica, SiO_2 (% by Weight)	30.83
Alumina, Al_2O_3 (% by Weight)	12.2
Ferric Oxide, Fe_2O_3 (% by Weight)	3.95
$SiO_2 + Al_2O_3 + Fe_2O_3$ (% by Weight)	**46.98**
Titania, TiO_2 (% by Weight)	0.57
Lime, CaO (% by Weight)	36.02
Magnesia, MgO (% by Weight)	1.58
Potassium Oxide, K_2O (% by Weight)	0.66
Sodium Oxide, Na_2O (% by Weight)	0.55
Sulfur Trioxide, SO_3 (% by Weight)	12.82
Phosphorus Pentoxide, P_2O_5 (% by Weight)	0.37
Strontium Oxide, SrO (% by Weight)	0.15
Barium Oxide, BaO (% by Weight)	0.27
Manganese Oxide, Mn_3O_4 (% by Weight)	0.03
Undetermined (% by Weight)	0
Alkalis as Na_2O, Dry Coal Basis (% by Weight)	0.95
Base to Acid Ratio	0.98
T250 Temperature (^oC)	2393

Note: (1) Data from SGS as provided by AES Puerto Rico, LP.

2.3.3. Physical properties of bottom ash

The physical properties of bottom ash are similar to those of natural sand, with particle sizes ranging from gravel to fine sand with low percentages of silt and clay-sized particles. Bottom ash is typically grey to black in color and has a large particle size, angular shape and high porous surface resulting in a higher water requirement and lower compressive strength. The angle of internal friction for this material can range from 35 to 50 degrees, depending of its compaction density, mineral content, and particle size and angularity. Information about corrosion potential for structures buried in bottom ash is limited in the literature, and usually corrosivity is verified with proper tests. Bottom ash is commonly used as a replacement for aggregate because it is well-graded in size which avoids the need for blending with other fine aggregates to meet construction gradation requirements.

As with fly ash, the specific gravity and the grain size distribution of the AES bottom ash were determined from a 55-gallon drum sample received in December 2004. The specific gravity for the AES bottom ash was determined to be 2.78 using procedures in general accordance with the ASTM standards. A representative sample was obtained by mixing sub-samples obtained following AASHTO Standard T-248. The gradation curve obtained following ASTM Standard C-136 is shown in Figure 2.

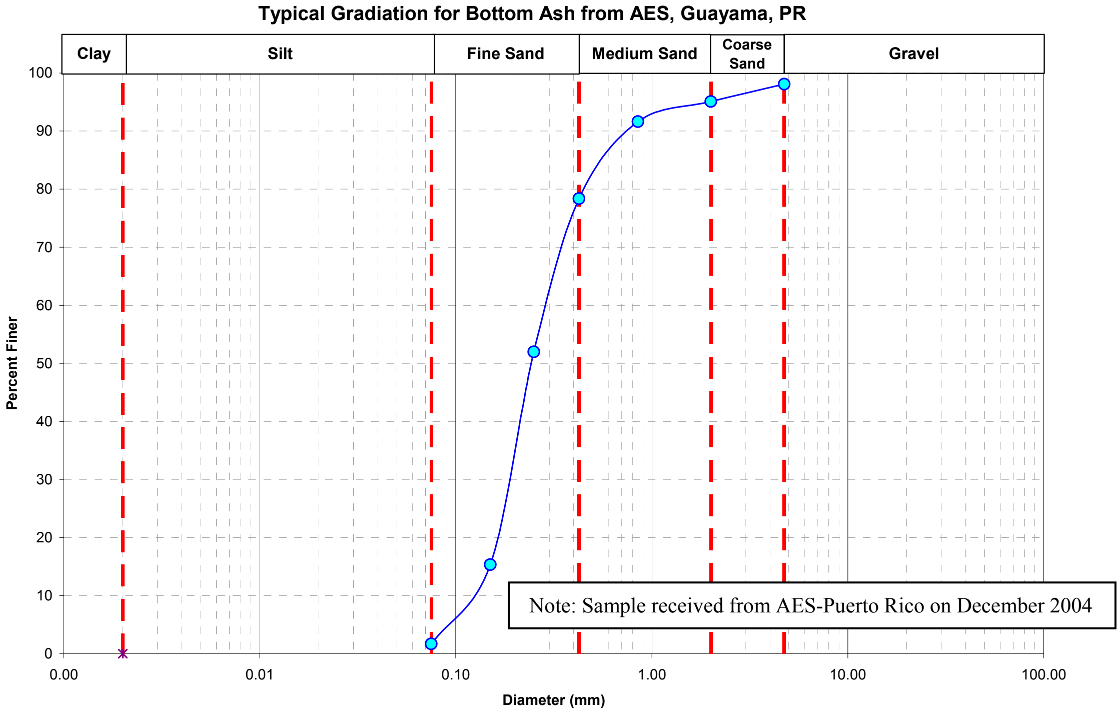


Figure 2. Typical gradation curve for the AES bottom ash.

Results from the gradation experiment are presented in Table 6. Gradation results indicate that the AES bottom ash has a gradation similar to a fine to medium sand. During testing of the bottom ash, a tendency of volume change was observed when the material was exposed to water. Even though no tests were performed to determine change in volume, it was observed that a saturated sample expanded as much as 25% of its original volume. Expansion due to moisture should be evaluated for this material. It is expected that the observed tendency to swell will mainly occur for low vertical pressure conditions.

Table 6. Typical gradation for AES bottom ash in tabular form.

Sieve Identification	Sieve size (mm)	Total % passing
#4	4.750	98.08
#10	2.000	95.09
#20	0.850	91.62
#40	0.425	78.36
#60	0.250	51.97
#100	0.150	15.35
#200	0.075	1.69
P-200	0	0.00

A detailed evaluation of the physical, mineralogical, and mechanical properties of the AES bottom ash is recommended in order to better determine the suitability of this CCP for the different applications identified in this review.

2.4. Manufactured Aggregate

2.4.1. Definition of manufactured aggregate

Manufactured aggregate (MA) is an agglomerate of fly and bottom ash particles. This material gains strength with time due to cementitious reactions. A detailed description of the manufactured aggregate from AES can be found in Kochyil and Little (2004). A summary of the main findings from this study is provided below.

2.4.2. Chemical properties of manufactured aggregate

Results of chemical analyses for the manufactured aggregate from the AES power plant in Guayama were supplied by AES and are summarized in Table 7. The information provided in this table is based on chemical analyses carried out by SGS North America Inc. on January 19, 2005 from a sample obtained on December 16, 2004. Based on the results listed in Table 7, the main components of the AES bottom ash are silica+alumina+ferric oxide (SiO_2 + Al_2O_3 + Fe_2O_3), lime (CaO), and sulfur trioxide (SO_3), representing 51%, 30%, and 14.7% by weight, respectively.

Table 7. Chemical description of manufactured aggregate[1].

Analysis of manufactured aggregate	% Wt
Silica, SiO_2	34.79
Alumina, Al_2O_3	11.97
Ferric Oxide, Fe_2O_3	4.19
$SiO_2 + Al_2O_3 + Fe_2O_3$	**50.95**
Titania, TiO_2	0.51
Lime, CaO	29.67
Magnesia, MgO	1.11
Potassium Oxide, K_2O	0.76
Sodium Oxide, Na_2O	1.52
Sulfur Trioxide, SO_3	14.66
Phosphorus Pentoxide, P_2O_5	0.32
Strontium Oxide, SrO	0.23
Barium Oxide, BaO	0.24
Manganese Oxide, Mn_3O_4	0.03
Undetermined	0
Alks. As Na_2O, Dry Coal Basis	1.76
Base:Acid Ratio	0.79
T250 Temperature	2198

Note: (1) Data from SGS as provided by AES Puerto Rico, LP.

2.4.3. Physical properties of the manufactured aggregate

The physical properties of the manufactured aggregate presented in this section are from the study by Kochyil and Little (2004). This study involved determination of several properties of manufactured aggregate from AES Puerto Rico, LP to determine its potential for using it in civil engineering applications.

Based on gradation tests from Kochyil and Little (2004), manufactured aggregate has a similar gradation as a natural gravel, with particle sizes ranging from gravel to fine sand with very low percentages of silt and clay-sized particles. The gradation curve obtained in this study is shown in Figure 3. Results from their gradation experiment are presented in Table 8. From the gradation results it can be seen that the AES manufactured aggregate has a gradation similar to sandy gravel.

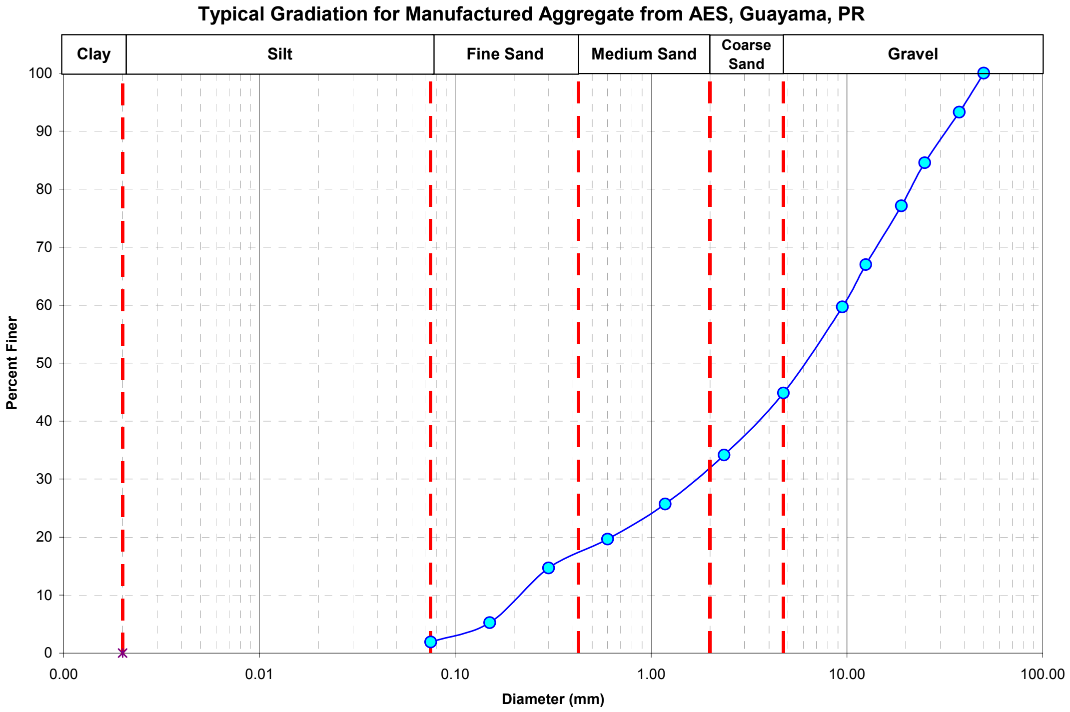


Figure 3. Gradation curve for the AES manufactured aggregate (Kochyil & Little 2004).

Table 8. Gradation for the AES manufactured aggregate (Kochyil & Little 2004).

Sieve Identification	Sieve size (mm)	Total % passing
2 in	50.8	100
1.5 in	37.5	93.27
1 in	25.4	84.55
0.75 in	19	77.12
0.5 in	12.5	66.99
3/8 in	9.5	59.7
#4	4.75	44.84
#8	2.36	34.16
#16	1.18	25.72
#30	0.6	19.65
#50	0.3	14.66
#100	0.15	5.24
#200	0.075	1.92
P-200	0	0.00

The specific gravity for the AES manufactured aggregate was determined by Kochyil & Little (2004) for the fine (smaller than 2.36 mm) and coarse (larger than 2.36 mm) fractions. The average specific gravity for the coarse fraction was found to be about 1.16, while the fine fraction had an specific gravity of about 2.69. The low specific gravity of the coarse aggregate is due to the high void content of this fraction. The high void ratio content of the coarse aggregate was found to be related to a structure of an agglomerate of particles. These large particles are actually agglomeration of finer particles that were found to be susceptible to abrasion and breakdown. The specific gravity value obtained for the fine fraction is consistent with typical values found in natural aggregates (Kochyil & Little, 2004). A detailed evaluation of the physical, mechanical, and chemical properties of the AES manufactured aggregate can be found in Kochyil & Little (2004).

2.5. Summary

This chapter presented a general description of the three types of CCP's produced at the Guayama facility of AES. The information presented was based primarily on information provided by AES.

A detailed evaluation of the physical, mineralogical, mechanical, and chemical properties of the AES CCP's was outside the scope of this study; however it is highly recommended in order to better determine their suitability for the different applications identified in this literature review study. Additionally, although negative environmental impacts from AES CCP's are unlikely environmental studies such as leachate composition are recommended.

Chapter 3: Utilizations of CCP's in Geotechnical and Structural Fields

The aim of this chapter is to provide readers with a summary of the potential applications of CCP's identified in this literature review study. This chapter presents applications related to geotechnical and structural engineering. Utilizations of CCP's in the field of environmental engineering and science are described in Chapter 4.

Utilizations of fly ash are first described, followed by those of bottom ash and then finally those of manufactured aggregate. A detailed summary can be found in the tables provided in Appendix A, which include listings of all the references consulted divided by topic and they include a summary of the main findings of each reference.

3.1. Geotechnical and structural utilizations of fly ash

3.1.1. Asphalt pavements

Fly ash has been reported as been used as mineral filler in asphalt paving mixtures (Hinislioglu and Bayrak 2004; Naik et al. 2001; Bin-Shafique et al. 2004). Fly ash has been found to increase asphalt stiffness and improve the overall resistance of pavements. According to AASHTO M17, any mineral filler of asphalt mixtures must meet the requirements shown in Table 9. These requirements are related to particle sizing, organic impurities and plasticity index. The AES fly ash meets the particle sizing requirements shown in this table. Tests to determine the organic impurities and plasticity index must be conducted to determine whether AES fly ash also meets these AASHTO criteria. References related to the asphalt pavement application are summarized in Table A.2 in Appendix A.

Table 9. AASHTO M17 requirements for mineral filler use in asphalt paving mixtures.

