Quantifying the Benefits of Using Coal Combustion Products in Sustainable Construction

1020552

Draft Final Report, December 2009

EPRI Project Manager
K. Ladwig

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Recycled Materials Resource Center

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This report was prepared by