Particle Sizing		Organic Impurities	Plasticity Index
Sieve Size	Percent Passing		
0.6 mm (No. 30)	100	Mineral filler must be free from any organic impurities	Mineral filler must have plasticity index not greater than 4
0.3 mm (No. 50)	95 – 100		
0.075 mm (No. 200)	70 – 100		

3.1.2. Structural fill for embankments and retaining walls

A popular application for fly ash is as structural fill for embankments and retaining walls (Hausmann 1990). This application is attractive because it involves recycling medium- to high-volumes of this CCP. Cost benefits can be considerable taking into account that significant quantities of soil could be substituted by fly ash. Martin et al. (1990) found that Class F fly ash from Pennsylvania, Delaware and New Jersey was compacted in a short time using similar methods to those used in granular soils. Further, the overall performance of fly ash was found comparable to graded natural borrowed material. Kim et al. (2005) and Pusadkar and Ramasamy (2005) reported successful use of mixtures of fly ash and bottom ash for highway embankment applications. However, they observed that hydraulic conductivity of compacted ash mixtures decreased with the increase of fly ash content. Pusadkar and Ramasamy (2005) studied the collapse potential of fly ash used in fills. The collapse of a fill using only fly ash was unavoidable, but mixtures of 50% fly ash and 50% bottom ash had negligible collapse. Additionally, the findings indicated that aging reduces the potential of collapse significantly and that collapse settlement increases linearly with rise of water.

The use of high volume fly ash fill is suitable for highway embankments if proper design and construction procedure are followed. The references reviewed (See Table A.4 in Appendix A) indicate the following considerations should be taken when fly ash is being considered for structural fill applications:

- Check for potential corrosion of buried steel pipes,
- Check potential impact to ground water (although considered low),
- Need good monitoring and quality control during construction,
- Check possibility of presence of radioactive components in some CCP's (not likely in FBC CCP's,
- Perform a thorough characterization of the CCP (e.g., compressibility, shear strength, permeability, compaction moisture-density relationship, etc),
- Check potential concern with wind and surface water erosion.

The literature reviewed indicates that utilization of fly ash for this application is viable and cost-competitive. However, use of mixtures of fly ash and bottom ash were reported to be more suitable.

3.1.3. Flowable fill

Flowable fill refers to cementitious slurry consisting of a mixture of fine aggregate or filler, water, and cementitious material(s), which is used primarily as a backfill in lieu of compacted earth. Flowable fill is capable of filling all voids in irregular excavations and hard to reach places (such as under and around pipes), is self-leveling, and hardens in a matter of a few hours without the need for compaction in layers.

Wilson (1999) conducted a study for the Wisconsin Department of Transportation to compare the performance of bridge abutments constructed with flowable fill using fly ash to those made with conventional granular backfill. The flowable fill used in this research was composed of sand, fly ash (class C), cement, and water. It was observed that the abutments with flowable fill performed slightly better it terms of settlements than those with conventional fill. However, cold weather and saturated conditions resulted in long set times. Wilson (1999) cited another project where abutments built with fly ash flowable fill performed satisfactorily. More details of this reference is provided in Table A-5 in Appendix A.

To determine the suitability of AES fly ash for this application additional the following tests are recommended:

- Evaluation of expansion potential,
- Determination of achievable compressive strengths,
- Perform flowability tests, and
- Verify corrosion potential.

3.1.4. Masonry

Use of fly ash in the manufacturing of masonry units has been investigated by many (e.g., Gonzalez-Otero et al. 2004, Phillips et al. 2005, and Kayali 2005). These authors indicate that fly ash is a potential source to manufacture this kind of construction element. Manufactured bricks with fly ash have good mechanical strength, low thermal conductivity and good insulation properties. Wu and Sun (2003) compared fly ash class C and F, and established that class C fly ash is more active, having better performance and consequently better results when used for building masonry units. Kayali (2005) found that masonry units made with fly ash had higher compressive strengths than commercial bricks.

The references found for this application are summarized in Table A-6 in Appendix A. The majority of the studies found used 100% fly ash to prepare the mix for the masonry units. It is important to mention that the addition of fiber is necessary to increase ductility and improve other important characteristics when using fly ash for masonry.

Since AES fly ash does not conform exactly to Class C or Class F fly ash, it is recommended to do a specific study to evaluate the feasibility of using this CCP for manufacturing of masonry units.

3.1.5. Road

This subsection presents a summary of references where fly ash has been used in road projects. The references reviewed included several applications related to road projects, for example: use for road base and subbase (Barenberg 1974, Lav and Lav 2000; Mulder 1996; Kroeger and Chugh 2003; Deschamps 1998), use as additive for improving concrete pavements (Kuennen 2004), use in rural roads (Basak, Bhattacharya and Paira 2004), etc. A summary of the references reviewed is presented in Table A-8 in Appendix A.

Many of the reported fly ash applications in road projects experimented positive results. However, an important consideration when using fly ash for roads is the potential for the formation of an expansive mineral called ettringite which can result in adverse effects in this application. The formation of ettringite is related to the quantity of calcium hydroxide available. In controlled quantities, ettringite may improve some characteristics of the fly ash, but in relatively high humidity (e.g., the tropical environment of Puerto Rico) it can increase crack formation. Evaluation of ettringite formation for AES fly ash is recommended.

The literature reviewed also recommends that fly ash should not have soluble sulphate contents exceeding 1.9 gm per liter (Basak et al. 2004). Mixtures of soils and fly ash can result in improved parameters such as plasticity index, liquid limit, plastic limit and values of CBR (Basak et al. 2004).

3.1.6. Soil stabilization

Expansive soils are a major problem in many countries around the world including Puerto Rico. Jones and Jones (1987) estimated the annual damage due to expansive soils in the United States to be about 9 billion dollars, constituting the most costly natural hazard in the US (ahead of earthquakes, hurricanes, and floods). Expansive soils typically involve the presence of clay minerals such as montmorillonite which have a tendency to absorb great amounts of water resulting in large volume increases.

Currently, there are various methods to improve soil conditions and avoid continuous damage to buildings. Typically these stabilization methods include using additives such as Portland cement, and lime. More recently fly ash and lime-fly ash mixtures have been used and tested. Specifically, the use of coal fly ash has been implemented for this application and has been investigated in various studies (e.g., Cokca 2001; Kukko 2000; Kumar and Sharma 2004; and Nalbangtoglu and Emin 2002). More details of these references are provided in table A-9 in Appendix A.

In general, these references indicate that mixing expansive soils with high calcium fly ash significantly reduces swelling potential. The admixture with fly ash results in a reduction of voids in the soil mass due to the small particle size of this CCP. The general trend observed is that fly ash amended soils have reductions in their plasticity, hydraulic conductivity, and swelling potential. Their dry unit weight and strength increases with increasing fly ash content. Increasing fly ash content and curing time decreases the activity of the mixtures of expansive soils. The optimum amount of fly ash addition depends on soil type, moisture content, fly ash type, but appears to be close to 20% by weight (Cocka 2001). The references reviewed recommend mixing dry fly ash for this application. Typically environmental agencies require a leaching test when using fly ash admixtures to stabilize soils.

Trzebiatowski et al. (2004) presented an interesting case study involving stabilization of a road subgrade using fly ash. The case history used Class C fly ash from the Pleasant Priarie Electric Power plant in Wisconsin. Before stabilizing, the road subgrade consisting of sandy clay was soft and very difficult to work on. The soft subgrade was stabilized in situ by spreading fly ash over the weak soil using a lay-down truck. Then a road reclaimer was used to mix the fly ash into the subgrade to a depth of about 1 foot. The mixture was then compacted with a field compactor. The resulting treated subgrade resulted in a firm working platform which provided good conditions for road construction. All field and laboratory tests indicated significant stiffness and strength improvement with the fly ash stabilization.

3.1.7. Other uses

This section presents recycling applications for coal fly ash including grout, glass, paints, and others generally studied outside the general field of civil engineering.

3.1.7.1. Grout

Markou and Atmatzidis (2002) investigated the feasibility of using pulverized fly ash for producing grout. This study indicated that grout made of pulverized fly ash (PFA) had strengths about 50% lower compared to conventional grout made with portland cement. However it had good injectability and setting times comparable to Portland cement grout. No more references were found for this application. The study by Markou and Atmatzidis (2002) involved a fly ash with containing 32% of CaO, a quantity close to the AES fly ash (which is close to 27%).

This application could be feasible. A detailed feasibility study is recommended. This application, if found viable, would be considered a low-volume recycling alternative.

3.1.7.2. Glass

Sheng et al. (2003) conducted research to study use of coal fly ash for glass production. Fly ash contains large amounts of SiO_2 and Al_2O_3, compounds that are main glass network formers, making it advantageous for use in glass production. This study revealed that fly ash alone is insufficient for glass production. Using 10% by weight of NaO_2 resulted in good quality glass with adequate durability and viscosity. The concern regarding the presence of some metals in the fly ash was dissipated as the metals were successfully solidified into the glass structure posing no harm. The fly ash used in this study had a very low content of CaO (2.97%). Further studies would be necessary to study feasibility of the AES fly ash for this application.

3.1.7.3. Paint

Companies like Pruett-Schaffer Paint are involved in the use of waste materials, including fly ash used in waste ink toners. The shape of the ash particles provides an adequate protective coating given its hardness and abrasion-resistance. Paint companies have used fly ash as filler and applied successfully to bridges in marine environments having good performance.

3.2. Geotechnical and structural utilizations of bottom ash

As mentioned in Chapter 2, bottom ash is a coarser material than fly ash with similar size characteristics to sand. The same applications discussed in Section 3.1, for fly ash, are presented below.

3.2.1. Asphalt pavement

Bottom ash has been used primarily in cold mix asphalts since they can contain lightweight and porous particles that make them less suitable for hot mix asphalts (Chesner et al., 2005). Robnett (1983) presents a data base of use of bottom ash as a paving material. Vassiliadou and Amirkhanian (1999) studied the effect of partially substituting the fine aggregates of an asphalt concrete mixture with bottom ash. Their study found that fine aggregate replacement with bottom ash was a feasible application that showed adequate pavement performance. Ksaibati and Conner (2004) present results of a laboratory evaluation that indicates bottom ash may be feasible for use in hot mix asphalts.

3.2.2. Structural fill for embankments and retaining walls

As mentioned in Section 3.1.2, mixtures of fly ash and bottom ash have been used successfully in highway embankment projects (Kim et al. 2005, Pusadkar and Ramasamy 2005). In fact, collapse behavior of compacted fill was found to be lessened with increasing bottom ash content (Pusadkar and Ramasamy, 2005).

3.2.3. Masonry

Phillips, Gropo and Peronne (2005) evaluated processed bottom ash for use as lightweight aggregate for concrete masonry units. The units containing bottom ash were compared to units that contained class C and class F fly ash, with the goal to reach 1000 psi strength in three days. The units that used bottom ash as aggregate did not reach this goal. The authors suggest, it may be possible to find use for bottom ash as a partial aggregate for masonry production in combination with other materials.

3.2.4. Roads

Bottom ash has been used in stabilized and unbound road subbase or base applications since the 1960's (Chesner et al. 2005). These authors report about several successful road projects involving use of bottom ash in Georgia, Illinois, Michigan, North Dakota, Ohio, and West Virginia.

3.3. Geotechnical and structural utilizations of manufactured aggregate

3.3.1. Asphalt pavement

Crushed manufactured aggregate (MA) could potentially be used as a fine aggregate in asphalt mixtures. However, Kochyil and Little (2004) do not consider this application as feasible due to the high abrasion potential they found for the manufactured aggregate. This same study considered MA should perform well as mineral filler in asphalt.

3.3.2. Structural fill for embankments and retaining walls

Kochyil and Little (2004) consider feasible the use of manufactured aggregate for fill material for applications such as retaining walls. These authors found MA has drainage similar to fine sand with a lower unit weight. However, recommend adequate drainage is provided and that it is not allowed to become saturated for extended periods of time. This could result in loss of strength and degradation.

3.3.3. Roads

Kochyil and Little (2004) list as another potential application for MA its use as subbase and base layers in roads with low traffic. This application requires use of MA in areas with sufficient drainage to prevent saturation.

3.3.4. Landfill cover

The final application identified by Kochyil and Little (2004) is using it for landfill cover. This study considers MA is best suited for daily landfill cover; however it can also be used for intermediate and final cover.

Chapter 4: Utilizations of CCP's in Environmental Engineering Fields

Utilization of coal combustion products has also been applied in the environmental engineering fields, although not as commonly as in structural and geotechnical engineering. These fields of applications are not individually separated. For instance, approximately one ton of carbon dioxide (CO_2) is produced for every ton of cement produced. In this regard, if one ton of cement is replaced by the same amount of fly ash, we can expect to reduce one ton of CO_2 emissions into the atmosphere, implying that such structural applications have an impact on the environment.

This chapter focuses on the application of Class C-type coal fly ash from power generation plants to environmental fields: removals of heavy metals, sulfur dioxide, organics and dyes, landfill liners and covers, acid mine drainage treatment, agricultural amendments, waste stabilization/solidification, and construction of artificial reefs and shoreline dikes. In addition, in order to gain general insight into environmental applications of combustion ashes, the applications of other ashes such as F-type fly ashes, bottom ashes, and ashes from municipal solid waste incinerators are also reviewed in this chapter. For further information, readers can refer to the Tables in the Appendix A.

4.1. Removal of heavy metals

In the U.S., the most commonly occurring metals at many contaminated sites (e.g., Superfund sites) are lead (Pb), chromium (Cr), arsenic (As), zinc (Zn), cadmium (Cd), copper (Cu), and mercury (Hg) as shown in Figure 4. The presence of metals in groundwater and soils can pose a significant threat to human health and ecological systems. The main sources of such metals are the mining and metal industries (Erol et al., 2005; Evanko and Dzombak, 1997).

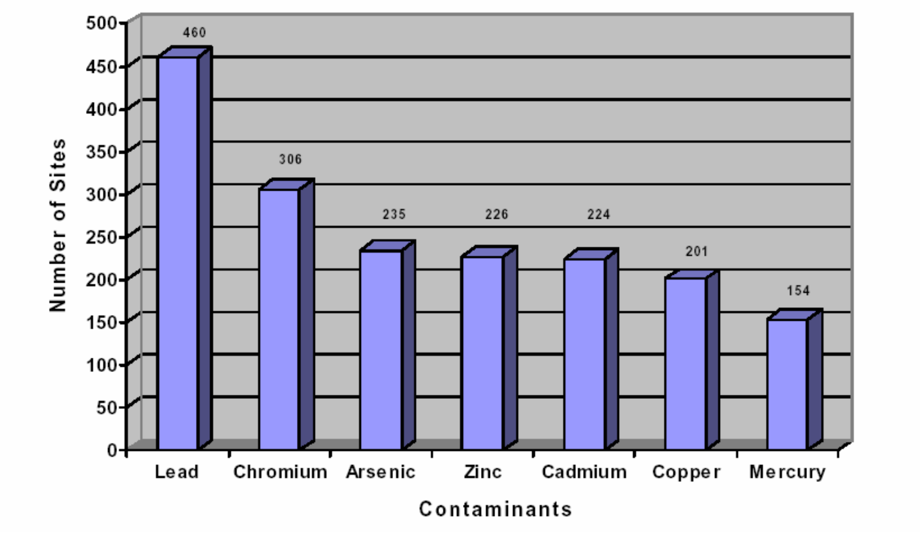


Figure 4. Metals most commonly present at Superfund sites (US EPA, 1996).

Coal ashes have been used to remediate heavy metal contaminated wastewater by precipitation in the form of metal hydroxides (Erol et al., 2005) or by adsorption (Lin and Yang, 2002). Recently, Erol et al. (2005) reported the removal of Cu and Pb by precipitation from aqueous solutions by using several fly ashes with different compositions. Results indicated that both Cu and Pb removal depended strongly on the CaO content of the fly ashes. The formation of metal hydroxide precipitation was found via scanning electron microscopy, and then confirmed through X-ray diffraction analysis. In another investigation, Lin and Yang (2002) studied bottom ash's adsorption capacity for heavy metals, nitrogen, phosphorus, and chemical oxygen demand (COD). They concluded that coal bottom ash was an efficient adsorption material for pollutant removal from landfill leachate. However, the authors remained concerned with the yet to be solved disposal of the ash loaded with pollutants.

4.2. Removal of sulfur dioxide, organics and dyes

Recent studies show the employment of fly ash as raw material for zeolite synthesis in the process of hydrothermal treatment of fly ash. Fly ash zeolites made of Class F fly ash can be used as sorbents for controlling sulfur dioxide (SO_2) emissions

(Srinivasan and Grutzeck, 1999). Suchecki et al. (2004) achieved up to 38 mg SO_2/g fly ash zeolite using class F fly ash zeolites as SO_2 adsorbent.

Fly ash has also been used as a low-cost sorbent that can remove organics (Alemany et al., 1996) and dyes (Janos et al., 2003) from water. As designated in American Society of Testing and Materials (ASTM) Method C 618, Class C fly ash contains at least 30 % calcium oxide as well as up to 50 % silica, aluminum, and iron oxides. The metal and metal oxide content in fly ash makes it a promising inexpensive source of alkaline material. It has been demonstrated that fly ash can immobilize internal and supplementary metals to prevent leaching into the environment (Mehta, 1998). Alkaline hydrolysis has previously been shown to degrade high explosives, such as 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX) (Figure 5).

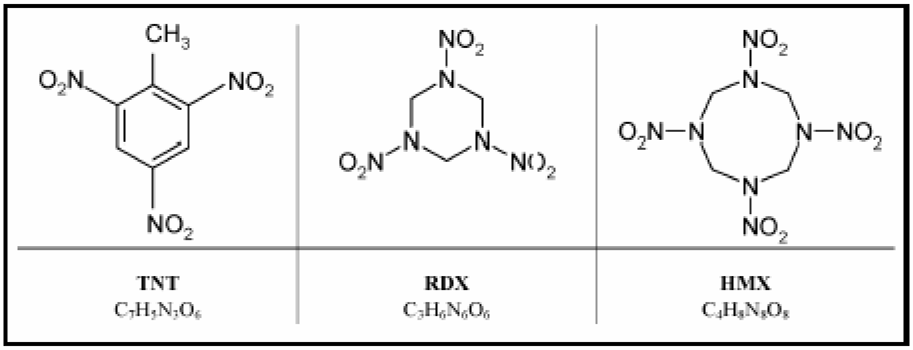


Figure 5. Structures of higher-order explosives TNT, RDX and HMX.

Preliminary results for TNT indicated that, while in water, the hydroxide ion and the active material reacted rapidly to form water soluble polymeric residues and low molecular weight degradation products (Felt et al., 2001). Base hydrolysis has been established at bench-scale as a promising technology to eliminate explosive contamination in water systems, and has been studied as an ex situ treatment technique for groundwater remediation (Hwang et al., 2006). Brooks et al. (2003) examined both basic and applied aspects of alkaline application as an inexpensive and effective means of reducing source-zone contamination on military ranges. In vessels packed with approximately 55 kg of soil, they investigated topical versus well-mixed applications of three alkaline materials: hydrated lime, quicklime, and Class C fly ash. TNT, RDX, and HMX in the mixture were removed quickly from both the leachate and soil. Although the topical application was not a satisfactory buffer for the soil pH, the authors pointed out that topical application of alkali material could still be a viable treatment technique by taking advantage of circumstances unique to training ranges.

For dye removal, Wang et al. (2005) recently demonstrated that heat-treated fly ash (at 800 ^oC for overnight) and acid-treated fly ash (1 N nitric acid, HNO_3 for 24 hrs) can remove methylene blue dye from aqueous solution. The raw fly ash showed adsorption capacity (the Langmuir monolayer adsorption capacity) for methylene blue at 1.4×10^{-5} mol/g. Furthermore, acid treatment resulted in an increase of its adsorption capacity to 2.4×10^{-5} mol/g, whereas heat treatment reduced the adsorption capacity of fly ash.

4.3. Landfill liners and covers

Landfill liners are used to hydraulically limit or eliminate the movement of waste leachate and landfill gases from the landfill site. In addition, covers are required at the end of each operating period to control disease vectors, fires, odor, blowing litter, and scavenging (Tchobanoglous and Kreith, 2002).

The utilization of fly ash alone and fly ash amended with bentonite for liner application has been reported in many studies. For example, Sivapullaiah and Lakshmikantha (2004) recently reported that Class C coal fly ash-bentonite mixtures (20% bentonite) were a promising material for landfill liners because they possess a hydraulic conductivity lower than 1×10^{-7} cm/s among other properties. F-type coal fly ashes have also been tested as landfill liners of covers. Mollamahmutoglu and Yilmaz (2001) concluded that 20% bentonite-Class F fly ash was suitable as a liner or cover material at waste disposal areas.

Coal bottom ash has been tested for use as landfill liners as well. Kumar and Stewart (2003) showed that pulverized coal bottom ash mixed with 15% bentonite had a similar hydraulic conductivity to the acceptable requirement for its use as landfill liners.

4.4. Acid mine drainage treatment

Alkaline Injection Technology (AIT) involves introducing alkaline coal combustion by-products (CCBs) into a mine void to impart alkalinity and increase the pH. During this alkaline alteration, metal species precipitate as hydroxides and carbonates; thus, improving the quality of acid mine drainage (AMD) (Canty and Everett, 2004). AMD results when the mineral pyrite (FeS_2) is exposed to air and water, provoking the formation of sulfuric acid (H_2SO_4) and iron hydroxide ($Fe(OH)_3$) as follows: .

$$FeS_2 + 3.75O_2 + 3.5H_2O \leftrightarrow Fe(OH)_3 + 2H_2SO_4$$

The acid and iron can devastate water resources by lowering its pH and coating the stream bottom in yellowish orange color. In a field demonstration, Canty and Everett (2004) injected 2,500 tons of fluidized bed combustion ash into the wells and monitored AMD in terms of water quality parameters such as alkalinity, pH, and metal content. After a 24 month period of monitoring, the results indicated that alkalinity and pH reached 65 ppm and 7.3, respectively, while metal concentrations were significantly lower than pre-injection levels.

4.5. Agricultural amendments

Coal fly ash is characterized by its alkaline pH, key nutrient content, and silt-size particle distribution. These properties respectively help increase soil pH, and the concentrations of macro- (Ca, Mg, K and S) and micro-nutrients (B, Fe, Mn, Cu, Zn, among others), in addition to improve the structure and moisture-holding capacity of soils. Mixing coal fly ash and sewage sludge, which is rich in nitrogen, phosphorous and organic matter, could produce a mixture with more balanced properties and less toxic characteristics when used as agricultural amendments. The benefits of mixing coal ash and organic wastes, e.g. sewage sludge, as soil amendments include: improving soil texture, modifying soil pH, increasing soil organic matter, and supplying essential plant nutrient for crop production (Li et al., 2002; Veeresh et al., 2003).

An investigation by Li et al (2002) showed that the application of coal ash amended with yard wastes, at a ratio of 1:1.1 (v/v), to a calcareous soil (50 to 75 tons/ha) improved the yields of tomato and the bioavailablity of Fe, Ni, and Mo. Moreover, due to its alkaline characteristics fly ash has been used in alkaline stabilization for sewage sludge management. Grillasca (1997) evaluated the potential agricultural use of the mixture of Class C coal fly ash and sewage sludge. The mixture at a ratio of 1:1, on a wet weight basis, showed both the nutrient benefits as a fertilizer or soil conditioner, and the alkalinity for pathogenic activity, i.e., fecal coliform treatment.

Composting is an aerobic biodegradation method in which biodegradable organic matter decomposes to produce stabilized residue and disinfecting pathogens (Rittmann and McCarty, 2001). Sewage sludge can be cost-effectively composted so that its final product can serve as a fertilizer or soil conditioner. However, high heavy metal concentrations have become a limiting factor in this type of application. The addition of coal ash during and after sludge composting can decrease heavy metal availability, and reduce their toxic effects on plants grown in compost-amended soil (Fang et al. 1999, Wong et al. 1997).

In a related study, Hackett et al. (1999) reported on the composting of pulp and paper mill fly ash with sewage sludge at a ratio of 1:1 (v/v) in mixed and static windrows for 34 weeks. The results showed that the C:N ratio, pH, and EC of the final product were 40 ~ 46:1 , 8.5 and 1.4 dS/m, respectively. During the composting study, the dioxin concentration decreased by 45% to a toxicity equivalent quotient (TEQ) of 41 pg/g. In addition, their demonstration on land application at a rate of 15 m^3/ha indicated an improved nutrient profile and a dioxin concentration of 3.0 pg/g TEQ, enabling the mixture to be classified as agricultural soil.

Coal bottom ash has also been used as a stabilizer. Mukhtar et al. (2003) documented potential use of blended coal bottom ash with composted dairy manure as a soil amendment, or even top soil replacement material. Although they were not able to achieve suitable results due to the exceedingly high portions (> 30% v/v) of composted dairy manure they applied, the authors showed that marked reductions of nitrogen and phosphorus compounds were achieved within one to three weeks in their column study.

4.6. Waste stabilization/solidification

Stabilization can be defined as a process employing additives to maneuver waste into a less mobile and toxic form, whereas solidification is a process by which a solidified matrix is formed to physically bind the contaminated material. Stabilization and solidification (S/S) has been widely applied to manage hazardous waste-contaminated sites (LaGrega et al., 1994; Raouf and Nowier, 2004). Within this technique, either inorganic binders such as cement, fly ash, or blast furnace slag; or organic binders such as bitumen; can be used to form a crystalline, glassy or polymeric framework around the waste. As a result, the hazardous waste is transformed into solid form, which is easier and safer to handle. When fly ash is used as the binder, a pressure of a few hundred lbs/in^2 must be applied to form a solidified product, where the cementitious process requires no pressure (Parsa et al., 1996)

Using either Class C or Class F fly ash as the only binding agent, Parsa et al. (1996) examined a fly ash-based S/S for the simulated mixed waste that consisted of nitrate salts, nitric acid, and water. Some key findings included that Class C fly ash was better than F-grade for this study, and that the resulting S/S blocks met toxicity characteristic leaching procedure (TCLP) requirements. Another investigation concentrated on the engineering properties of sludge modified by lime and Class F fly ash (Lim et al., 2002). In this case, the role of lime was to sterilize pathogens in sludge. Results showed that the unconfined strength of the blocks satisfied the criteria for construction materials, i.e. larger than 100 kPa, while their permeability was found to be around 1×10^{-7} cm/s. In addition, the extraction test met the TCLP requirements, particularly for Cd, Cu, and Pb.

4.7. Artificial reefs and shoreline dikes

Puerto Rican coral reefs, as shown in Figure 6, are known to be the richest in the US Caribbean. However, unfortunately they are among the most threatened coral reefs in the Caribbean. Overall, 93% of the reefs were rated as threatened, with as much as 84% at high risk, according to the World Resources Institute (2005).

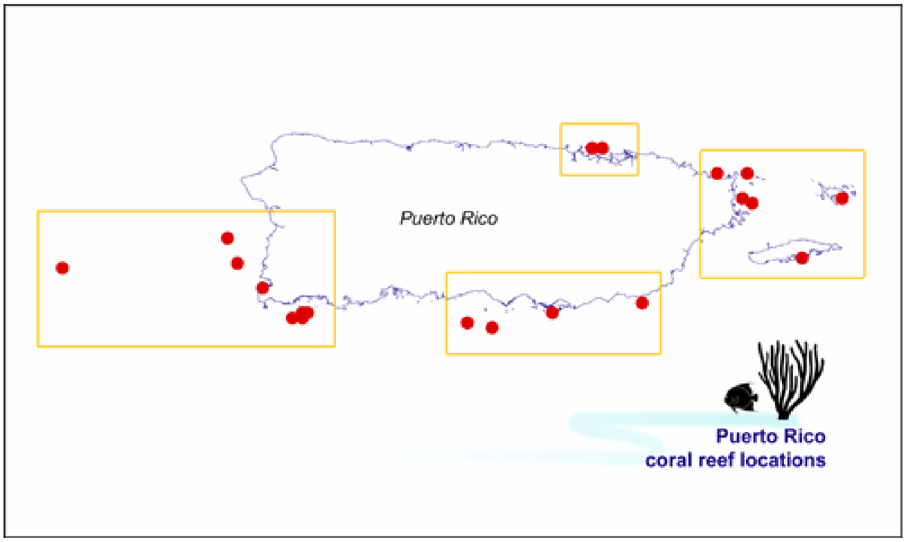


Figure 6. Puerto Rican coral reef locations.
(http://www.nodc.noaa.gov, accessed on July 26, 2005)

Artificial reefs are known to attract fishes and invertebrates and enhance the local aquatic environment so that fishing catches are improved (Woodhead et al., 1986). Simply put, a man-made object is sunk into the sea to create an artificial reef, which can become part of the ocean ecosystem (Figure 7).

A wide variety of materials have been used to construct artificial reefs. Among these are natural materials, such as rocks, and man-made materials such as concrete, iron and steel, reinforced concrete, ceramic, plastic, fiber-reinforced plastic and asbestos fiber. After thorough cleansing to eliminate any environmental hazards, derelict ships, automobile bodies and tires, debris from demolition projects, and discarded offshore oil platforms can also be used to construct artificial reefs (Lam, 2003; Grove et al., 1991; Vose and Nelson, 1998).

Figure 7. An example of man-made artificial reef.
(http://www.reefball.com, accessed on July 26, 2005)

Coal combustion by-products can be used as well for artificial reef construction. Woodhead et al. (1986) tested the feasibility of using solid blocks of mixtures of fly ash and flue-gas desulfurization scrubber sludge from coal-burning power plants as artificial reefs. A 500-ton demonstration reef with 15,000 solid blocks was employed in the investigation. Results indicated that the fixation and processing of coal wastes into blocks could provide a potentially valuable resource for artificial reef construction.

Lam (2003) also reported that a stabilized pulverized fuel ash (PFA)–concrete artificial reef could be able to rehabilitate the target scleractinians, *Oulastrea crispata* and *Culicia japonica*. The author concluded that PFA–concrete is a potential material for artificial reef construction.

Rusch et al. (2002) developed a mechanically stabilized shoreline erosion dike by mixing FGD sludge (60 - 70% $CaSO_4 \cdot 2H_2O$ and 30 - 40% $CaSO_3 \cdot 0.5H_2O$), Class C fly ash and Portland type II cement as the core material (Figure 8). They emphasized that this configuration would not only cut costs dramatically by reducing the amount of needed limestone and the overall weight burden, but would also provide a new use for coal combustion by-product materials that could result in the establishment of a marketable industry. Briquette mixtures of 64%:35%:1%, 63%:35%:2% and 69%:30%:1% of FGD to fly ash to cement produced low effective sulfur diffusion coefficients of 1.34 - 3.96

$\times 10^{-13}$ m^2/s. These briquettes survived for more than 4.5 months in the field salt water submergence experiment. The TCLP test showed that the content of Cr, Cd, As, Pb and Se was far below the maximum concentration limits set by USEPA. In addition, they reported that the briquettes could be manufactured at large scale at a cost of $13/ton.

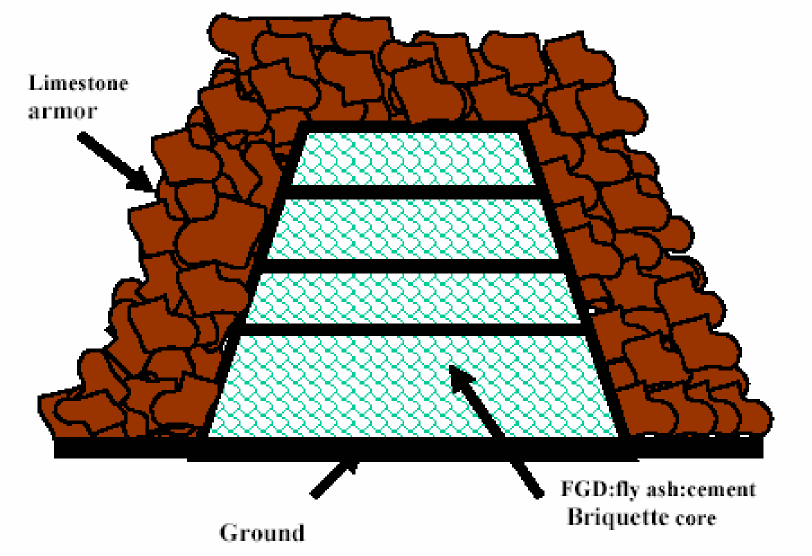


Figure 8. Schematic of shoreline erosion dike with FGD, fly ash and cement core (Rusch et al., 2002).

4.8. Agricultural and environmental uses of lime

The application of lime to soil for agricultural or engineering purposes is a well-established practice. Because CCP's have similar physical and chemical characteristics of CCP's to those of lime, CCP's can replace lime in various agricultural and environmental situations. Therefore, this section will address liming practices in agricultural and environmental fields, focusing on their possible effects on soil chemistry and ecology.

Topical lime application is common in no-till agricultural practices. These are mainly for increasing the pH of acidic surface and subsurface soils (Howard and Essington, 1998). Both positive and negative effects of liming on soil physical conditions (e.g., aggregate stability and infiltration rate) have been reported. Haynes and Naidu (1998) pointed out that negative effects of liming on soil structure were measured in the short period of time (i.e., in the first 1 – 3 months), whereas liming normally resulted in improved soil aggregation and increased aggregate stability and infiltration capacity.

Farina et al. (2000) found little vertical or horizontal movement of the alkalinity through the soil layers even when unreacted lime was visible in the soil. When a soil of neutral pH was limed, a portion of the light fraction of organic carbon was lost (Chan and Heenan, 1999). However, limed soil was still able to achieve aggregate stability due potentially to the formation of calcium bridges as new bonds between aggregates.

Researchers have studied the effect of lime application on soil ecology, specifically effects on microbial communities, animal populations, and plants. Some bacteria, known as alkaliphiles, have adapted to life at high pH by modifying enzymes to function at pH>8 (Acosta-Martinez and Tabatabai, 2000). He et al. (1997) found that the addition of lime to acidic forest soil promoted microbial biomass. Simek et al. (1999) found that, over extended periods of time, the application of lime, with and without organic and inorganic fertilizers, increased the microbial biomass of the soil. Lime was also an important factor in the change in microbial community composition between organic and inorganic fertilizers. While bacterial respiration and community composition were not immediately affected by reduced application of lime to pasture land, fungal community growth increased (Bardgett et al., 1996).

Lime application may also influence the size and activity of earthworm populations. Most earthworm species prefer a soil pH of around 7, being particularly sensitive to acid soil conditions. If soil is acidic, then lime application promotes worm biomass (Lawson, 2000), which may have significant effects on soil structure with respect to aggregate stability through their casting actions and macroporosity increase through its burrowing actions (Lee and Foster, 1991).

The effect of alkaline pH on plants is a secondary effect of high pH on soil and microbial chemistry that alters the bioavailability of various minerals and metals. The effects of liming on root and shoot development were examined by Kerley (2000). At 2.5 percent CaO (w/w), combined lateral and taproot development was 57 percent less than in controlled soil (pH 7). However, the cluster root development was enhanced in limed soil. Shoot development was slower and some chlorosis was observed in high pH soil. In the long term, positive effects of liming on crop growth and yields could occur through reduction of aluminum (Al) and manganese (Mn) toxicity and/or alleviation of calcium (Ca) deficiency. This in turn increases the returns of carbon to the soil in the forms of dying roots and decaying crop residuals, leading to an increase in soil organic matter content (Haynes and Naidu, 1998). Baligar et al. (1997) reported that the addition of lime to acidic forest soil promoted a plant growth due possibly to alleviation of Al and increased availability of Ca and magnesium (Mg).

Chapter 5: Recommended Applications of CCP’s in Geotechnical and Structural Fields

This chapter presents the recommended applications for AES CCP’s based on the literature review carried out for this project and taking into account the context of Puerto Rico. Three potential utilizations are recommended for detailed feasibility studies in the area of geotechnical/structural engineering: 1) use of fly ash for ground improvement (e.g., soft or expansive soils); 2) use of all three CCP’s as subbase and base materials for roads; and 3) use of bottom ash and/or manufactured aggregate as structural fill for retaining walls. The following subsections describe these 3 alternatives in more detail.

5.1. Recommendation 1: Fly ash for ground improvement

Use of fly ash for ground improvement applications appears to be an attractive application for the AES CCP. As indicated in Chapter 3, several studies indicate fly ash has good potential for stabilizing expansive soils and to strengthen weak or soft soils (e.g., Cocka 2001; Kukko 2000; Trzebiatowski 2004).

The application of expansive soils is attractive given the severity of the problem in Puerto Rico (Ochoa and Pando 2005). Expansive soils are a major concern in several regions of Puerto Rico where clay soils are expansive in nature. The traditional way of dealing with these soils is excavating them and replacing them with select granular material. This mitigation technique is expensive and time consuming. Treatment of soils by mixing it with fly ash would be more economical and environmentally friendly since it would help recycle a by-product and also decrease the amount of destruction of land associated with quarrying rock for construction materials. A detailed experimental study is recommended to study the feasibility of using the AES fly ash for treatment of expansive soils.

The application of improvement of soft/weak subsoils is considered attractive because it has applications for road projects with poor subgrade soils and for improvement of bearing capacity of shallow foundations. In Puerto Rico, many road projects involve crossing portions of land involving weak and compressible soils. Typically, road construction in these areas involves using expensive ground improvement techniques such as: excavation and replacement, geosynthetics, preloading, stone columns, or even road alignment relocation. The Puerto Rico Highway Authority is constantly looking for attractive and cost effective alternatives. The improvement of weak subgrades using fly ash has been successfully carried out in mainland US (e.g., Trzebiatowksi et al. 2004). This alternative has good potential and would involve large volumes of this CCP.

A detailed feasibility study is recommended preferably involving both a laboratory and field component. The experimental validation of this alternative should show an increase of strength and stiffness of the treated soil after some curing time. The experimental results from the treated soils should be compared with untreated control samples.

5.3. Recommendation 2: Road construction

The literature review presented in Chapter 3 indicated that all three CCP's types have good potential for using in road construction. Fly and bottom ash have good potential for use in asphalt pavements. All three CCP's were found to have good potential for subbase and base materials.

Manufactured aggregate was tested by Kochyil and Little (2004) and results indicated very good potential for use as subbase and base layers in low traffic roads. AES has recently initiated field trial testing in internal roads within their property.

Additional testing and evaluations are recommended to determine the feasibility of this application.

5.4. Recommendation 3: Structural fill

Based on the references reviewed in Chapter 3, use of bottom ash and manufactured aggregate for structural fill and backfill is considered as an application with good potential. This utilization is attractive because it involves large volume of CCP material. The main concern would be the potential degradation that can occur during handling, placement and compaction of the materials and the possible loss of strength and stiffness if they become saturated. A detailed study is recommended to evaluate these concerns.

The lower unit weight and shear strength of the manufactured aggregate would result in lower earth pressures in retaining wall applications compared to conventional fill materials (Figure 9). As a consequence, less steel reinforcement is needed thus resulting in cost savings. This cost saving would be in addition to the savings associated with the use of a CCP material. It may be useful to include a cost analysis component as part of the feasibility study for this application.

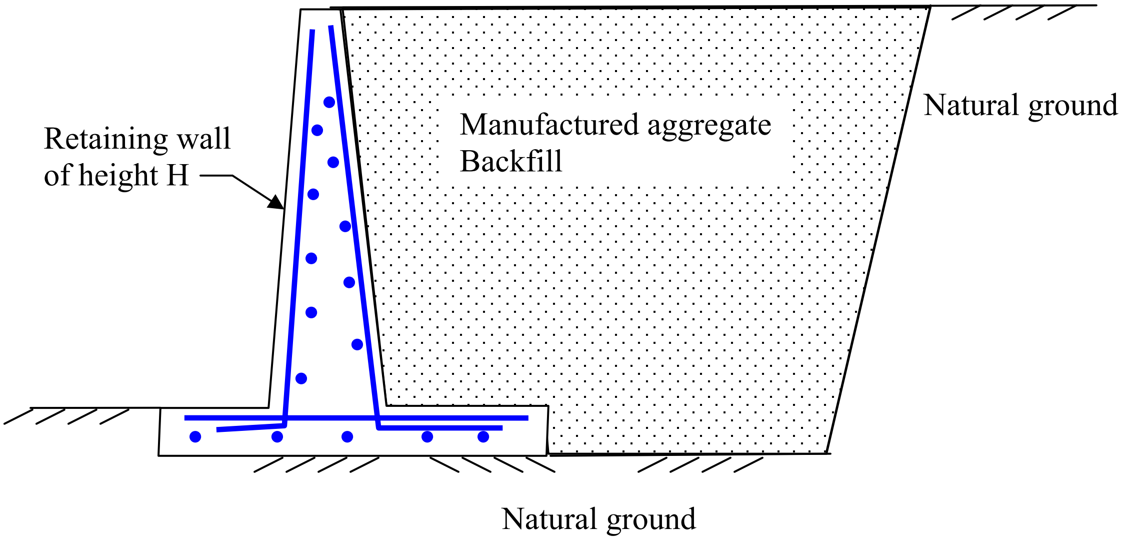


Figure 9. Schematic of a retaining wall with manufactured aggregate backfill.

Chapter 6: Recommended Applications of CCP's in Environmental Fields

Based on the available information on AES CCP's and the literature complied in this review, the authors present recommended environmental utilizations for their CCP's. Two potential utilizations are recommended in the area of environmental engineering, based on alkaline characteristics of the CCP's: explosives remediation and agricultural amendment. The first subsection will provide a key rationale for those applications in accordance to preliminary experimental results completed as a part of this project.

6.1. Alkaline characteristics of AES CCP's

A series of laboratory experiments has been conducted to evaluate alkaline characteristics of the AES CCP's. The pH of CCP solution has been assessed for this purpose.

6.1.1. Methodology

In order to assess the kinetics of pH evolution in the CCP solutions, 20 g of ash and 50 mL of distilled water was added in Nalgene 60 mL plastic bottles. For the manufactured aggregate, a representative samples were collected and crushed. The fractions passing the sieve #4 (4.75 mm) were used for the experiments. Enough reactors were prepared to sacrifice two reactors for the pH measurement at a predetermined sampling time. The reactors were put on the shaker at room temperature. At the sampling time, two reactors were removed from the shaker and were left to settle for 5 minutes before the pH measurements. Equilibrium time of the pH evolvement was determined from this experiment.

For evaluating the effect of CCP concentrations on pH evolvement, varying amounts of CCP's were used: 1 to 60 g/L for fly ash and 5 to 30 g/L for both bottom ash and manufacture aggregate. Duplicate reactors for each ash were put on the shaker. The reactors were removed from the shaker after the equilibrium time determined from the kinetic experiment. The pH of CCP solution was measured in same manner as the kinetic experiment aforementioned.

6.1.2. Experimental results

The AES CCP's were turned out to be very alkaline. As shown in Figure 10, the fly ash solution reached a pH of 12.7 after 5 minutes of reaction time and established a plateau in pH strength during the 60-minute experiment. The bottom ash also attained a pH higher than 12 almost instantly in the experiment. After 5 minutes, the pH of bottom ash solution reached 12.3 and evolved up to 12.7 after 60 minutes. The manufactured aggregate showed less alkaline strength than both fly ash and bottom ash. However, it still produced a pH greater than 10.7 by the middle of the experiment time.

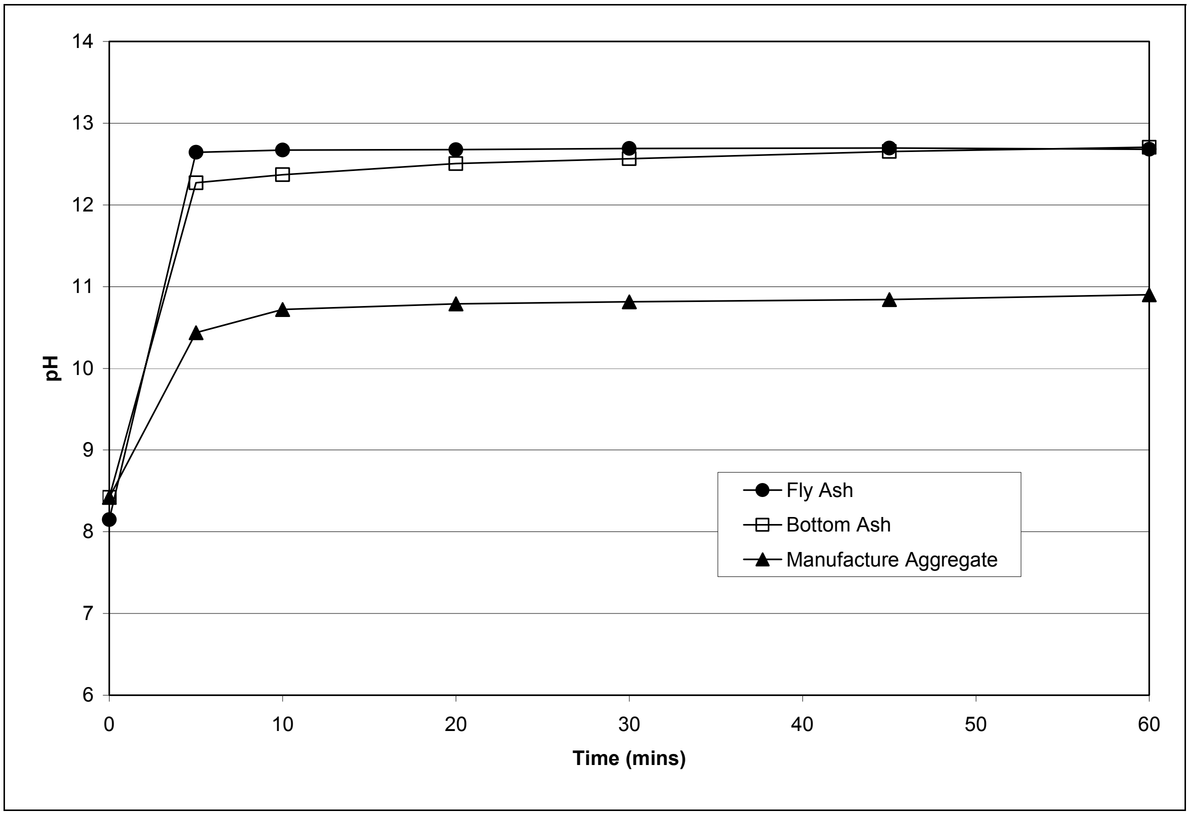


Figure 10. Kinetics of pH evolvement in 20 g/L CCP solution.

The amount of CCP's present in the solution did not show a significant effect on the pH strength as shown in Figure 11. At concentrations between 5 to 30 g/L CCP concentrations, the difference in the pH was only about 0.5 unit (12.3 for 5 g/L vs. 12.8 for 30 g/L) for both fly ash and bottom ash, whereas manufactured aggregate showed even less difference of pH strength, being 10.7 and 10.9 for 5 and 30 g/L, respectively.

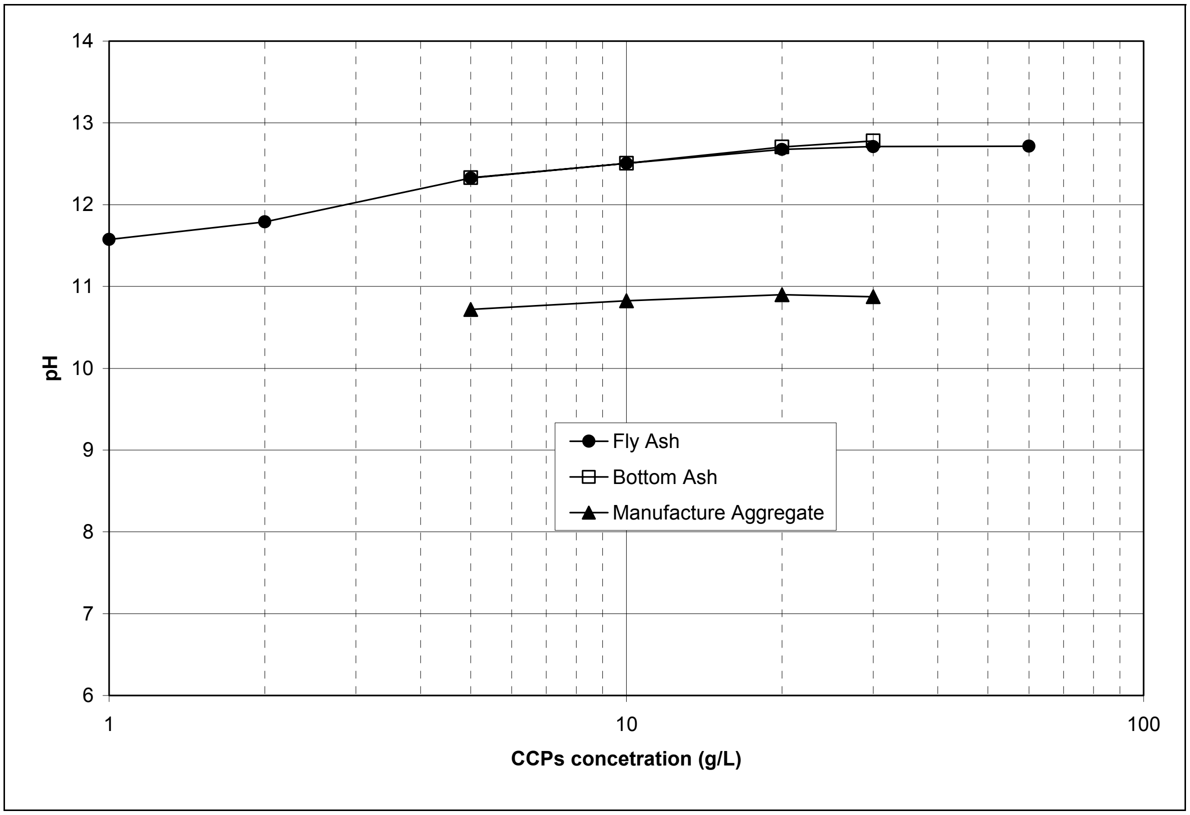


Figure 11. Effect of CCP concentration on pH strength.

6.2. Recommendation 1: Alkaline explosives remediation

Military activities such as the manufacturing, assembling, loading, live-fire training ranges and disposal of explosive compounds have generated widespread contaminations with explosives and their derivatives (Resenblatt et al., 1991; Spain, 1995). Due to the adverse effects of explosives and their derivatives on humans and other natural receptors (Peres and Agathos, 2000; Won et al., 1976), a low cost means of decontaminating these areas of contamination is needed.

Alkaline treatment has previously been shown to degrade high explosives TNT, RDX, and HMX. It has been studied as an ex situ treatment technique for groundwater remediation (Hwang et al., 2006) and as an in situ means of reducing source-zone contamination on military ranges (Brooks et al., 2003).

Fly ash contains a number of metals and metal oxides. Because it contains these metal oxides, fly ash may be an potential inexpensive source of alkaline material. Indeed, the AES CCP's did show strong alkaline characteristics, producing a high pH in the solution as shown in the current laboratory experiments.

Topical CCP's application on range soils to remediate explosives contamination would reduce the overall remediation costs by destroying explosives in situ, and thereby eliminating the extensive capital costs and safety concerns associated with ex situ remediation strategies. The technique is applicable to ongoing military training activities, ensuring the long-term availability of training ranges and minimizing the potential for off-range explosions of explosives. Also, this technology would provide the AES with potential both for beneficial utilization and for by-product management.

6.3. Recommendation 2: Agricultural amendment

It is known that low nutrient availability (P, Ca, Mg) and metal toxicity (Al, Mn) in acidic soils make normal plant growth difficult. In this regard, lime application has been conducted on acidic soils to sustain soil productivity. Positive effects of liming on crop growth and yields can occur through reduction of Al and Mn toxicity and/or alleviation of Ca deficiency. This, in turn, increases soil organic matter content by returning carbon to the soil in the forms of dying roots and decaying crop residuals (Haynes and Naidu, 1998).

Coal fly ash is characterized by its alkaline pH, key nutrient content, and silt-size particle distribution. These properties, respectively, help increase soil pH, and the concentrations of macro- and micro-nutrients, and improve the structure and moisture-holding capacity of soils. Mixture of CCP's and organic waste (e.g., sewage sludge) rich in N, P and organic matter could produce a mixture with more balanced properties and less toxic characteristics than used alone, improving soil texture, modifying soil pH, increasing soil organic matter, and supplying essential plant nutrient for crop production (Li et al., 2002; Veeresh et al., 2003).

Fly ash, bottom ash or manufactured aggregate from the AES power plant can beneficially be utilized in combination with organic wastes, sustaining soil health and productivity. Different physiochemical properties of each CCP will produce diverse effects on soil fertility with dissimilar organic wastes. Engineering parameters which should be carefully considered for this case include: the ratio of CCP's with organic wastes, moisture content, tillage, short- and long-term monitoring, the types of CCP's, organic wastes, soils and plants. Response variables to be assessed include: plant productivity and soil biological activity.

Chapter 7: Summary and Conclusions

Every year millions of metric tons of industrial by-products are produced in the United States. To date, only a small portion of these materials are reused beneficially and most are simply landfilled as solid wastes. Finding recycling alternatives for industrial by-products would save millions of dollars annually to US industries in avoided landfill costs, generate cost-effective alternatives, and minimize environmental damage due to aggregate mining. Finding recycling alternatives of by-products such as the ones from AES requires a well-planned and deliberate development plan. This literature review study is intended as a first step towards this goal.

This report summarized the different recycling alternatives that were identified in the literature review study. Recommendations were also made on CCP recycling applications that were considered as having good potential for AES and Puerto Rico. The feasibility of the recommended applications will require detail studies that ideally should include a field demonstration element whenever possible. Demonstrations validate the properties anticipated based on laboratory work at full scale field condition. Finally, results of beneficial recycling applications need to be disseminated to the engineering and industrial communities as well as government. Research results need to complemented with design guideline documents to facilitate the implementation of the proposed recycling application.

An important consideration when selecting the recycling alternatives for detail feasibility studies will be to take into account the unique composition and characteristics of the CCP's from AES. As mentioned in this report, the AES CCP's are the result of circulating fluidized bed coal combustion and their composition is not quite the same as the ones reported in the literature. A comprehensive characterization of the CCP's is recommended.

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Appendix A. Literature Review Summary Tables

Table	Review Topic	Page
A-1	Agriculture	67
A-2	Asphalt concrete	69
A-3	Characteristics of coal ash	73
A-4	Embankment	79
A-5	Flowable fill	81
A-6	Masonry	82
A-7	Other uses	84
A-8	Road	89
A-9	Soil stabilization	94
A-10	Waste material	99

Table A-1. Agriculture

Source	**Type of ash**	**Description**	**Summary**
Pathan, Aylmore and Colmer (2003)	Fly ash (class not specified)	Soil properties and turf growth on a sandy amended with fly ash. Field lysimeters of a soil were amended to a depth of 100 mm with four rates (0, 5, 10 and 20%, wt/wt) of fly ash, and effects on soil water content, nutrient leaching, turf growth and nutrition, and uptake of trace elements by turf were assed.	• Study showed that amended of coarse-textured sand with fine textured fly ash significantly improved soil water holding capacity and reduced drainage. • Fly ash amendment may have the potential to improve plant growth in sandy soils by increasing the amount of plant available water in the root zone. • Fly ash increased extractable P in the soil and reduced NO_3^-, NH_4^+ and P leaching in the sandy soil without turf. The sorption of NO_3^-, NH_4^+ and P on some fly ashes can be higher than in same sandy soils. • The low levels of NO_3^-, NH_4^+ and P leached under turf in the present study indicate that the fertilizer application rate and frequency used was suitable for the demand and uptake capacity of the turf.
Gupta, Rai, Tripathi and Inouhe (2002)	Fly ash (class not specified)	Study about the impact of fly ash on soil plant response. This article explains properties of fly ash in terms of environmental impact, quality control and remediation.	• Fly ash in soil increases the electrical conductivity by increasing the levels of soluble major and minor inorganic constituents. • Hydraulic conductivity of soils can be improved using controlled amounts of fly ash but can be deteriorated if more than 20% of this material is applied in calcareous soils and 10% in acidic soils. • Fly ash reduces the modulus of rupture in all soils tested. • Excessive use of fly ash to alter pH causes an increase in soil salinity. • Fly ash causes injuries to plants if it remains airborne also inhibit transpiration and photosynthesis. • It can be used as an economical fertilizer and soil amendment in small-scale cultivation of plants.

			• Retardation of growth and development of plants on fly ash landfill can occur due to the unavailability of nitrogen and phosphorus.
Li, Zhang, Stoffella and Bryan (2002)	Fly ash class F	Fly ash, pigs and tomatoes. Experiment using mixtures of fly ash, yard waste and sewage sludge to evaluate the effect on physical and chemical characteristics of soil and in tomatoes plantations.	• The mixture of fly ash with yard waste improves soil texture, provides essential nutrients and modifies the pH. • Application of fly ash mixed with yard waste increased the total marketable tomato yield by 35 to 71%. • There was an increase in soil temperature and soil water holding capacity when using the mixture of ash. • No indication of leaching of trace metals into groundwater. • The quantity of large fruits increased when compared with the control plot.
Stehouwer, Dick and Sutton (1999)	FBC ash	Acidic soil amendment with magnesium-containing fluidized bed combustion by-product. In this study, in investigated the responses of alfalfa, and corn grown on two acidic agricultural soils amended with Mg-FBC.	• Application of Mg-FBC increased alfalfa yields in all six site-years, whereas it had no effect on corn grain yield in five site-years and decreased grain in one site-year. • Mg-FBC increased surface soil concentrations of Ca, Mg, and S, which promoted downward movement of Mg and SO_4. • The Mg-FBC was an effective liming material and, because of the presence of both Mg and SO_4 may be more effective than gypsum in ameliorating subsoil Al phototoxicity. • In both the Wooster and Coshocton soils, Mg-FBC rapidly increased soil pH_w • The effects on the soil chemistry can be attributed to two components of the Mg-FBC, the residual alkaline component and the anhydrite component.

Table A-2. Asphalt concrete

Source	Type of ash	Description	Summary
Hinislioğlu and Bayrak (2004)	Fly ash class F	Optimization of early flexural strength of pavement concrete with silica fume and fly ash by the Taguchi Method. In this study, an attempt has been made to optimize the early flexural strength of concrete pavement by using the Taguchi method.	• The strength development of fly ash concrete is relatively slower at early age because the pozzolanic reaction is slow to start and does not progress to any significant degree until several weeks after the start of hydration. • The Taguchi method has been commonly used to decrease the number of experiments for such experimental studies. • The results show that fly ash causes reduction of the flexural strength at all levels of replacement at 7 days, except for the case of 5% fly ash replacement for Portland cement where the flexural strength increase a little due to the increase in workability when compared with plan concrete. • The strength reduction caused by fly ash replacement increased with increase of fly ash content.
Naik, Chun, Kraus, Singh, Pennock and Ramme (2001)	Fly ash class C	Strength and durability of roller-compacted HVFA concrete pavements. This investigation was conducted in two projects: Project I deals with performance of conventional high volume fly ash (HVFA) concrete pavement having a roller-compacted, no fines permeable base coarse containing fly ash obtained from an SO_2	• Roller-compacted concrete (RCC) for pavements is a relatively stiff mixture of aggregate, cementitiuos materials, and water that is generally placed by asphalt pavement equipment and compacted by vibrating rollers. • Laboratory testing specimens derived from the pavements showed excellent results for conventional HVFA pavement, and satisfactory performance of the RCCP except for freezing and thawing resistance. • Based on data collected, for Project I, it can be concluded that the performance of the HVFA concrete pavement was excellent with respect

		control technology (dry desulphuring process; Project II deals with RCC pavement (RCCP) containing 30% ASTM Class C fly ash.	to strength and durability. The compressive strength of pavement has increased to a high value during the last 6 years. • For Project II can be concluded that the mechanical behavior of the RCC was similar to that of conventional paving concrete. The performance of the Pullian RCCP was adequate with respect to strength and durability, except for freezing and thawing durability measured in accordance with ASTM C 666 procedure A. • Roller compacted concrete pavement that are resistance to freezing and thawing can also be produced by providing a draining base course, achieving maximum concrete density and a close pavement surface texture, and using supplementary cementitious materials such as fly ash.
Bin-Shafique, Edil, Benson and Senol (2004)	Fly ash class C with 89% silt-size particles, SG=2.68, CaO=23%	Incorporating a fly-ash stabilized layer into pavement design. Study of a historical case in which fly ash is used as structural support in two flexible pavements constructed in the south of Wisconsin in August, 2000.	• Procedures describe in AASHTO (1993) were used for the design of the pavements. • Values of CBR and resilience modulus were estimated. • In both sites the sub-base material was replaced by fly ash. • The maximum dry unit weight and optimum water content for the soil-fly ash mixture is comparable to those for the soil alone. • At both sites, stabilization with fly ash improved the strength and stiffness of the subgrade significantly. • The deflection and stiffness at the centerline of the pavements were comparable structurally for the fly ash and the control sections.
Ali, Chan, Simms,	Fly ash class F	Mechanistic evaluation of fly ash	• Using up to 30% of fly ash at some asphalt contents showed noticeable

Bushman and Bergan (1996)		asphalt concrete mixtures. Four groups of specimens with different fly ash contents from Nova Scotia where studied to find the effect of the ash in the mechanical properties of asphalt concrete mixtures.	improvements for density, tensile strength and resistance to asphalt hardening (1983). • Addition of class C fly ash to recycled mixtures increased permeability, stiffness and compressive strength values (1994). • Considerable saving in energy using fly ash without an additional asphalt cement requirement (1994). • Fly ash can be used as a mineral filler to improve stripping resistance and characteristics of the resilient modulus. • Addition of fly ash increases the amount of surface cracking in pavements. • There is no indication that the addition of fly ash to asphalt mixtures reduces pavement distresses and improves field performance on asphalt. • Fly ash can be added as a stiffening and void filling-material.
Vassiliadou and Amirkhanian (1999)	Bottom ash & Fly ash (class not specified)	Coal ash utilization in asphalt concrete mixtures. Study the effect of coal ash when it partially replaces fine aggregate in asphalt concrete mixtures.	• Substitution of fine aggregate by coal ash is feasible. • Partial replacement of fine aggregate by ash sources decreases short term indirect tensile strength (ITS) values on asphalt samples. • Metal concentrations did not increase as a result of coal use in asphalt. • Addition of hydrate lime in asphalt mixtures with and without coal ash significantly increase wet ITS.
Winschel and Wu (1996)	Fluidized bed combustion residues (fly	Use of aggregates produced from coal-fired fluidized bed combustion residues as a component in bituminous concrete.	• The unit weight of the synthetic aggregate is lower than that of the natural aggregates. • The pavement surface remained uniformly hard and there was no

	ash)	An experiment was conducted to verify the quality of a road using in the asphalt mixture synthetic aggregate.	evidence of degradation in the pavement or in the aggregates. • The production of synthetic aggregates is economically feasible if avoided waste disposal costs are considered. • Synthetic aggregate resulted in a strong material resistant to abrasion and durable. • The more durable the aggregate the less the repairs that must be done to it. • Synthetic aggregate meet the engineering specification for use as class A aggregate in Portland cement and asphalt concrete.
Baig and Wahhab (1998)	Lime (possibility of using lime substitute)	Mechanistic evaluation of hedmanite and lime modified asphalt concrete mixtures. Studies were made to determine the effectiveness of hedmanite as filler in asphalt concrete and to compare with mixtures using lime as filler.	• The type and amount of filler in the asphalt mixture can have a significant effect on its fundamental properties. • The substitution of 4% lime as filler in the mixture presented an improvement in tensile strength from 24% loss to 8% loss. It also improved the stability from a 28% loss to a 4% gain.
Ksaibati and Conner (2004)	Bottom ash	Evaluate feasibility of using bottom ash from power plants in Wyoming for Hot mix asphalts	• Comprehensive laboratory testing program to evaluate the effects of addition of bottom ash into hot mix asphalts (HMA). • HMA mixes prepared with bottom ash did not show any significant degradation compared to mixes containing no bottom ash. • Moisture susceptibility was observed. Lime additive was found to be very effective in reducing moisture susceptibility of HMA mixes.
Robnett (1983)	Bottom ash	Database of projects that use boiler bottom ash as a paving material	• Provides a database with technical information of projects involving use of boiler bottom ash as a pavement material.

Table A-3. Characteristic of coal ash

Source	Type of ash	Description	Summary
Kaniraj and Gayathri (2004)	Fly ash class F	Permeability and Consolidation characteristics of compacted fly ash. The paper explains the details and results of the tests (X-ray test, classification tests, compaction test, permeability test), especially those of the consolidation and permeability behaviors. Fly ash used from Dadri thermal power sation, New Delhi.	• The results showed that the coefficients of permeability and consolidation of the compacted fly ash were comparable to those of nonplastic silts. Even at high effective stress there was no appreciable reduction in the coefficient of permeability. • Dadri fly ash was classified as a class f fly ash. • The XRD pattern showed the presence of quartz, mullite, gehlenite, silimanite, melilite, magnetite and hematite crystalline phases in the Dadri fly ash. • Dadri fly ash may be classified as equivalent to a low plastic silt or ML type soil. • The compression indices were small. Properly compacted Dadri fly ash embankments and fills, when resting on firm strata, would not suffer large settlements. • The values of coefficients of permeability and consolidation were similar to those of nonplastic silt. • As a foundation material, fly ash has lesser bearing capacity than silt; fly ash exerts lesser lateral thrust on retaining walls than silts; and embankments on soft soils have a higher factor of safety and settle less when they are made of fly ash than of silt.
Kaniraj and Havanagi (2001)	Fly ash class F Max. dry unit	Correlation analysis of laboratory compaction of fly ashes. In the present	• There is a large variation in the maximum dry density (MDD) and optimum moisture content (OMC) of different fly ashes due to the

	weight=13.8k N/m^3, moisture content=21%	study, data regarding the compaction characteristics and specific gravity (G) of different fly ashes were collected. Correlation analysis of the data for 57 samples for light (standard Proctor) compaction and 21 samples for heavy (modified Proctor) compaction were carried out.	differences in their characteristics. • The correlations between MDD and OCM and G, can be used to make a preliminary estimate of the likely range of MDD and OMC if the specific gravity of fly ash is known. • Fly ash makes an ideal landfill cover because: 1. Well compacted fly ash has low permeability that will keep water out of the refuse and thus minimize leaching. 2. Fly ash does not shrink upon drying. 3. The strength increases with time due to the cementitious or pozzolanic properties. • Fly ash either alone or in combination with bentonite meets the requirements of liner material for waste containments. • Fly ash also contains nutrient elements and could be used in agriculture as soil amendment.
Bernardo, Telesca, Valenti and Montagnaro (2004)	FBC ash	Role of ettringite in the reuse of hydrated fly ash from fluidized bed combustion as a sulfur sorbent: a case study. The aim of this paper is to investigate the conditions under which ettringite is formed by the liquid-phase hydration of FBC waste.	• Ettringite could play a dual role in SO_2 capture: (i) a chemical role related to the sulfur capture ability of the three available moles of CaO per molecule and (ii) a physical role related to its porous structure, which improves the contact between the gas and solid phases. • Ettringite is much more reactive than a commercial limestone commonly employed as a sulfur sorbent. • Two FBC fly ashes were used from the same power plant; termed SIA and SUC. • The ettringite concentration in SIA and SUC hydrated samples increases as both the aging time and the curing temperature increase.

			• FBC waste hydration is regulated by its chemical composition. • For both industrial samples investigated, calcium sulfate is the limiting reactant for the formation of ettringite. • The results can be useful for the reuse of hydrated/reactivated FBC ash as a sulfur sorbent a fraction higher than its lime content can be exploited.
Botha (2001)	Fluidized bed combustion ash (FBC ash)	Overview of the fluidized bed combustion process and material.	• FBC bottom ash is a mixture of fuel ash, unburned carbon residues, and lime particles coated with sulfate layers. • FBC fly ash composition distinctly differs from that of fly ash produced by conventional combustion, above all by the absence of glass, mullite and other high-temperature phases, showing on the other hand much higher calcium sulfate content and higher portion of unmetamorphosed or only slightly thermally influenced coal mineral. • Diverse utilization options have been studied for FBC coal ashes. 1. construction applications: cement substitute, concrete block production, brick production, soil stabilizer, roadbase/subbase materials, structural fill material, and synthetic aggregates 2. agricultural applications: liming and soil amendment 3. waste stabilization: acidic waste stabilizer and sludge stabilizer
Rajczyk, Giergiczny and Glinicki (2004)	FBC ash	Use of Differential Thermal Analysis (DTA) in the investigations of fly ashes from fluidized bed boilers. DTA method was used to follow the hydration process of cement admixtures containing fluidized bed combustion	• For the potential use of fly ash the determination of the un-burnt carbon residue is critical because of limitation in standards for fly ash implemented as cement and concrete component. • In neat cement paste just after 1 hr hydration the peaks attributed to the formation of C-S-H and ettringite are clearly visible. • It is apparent that the FBC admixture modified substantially the course of

		by-product, formed on joined combustion and desulphurization in some installations with fluidized bed.	hydration process, particularly in relation to the enttringite phase. • The XRD data also indicate the so-called delayed formation and crystallization of ettringite in the samples admixture with fluidized bed fly ash.
Sellakumar and Conn (1999)	FBC ash	A comparison study of atmospheric circulating fluidized bed (ACFB) and pressurized circulating fluidized bed (PCFB) ash characteristics. The overall objectives of this study were to determine the market potential and the technical feasibility of using PFBC ash in high-volume use applications.	• The main components in ACFB and PCFB are from the inorganic constituents in the coal and incorporated sediments, sorbent derived elements and sulfur from the coal during combustion that is captured by sorbent. • PCFB should have a relatively lower content of calcium but higher content of coal-derived constituents than those from ACFB units. • CFB ashes generally contain a higher content of calcium as oxide and as a sulfate, but a lower content of silica and alumina than ashes generated from pulverized coal boilers. • The ashes are composed principally of anhydrite ($CaSO_4$), lime (CaO), quartz (SiO_2), and associated oxides of iron, magnesium, and dehydroxylated clays originating from the fuel ash components. • ACFB contains large amount of lime than PCFB. • Potential applications include construction and agricultural applications, waste stabilization • ACFB and PCFB cannot be classified as class C or class F fly ash because of low ferric oxide, alumina and silica and high SO_3 content. • It is possible to modify the hydration reaction chemistry of the PCFB ashes through such processes as lime enhancement to produce the geotechnical properties required for construction applications.

Kim (1999)	FBC ash	Environmental remediation with products of fluidized bed combustion.	• The alkalinity of the FBC material, residual lime and pozzolanic properties are desirable characteristics for use in soil stabilization and mine reclamation. • Coal mine remediation is a beneficial environmental use of FBC products, its effectiveness may be related to the amount of FBC products used and the method of emplacement. • Chemically, FBCP contains more calcium than class C ash from PC units. • The compressive strength is dependent on composition, moisture content, compaction, curing conditions and mineralogical changes during aging. • Loss of cohesiveness with time, may limit use in application where physical stability is required. • FBCP may be a superior reagent for acid mine drainage (AMD) control in inactive or abandoned mines, because of the high concentration of calcium and the formation of cementitiuos compounds. • Compared with coal combustion products from conventional power plants, FBCP was more effective at increasing pH, reducing acidity and released lower concentration of trace elements. • FBCP is used as a pit liner, cap material prior to the emplacement of top soil, and also to encapsulate acid producing spoil. • The use of FBCP reduces water infiltration and adds alkalinity to the post-mining groundwater. • FBCP is an adequate reagent for the neutralization of AMD and can be used for pyrite encapsulation and water diversion.

Tsuo, McClung and Sellakumar (1999)	FBC ash	Improving limestone utilization in a commercial-scale circulating fluidized bed boiler through ash reactivation and recycle. The effect of hydrated ash vs dry ash recycled and fly ash vs bottom ash recycled on boiler efficiency, limestone consumption and NO_x emissions were investigated.	• Test results in these field tests, showed that about 10 – 20% limestone saving can be achieved without any negative effect on boiler efficiency. • It has been demonstrated that the partially utilized sorbent present in the ash can further be utilized by various ash reactivation and recycle process. • The recycle of the hydrated ash can improve the limestone effectiveness and reduce the limestone requirement. • The hydrated ash recycle also affect the ash split, boiler gross efficiency and NO_x emissions. • The hydrated bottom ash was finer than the original bottom ash due to particle attrition and fragmentation in the mixer. • The bottom ash recycle process led to an increase in the calcium utilization in the fly ash. • The bottom ash recycle did not cause any net efficiency loss.

Table A-4. Embankment

Source	Type of ash	Description	Summary
Biehl, Martin, Browning and Collins (1989)	Fly ash class F with low metal leaching characteristic.	Properties and use of fly ashes for embankments.	• This study was made using class F fly ash. • Several problems that concern the use of fly ash are concerns for environmental impact, designer's unfamiliarity with compaction methods, construction difficulties, inferior properties of similar graded silt-size materials, etc. • Major environmental concerns are wind erosion, surface water-erosion, dissolution in surface runoff, and dissolution in rainfall percolating to ground water. • Overall performance equals or exceeds that of similarly graded natural material. • Fly ash generally does not posses the properties required for use as a roadway base course or select fill for slabs on grade. The chief value of this material in highway and building-site development is as common fill to raise and/or level grades. • It is probable that fly ash, available at little or no cost, will often be quite competitive with customary common fill materials.
Kim, Prezzi and Salgado (2005)	Mixtures of class F Fly ash & Bottom ash.	Geotechnical Properties of fly ash and bottom ash mixtures for use in highway embankments. Representative samples of class F fly ash and bottom ash were collected	• Ash mixtures compare favorably with conventional granular materials. • There is a slight decrease in hydraulic conductivity of compacted ash mixtures with the increase of fly ash content. • At 95% relative compaction, ash mixture exhibited comparable shear strength than these from compacted sands at same levels of compaction.

		from two power plants in Indiana to get their mechanical properties.	• Increasing bottom ash content decrease dilatancy due to crushing of bottom ash particles. • High volume fly ash mixtures are suitable for highway embankments if proper design and construction procedure are followed.
Pusadkar and Ramasamy (2005)	Class F Fly ash & Bottom ash. FA SG=2.06 BA SG=1.86	Collapse behavior of compacted coal ash fills. Factors influencing collapse potential of coal ash. Materials used from the National Thermal Power Corp. in New Delhi	• Fly ash is susceptible to collapse • Bottom ash and mixtures of 50% fly ash and 50% bottom ash showed negligible collapse. • For fly ash, the collapse potential increases with increase in inundation stress at all values of moisture content. • Aging reduces collapse potential significantly. (Based on a comparison between 0 days and 28 days of curing) • Collapse settlement increase almost linearly with rise of water.

Table A-5. Flowable fill

Source	Type of ash	Description	Summary
Wilson (1999)	Fly ash class C	Flowable fill as backfill for bridge abutments. This study attempted to document the effectiveness of using a controlled low strength material (CLSM) as backfill for two county highway bridge abutments. The west ends of the two structures were constructed with the CLSM, while the east ends were constructed with conventional granular materials / compaction methods.	• The CLSM used consisted of a mixture of foundry sands, Class C fly ash, cement and water. • It appears that the cold weather and the saturated surroundings soils significantly lengthened the set time. The cold temperatures likely reduced the rate of hydration and the saturated surrounding silty/clay soils may have prevented the release of moisture from the CLSM. • After 10 – 11 months, there did not appear to be any difference in performance between the granular backfill and the flowable fill. • From available data, it appears that the use of flowable fill as backfill for both of these structures performed slightly better than the conventional granular fill, however the differences is not significant. • A literature search discovered a similar project that reported flowable fill to have superior settlement properties under heavy traffic loading as compared to conventional backfill.

Table A-6. Masonry

Source	Type of ash	Description	Summary
Otero, Blanco, Garcia and Ayala (2004)	Fly ash class F	Manufacture of refractory insulating bricks using fly ash and clay. Study the possibility of using fly ash for the manufacture of bricks by means of an experiment using fly ash, clay, sodium silicate and water. The fly ash came from Asturias, Spain.	• Densities of assayed bricks are very similar to that of the fly ash bricks. • Thermal conductivity of manufactured bricks is good but their refractoriness is inferior. • Refractoriness can be increased by increasing the quantity of clay in the mixture with fly ash. • Manufactured bricks can be used industrially. • In general, manufactured bricks have good mechanical strength, low thermal conductivity and are good insulating material.
Phillips, Gropo and Peronne (2005)	Bottom ash and fly ash class C&F	Evaluation of processed bottom ash for use as lightweight aggregate in the production of concrete masonry units. The objective is to study the behavior of blocks and cylinder using cement and substituting with ashes part of the aggregate. The material comes from Rockport Power Plant in Indiana.	• Cylinders and blocks were tested at 3,7,14 &28 days to obtain the compressive strength. The goal is to obtain strength of 1000 psi in 3 days. • When substituting 30% of the aggregate by fly ash class C, the resulting f'c for 28 days was 3000psi. When substituting the same percent but with fly ash class F, the resulting f'c was 700 psi. • Rockport bottom ash when used alone as aggregate does not achieve the strength of 1000 psi in 3 days. • The substitution of fly ash for aggregate improves the compressive strength. • At a 30% of substitution of fly ash as aggregate can be obtained beneficial results for strength development. • Blocks did not develop the strength as the cylinders did with the same ash because the block machine has no independent control of mechanisms as

			vibration and compaction and for the cylinder this could be controlled.
Wu and Sun (2003)	Fly ash	High-performance masonry products from 100% fly ash: A Synergistic Approach. Study to investigate the potential use of fly ash in masonry units. This is a study made by Michigan's Wayne State University to verify the use of fly ash in masonry units.	• Class C fly ash is more active than Class F fly ash, this makes class C to have a better performance and consequently better results. • NaOH is considering as a good activator for fly ash. • Increasing the NaOH content increases the mechanical properties of the samples. • The fly ash samples show a very positive short term performance in the construction area.
Kayali (2005)	Fly ash	High performance bricks from fly ash. Study the performance of bricks 100% fly ash manufactured using similar techniques to those used for clay bricks.	• Using fly ash the weight of the bricks is 28% less than those made with clay. • The compressive strength of the flash bricks is about 40 Mpa, much better than commercial bricks. • Characteristics as absorption capacity, modulus of rupture, durability and bond streght were studied and the result showed that flash bricks are excellent and in some cases better than commercial bricks. • Flash bricks have a less complex manufacturing process and lower cost than commercial bricks. • The manufacture of these bricks increases fly ash use close to 100%.

Table A-7. Other uses

Source	Type of ash	Description	Summary
Kumar and Vaddu (2004)	Bottom ash	Time dependent strength and stiffness of PCC bottom ash-bentonite mixtures. In this study, changes in strength and stiffness characteristics of Illinois PCC bottom ash and bentonite mixtures with time are evaluated. A series of unconfined compression tests on bottom ash-bentonite mixtures at various curing ages was performed in the laboratory.	• Studies have shown that the physical properties of bottom ash obtained from burning of pulverized coal are similar to that of natural sand with particle sizes ranging from gravel to fine sand and low percentages of silty and clay sized particles. • Results presented show that strength and stiffness of bottom ash-bentonite mixture changed significantly with time. • The failure strain increased with increase in bentonite content and decrease with the curing age. • At all curing ages, secant modulus decreased with the increase in bentonite content up to 15% and increased slightly beyond 15% bentonite.
Shenbaga, Kaniraj and Gayathri (2003)	Fly ash	Geotechnical behavior of fly ash mixed with randomly oriented fiber inclusions. An experimental study was carried out to investigate the influence of randomly oriented fiber inclusions on the geotechnical behavior of two Indian fly ashes. Polyester fibers of two different types and a constant fiber content of 1% (by dry weight) were used in the experiments.	• This paper presents the results of compaction tests, triaxial shear tests, and other geotechnical characterization tests carried out on the raw and fiber-reinforced fly ashes. • The fiber inclusions increased the strength of the raw fly ash specimens and changed their brittle behavior into ductile behavior. • The length of the fiber seems to have an influence on the behavior of the specimens. • The fiber inclusions increased the failure deviator stress and the shear strength parameters c_{uu} and φ_{uu}.

Kumar and Stewart (2003)	Bottom ash	Evaluation of Illinois pulverized coal combustion dry bottom ash for use in geotechnical engineering applications.	• Physical properties of bottom ash are similar to those of natural sand. • Characteristics depend on type of coal burned and type of furnace used. • Bottom ash is more inert than fly ash. • Bottom ash displays less pozzolanic properties than fly ash. • The liquid limit, plastic limit, and plasticity index of bottom ash-bentonite mixtures increased with the increase in bentonite content. • The addition of bentonite to bottom ash increased cohesion while decreasing φ, σ_1, maximum unit weight, and hydraulic conductivity. • Increase in Q_u occurred with the increase of unit weight and amount of bentonite.
Conn, Sellakumar and Bland (1999)	Fly ash class C & class F	Utilization of CFB fly ash for construction applications. This paper studies different types of fly ashes and what applications they can be used for.	• The high sulfur bituminous coal fly ash nearly qualifies as class C fly ash. • The high sulfur fly ash may have potential uses as structural fill, soil stabilization purposes, road base, and aggregate.
Trivedi and Sud (2004)	Fly ash class F	Collapse behavior of coal ash. Examine factors influencing collapse settlement of the compacted coal ash due to wetting. Coal ash used from Ropar Thermal Plant in India.	• The collapse of ash is correlated with its grain size. • Ashes with difference in void ratio and different friction angles in dry and submerge states have a tendency to collapse upon wetting. • The highest the degree of compaction the smaller the collapse potential. • Collapse potential decrease at a high moisture content. • Ashes with particles of silt size of more than 50% have tendency to collapse. • Field test confirm that rising in water table implies an incidence in collapse.

Markou and Atmatzidis (2002)	Fly ash (class not specified). 32% of CaO	Properties and performance of a pulverized fly ash grout. A laboratory investigation was made to develop a new grout using fly ash from Greece.	• Mortar and concrete samples with fly ash developed strength of about 40 and 65% compared with similar samples with only Portland (1986) • PFA suspensions have similar viscosity, low bleed capacity and comparable setting time to Portland cement type II • Hydraulic conductivity of soils injected with suspension grouts is reduced due to the reduction of the volume and interconnectivity of soil voids caused by grout. • Qu of PFA grouted sands was up to 3000 kPa. • Hydraulic properties can be improved by pulverization and this also improves injectability.
Sheng, Huang, Zhang, Zhang, Sheng, Yu and Zhang (2003)	Fly ash class F	Production of glass from coal fly ash. Study the vitrification capacity of Chinese coal fly ash to produce glass matrices	• Coal fly ash does not have good ratios of materials, this is a reason to use additive. • Fly ash has insufficient glass network modifiers. • Glasses obtained from the study resulted homogeneous. • Glasses produced from the coal fly ash are classified as non-hazardous. • When 10%wt of Na2O is added, glasses showed good durability and suitable viscosity. • Heavy metals were successfully solidified into the glass structure.
Tsimas and Moutsatsou-Tsima (2005)	Fly ash class C	High-calcium fly ash (HCFA) as the fourth constituent in concrete: problems, solutions and perspectives. This paper studies the possible use of	• Most of the class C fly ashes don't fully meet the requirements from the standards to be used in concrete. • However, under tight control of the whole process of design-production-application, the use of HCFA is more beneficial than LCFA in terms of

		High-calcium fly ash (class C) in concrete.	strength. • The use of HCFA in large amounts presents some difficulties because of its heterogeneity in its composition, its need to be grinded to better its properties, high amounts of free CaO may cause soundness problems and temperature increase, and the periodically elevated proportions of SO_3 may cause expansion problems. • Despite these negative effects, in 1992 Power Public Corporation decided to go forward with the construction of Platanovrissi dam using 150,000 tons of class C fly ash. • This paper explains the different measures taken to upgrade the class C fly ash. • It is possible to obtain several qualities of treated fly ashes by adjusting the grinding mill operation parameters. • Experiments showed that the best results concerning strength development occurred in mixtures containing HCFA with free CaO content in the range of 3-3.5%.
Tishmack, Peterson and Flanagan (2001)	Fluidize bed combustion ash (SoilerLime) and Class C fly ash (Nutra-Ash)	Use of Coal Combustion By-Products to reduce soil erosion. This paper presents the studies made to Nutra-Ash, SolirLime, turkey compost, and gypsum for the purpose of reducing soil erosion. Nutra-Ash is class C fly ash obtained from a power plant in Indiana. This fly	• Calcium ions are effective at improving soil structure and increasing water infiltration. • Soil erosion is mainly caused by the impact of rain drops, flowing water, and chemical dispersion of clay particles. • Nutra-Ash presented the least amount of calcium in the solution, while SoilerLime presented the most. • Because of Nutra-Ash had been exposed to moisture for several years in

		ash is from a landfill that has spent several years in place. SoilerLime is a mixture of fluidized bed combustion ash from the Purdue power plant and an organic by-product from Eli Lilly & Co.	the landfill, it contained less soluble minerals than fresh material, therefore it was the least effective material. • A reduction in runoff indicates improved infiltration and a decrease in sediment yield indicates improved resistance to soil erosion. SoilerLime was the most effective reducing total runoff by 48% and sediment loss by 30%.The Nutra-Ash reduced runoff by 9% and sediment loss by 15%. • An unhydrated class C fly ash would perform better than Nutra-Ash, particularly one with CaO content greater than 25%. • Dry coal combustion by-products may be used as effective tools for the reduction of soil erosion.

Table A-8. Road

Source	Type of ash	Description	Summary
Barenberg (1974)	Fly ash	Lime-Fly Ash aggregate mixtures in road construction.	• Provides guidelines for design and construction for using lime and fly ash mixtures with aggregates for bases and subbases of pavements.
Lav and Lav (2000)	Fly ash class F	Microstructural development of stabilized fly ash as pavement base material. Microstructural, chemical, mineralogical and thermal analysis was carried out in a study to use Eraring Power Station (New South Wales Australia) fly ash as pavement base material. The fly ash was stabilized with cement and lime separately.	• Eraring fly ash is (ASTM) Class F ash – a low-calcium fly ash – and has a very low loss of ignition. • The results obtained from cement and lime stabilized samples showed that the hydration products that account for strength gain of the stabilized fly ash are almost the same for both types of stabilizing agents. • During the period of 1 to 28 days, the following microstructural developments were identified in cement-stabilized fly ash. 1. Ettringite was formed using the fly ash spheres as nucleation sites. 2. Fibrous hydration products were found, indicating C-S-H type I gel and ettringite rods joined together, resulting in strength gain in the cement-stabilized fly ash matrix. 3. There was also evidence of carbonation of calcium hydroxide due to the reaction with carbon dioxide in air.
Kuennen (2004)	Fly ash class C	Reclaimed by-products boost concrete performance. How waste materials from manufacturing are making longer lasting, more durable concrete for highways and bridges.	• Fly ash reduced permeability in the finished cured concrete. Fly ash reacts with lime and alkalis, creating cementitious compound that block-up Portland cement concretes porous structure. • Mixtures designed to produce equivalent strength at early ages will ultimately exceed the strength of conventional Portland cement concrete mixes.

			• Fly ash provides improved workability, too, due to the spherical shape and small size of its particles. • Fly ash can also reduce bleeding in concrete, because lowers amounts of water are required due to its improved workability.
Kroeger and Chugh (2003)	Fly ash class F	Development and demonstration project using fly ash as a road subbase. The goal of this project was to develop, demonstrate and document the beneficial use of a ponded F-fly ash as a road subbase material for portions of a 3.4km (2.1 mile) long stretch of county highway without negative environmental impacts to surface water or ground water.	• Laboratory testing indicate the flay ash would serve adequately as a road sub base, conforming to Illinois Department of Transportation (IDOT) standard specifications. • The performance of the fly ash fill exceeds expectations. The road way performed well during the year following construction with no visible signs of settlement or distress. • Like loess, the fine-grained fly ash was susceptible to water erosion, and the fly ash fill needed to be protected by a native soil cover.
Mulder (1996)	Pulverized fly ash (PF ash) class F and atmospheric fluidized bed combustion ash (AFBC ash)	A mixture of fly ash as road base construction material. This study presents the results of some tests that were made to specimens with different type of fly ash to verify the potential use for road base applications. Specifically study the behavior of specimens based in the formation of a	• Ettringite is formed by the reaction of calcium hydroxide, calcium sulphate and aluminum oxide. • The formation of ettringite it's limited by the quantity of calcium hydroxide available and contributes to the strength development in the samples. • Higher relative humidity will lead to higher compressive strength but this induces the formation of more ettringite which can increases crack formation because of expansion.

		mineral called ettringite. This was made in The Netherlands.	• Ettringite does not cause any crack formation in specimens if the calcium content in the mixture of fly ash does not exceed 12% • Calcium oxide is necessary to obtain high strength stabilization. • Mixtures of AFBC ash and PF ash when are used as a road base construction material does not need binding agents like lime or other calcium components. • The stabilization of mixtures of AFBC ash and PF ash is a cheap substitute for sand/cement stabilization.
Basak, Bhattacharya and Paira (2004)	Fly ash (class not specified)	Utilization of fly ash in rural road construction in India and its cost effectiveness. Study the application on fly ash in roads and embankments and the possible economic advantages that the use of this kind of material can bring.	• Fly ash that is going to be used as filling material should not have soluble sulphate content that exceeds 1.9 gm per liter. • If the soil available responds to pozzolanic action with fly ash parameters related to strength would be improved. • Adding lime to silty soils and fly ash mixtures reduces leaching action also mixing of lime helps to keep adequate strength and durability. • Mixtures of soils and fly ash can improve parameters as plasticity index, liquid limit, plastic limit and values of C.B.R. • In rigid pavement it is found that fly as can replace part of cement or sand. • For the construction of embankments in the vicinity of thermal power stations, fly ash can be used economically in distance less than 10 to 15 km from the site. • For rigid pavement construction it is acceptable replace cement with dry fly ash and also is economic to transport it even if the distance to haul it is more than 50 or 100 km.

Deschamps (1998)	FBC ash	Using FBC and stoker ashes as roadway fill: a case study. And overview of the project and construction operations is described, and the results of geotechnical laboratory tests and field monitoring are presents.	• A large road way embankment was constructed using 60% FBC, 35% stoker and 5% class F fly ashes. • FBC contains products that react with water and cause the material to both harden and swell with time. • The coal combustion by-products tested are nonplastic and would be classified as silty sand (SM) or poorly graded sand (SP) for the FBC ash and mixtures. • The optimum water content is larger than and maximum dry density lower than typical soils of comparable gradation. • The hydraulic conductivity of the compacted CCP's ranged between 1 x 10^{-5} and 1 x 10^{-4} cm/s. • The strength of the uncured materials is more than adequate for use as a structural fill with friction angles typically >36º in a loose condition. The strength of cured samples can be much larger due to cementitious hardening that occurs with the formation of hydration products • FBC ash compacted fresh can develop large swell pressures and swell strains. • The FBC lecheates does exceed the standards with respect to pH, sulfate, and total dissolved solids. Other sources of contamination present at the site make it difficult to interpret the impact of the embankment on ground-water quality. • The CCP's in the embankment initially caused elevated sulfur levels in the ground water but that these levels are diminishing with time. • The ultimate strength and stiffness of the compacted material far exceed

			that which was needed in structural fill. • Due to the formation of minerals gypsum and ettringite, vertical strain was developed. • Large swell strains resulted even under high vertical stresses and the strain were complete within a few days. • All of the settlement plates were eventually damaged by construction operations or by swelling of the CCP's. • In the lower portion of the embankment the settlement dominated, while at the top of the embankment the swell dominated. • The weathered CCP's have higher shear velocities than the fresh CCP's. • The FBC and stoker ash embankment was easily built with conventional construction equipment. • The properties of the FBC and mixtures with stoker ash vary with the degree of weathering before compaction. • The uncompacted CCP's are very erodible while the compacted material is not. • Expansion is still taking place two years after construction of the embankment.
Chesner, Collins, MacKay, and Emery (2005)	Bottom ash	Provide general guidelines for waste and by-product material in road construction	• Provide general guidelines, and overview, and a literature of relevant case histories. • FHWA online manual.

Table A-9. Soil Stabilization

Source	Type of ash	Description	Summary
Cokca (2001a)	Fly ash class C	Uses of class C fly ash for the stabilization of an expansive soil. Evaluation and comparison of effective lime and cement mixtures for soil stabilizing with class C fly ash mixtures.	• Lime required for stabilizing expansive soils range from 2 to 8% by weight. • Cement required for stabilizing expansive soils range from 2 to 6% by weight. • Addition of fly ash to the soil mixture altered the grain size distribution. Silt fraction increased with the addition of fly ash. • The mixture of 25% high-calcium fly ash reduced swelling potential by 65%. The mixture of 25% low-calcium fly ash reduced swelling potential by 68%. • Plasticity index, activity, and swelling potential decrease with the increase of fly ash and curing time. • The mixture with 20% fly ash had nearly the same effect on swelling potential as a mixture with 8% lime. • High-calcium class C fly ashes can be recommended as effective stabilizing agents for expansive soils.
Kukko (2000)	Fly ash	Stabilization of clay with inorganic by-products. This study focuses on different binder alternatives based on industrial by-products. Among these are commercial stabilization binders which are mainly based on coal fly ash.	• Commercial by-product binders give higher strength than Portland cement binder. • The rate of hardening is lower than that of cement-based binders. • There is a certain amount of binder that has lower strength gain than stabilized clay. This depends on the type of soil and binder.
Ghataora, Alobaidi and Billam (2000)	Fly ash	Use of pulverized fuel ash in trench backfill. This paper studies different	• The PFA/sand/cement ratio that presented the highest compressive strength is 4/8/1. This strength was 6 times higher than that of PFA/cement and 2.5 times

		pulverized fly ash (PFA), sand and cement mixtures as backfill for shallow trenches.	higher than that of sand/cement for the same (PFA + sand)/cement ratio. • The PFA/sand/cement ratio of 4/8/1 presented a permeability of 1.2×10^{-9} m/s. • The mixture of PFA, sand and cement reduces void ratio. • Field performance tests showed that the mixture performed better than a conventional Type 1 granular sub-base. It had less permanent deformation and less elastic deflection.
Kumar and Sharma (2004)	Fly ash	Effect of fly ash on engineering properties of expansive soils. This paper studies the efficacy of fly ash as an additive in improving the characteristics of expansive soils.	• The plasticity, hydraulic conductivity and swelling properties of the blends decreased and the dry unit weight and strength increased with an increase in fly ash. • The soil tested is a class CH soil with free swell index of 250% and natural water content of 14%. This soil was mixed with fly ash ranging from 0 to 20% of the dry weight. • When fly ash content is 20%, the plasticity index is reduced by about 50%. • Liquid limit decreases and plastic limit increases with the increase of fly ash. Free swell index is also reduced by the addition of fly ash. • With the increase of fly ash content, it was observed that the compaction curves shifted up and to the left. Therefore since more effort is needed to compact the soil, it is considered to be more stable. • Good correlation values were obtained for undrained cohesion using equation. • Fly ash blended expansive soil is a suitable material for sub-grade, embankment, and backfill uses.
Cokca (2001b)	Fly ash class	Effect of fly ash on swell pressure of	• Soils containing the clay mineral montmorillonite have tendency to be

	C	an expansive soil. This work investigates the effectiveness of fly ash in reducing swell pressure in expansive soils. Some specimens were tested with no curing and with 7 to 28 days of curing. The fly ash comes from Soma and Tuncbilek thermal power plants in India.	expansive. • As the fly ash percentage increases, the soil becomes more granular. • Values of liquid limit of the soil decreased with increasing the amount of fly ash. • Fly ash was effective in reducing the swell pressure when 25% by wt dry of soil were introduced. • Increasing fly ash content and curing time decreases the activity of the mixtures of expansive soils. • The optimum fly ash addition percent appears to be close to 20%.
Glazewski	Fly ash class C	Implementation of fly ash as a stabilization device in clay soils. Determine if coal fly ash from Bio-recycle plant in Pennsylvania can be used to reinforce clay soils and to find the optimum percent that gives the best results.	• The application of fly ash increases plant available water also neutralizes acidity and reduces the toxicity of trace metals. • 54% of coal fly ash by dry weight provides the maximum angle of internal friction on the clay soil. • Calcium content in the ash controls the rate of heat developed in Portland cement fly ash mixture. • Fly ash must be dry when used as a mineral admixture. • The maximum bearing capacity was obtained with 62.5% dry fly ash mixture.
Nalbangtoglu and Emin (2002)	Fly ash class C with 16% CaO	Utilization of an industrial waste in calcareous expansive clay stabilization. Study to improve the condition of calcareous soils and make it more granular in nature	• Mixtures of Soil and fly ash 15-25% by dry weight of soil where prepared. • Fly ash and lime-fly ash caused changes in the classification of the soil. • Class C Soma fly ash is used as a chemical additive. • There was a decrease in the plasticity index in the treated soil due to cation exchange.

		using fly ash.	• Hydraulic conductivity increases with increase in the fly ash percent and curing time. • Effective methods of soil stabilization are produced with fly ash and lime mixtures. • At zero fly ash percent the swell potential was 19.6%, at 25% of fly ash content the swell potential decreases to a value of 4.8 with curing time of zero.
Norton, Chaudhari and Flanagan (2002)	FBC ash	Erosion control using soil amendments and other low cost methods prior to establishment of vegetation. The objective of this work was to prevent runoff from occurring or reduce its magnitude or to slow the movement of water on slopes after it has occurred.	• The use of organic polyacrylamide (PAM) in combination with gypsum on 2:1 slopes proved the most effective treatment at controlling erosion and also in establishment of vegetation. • The inorganic material used included fluidized bed combustion bottom ash (FBCBA), flues gas desulfurization (FGD) sludge and forced oxidized (FO) FGD • The FBCBA is largely anhydrite, FGD is various forms of $CaSO_3xH_2O$ and FO is 99.9% pure gypsum. • By adding FBCBA on the surface at 5 MT * ha^{-1} infiltration rates can be significantly increased even at rain intensities up to 110 mm/hr. • FBCBA improved infiltration by promoting clay flocculation and maintaining aggregate stability. • The concept of using low cost materials that treat the cause of erosion at the source has been proven viable and in being adopted in a large scale in the USA by producers. • The utilization of hither to for wastes, both inorganic and organic show great promise in control erosion and its off-site environmental problems.

Beeghly (2003)	Mixture of lime and class F fly ash	Recent experiences with lime-fly ash stabilization of pavement subgrade soils, base and recycled asphalt.	• Renewal of interest in soil subgrade stabilization because of its potential to reduce construction costs. • Combination of lime and fly ash is beneficial for lower plasticity with higher silt content soils. • This combination has beneficial effects in the compaction of wet soils since the maximum density occurs at higher moisture contents. This allows the contractors to work under wetter conditions. • Helps reduce costs: 1. Permanently improves the pavement subgrade which allows a reduction in pavement thickness. 2. For large areas, it is less expensive than undercutting and replacing the material. 3. Stabilization with lime-fly ash is less expensive than Portland cement.
Trzebiatowski, Edil, and Benson (2004)	Fly Ash Class C	Case study involving the stabilization of a subgrade using fly ash. Project located in State Highway 32, Port Washington, Wisconsin	• Weak subgrade consisting of a soft, sandy clay. Road difficult to build. • Typical DoT solution: overxcavation and replacement with gravel. Expensive. • Stabilization with fly ash by-product from local power plant. • Field and laboratory results showed excellent results. • Alternative solution cheaper and environmentally friendly.

Table A-10. Waste material

Source	Type of ash	Description	Summary
Rebeiz, Rosett and Craft (1996)	Fly ash	Strength properties of polyester mortar using PET and flay ash wastes. The effect of sand and fly ash on the strength properties of polyester mortar (PM) using unsaturated polyester resins based on recycled poly(ethylene tertphthalate) (PET) plastic waste have been evaluated in this study.	• The test results show that the use of fly ash and PET wastes is very beneficial for the production of good-quality and relatively low-cost PM. • The utilization of these wastes in PM would help save energy and alleviate an environmental problem. • PM is a strong, durable, and virtually impermeable material. • The main disadvantage of PM is the relatively high cost of its resin component. • The addition of sand decreases the compressive strength of the PM • The addition of fly ash of 10% and 20% by weight of fly ash to the PM results in a compressive strength significantly higher than the compressive strength of the neat resin. • The compressive strength of the PM using 30% and 40% by weight of fly ash is slightly lower than the compressive strength of the neat resin. • The tensile strength of PM decreases with an increasing amount of filler. • The modulus of elasticity of PM increases significantly with an increasing amount of fillers. • The replacement of sand with up to 50% by weight of flay ash increases the tensile strength of PM. A 50 % by weight replacement of sand fly ash provided the optimum packing for the different aspect ratios of sand and fly ash. • The replacement of sand with fly ash decreases the tensile modulus of elasticity of PM since fly ash has lower stiffness than sand.

Jaturapitakkul and Cheerarot (2003)	Bottom ash	This study is about the potential use of bottom ash as a pozzolanic material. Bottom ash with large, porous and irregular particles from the Mae Moh power plant in Thailand.	• Increase of ground bottom ash to replace Portland cement resulted in higher water requirement of mortar. • Replacing cement with original bottom ash require less water. • When the percent of bottom ash replacing cement was higher, the lower the compressive strength of mortar occurred. • Bottom ash should not be used as a pozzolanic material unless the particle size and porosity are being reduced.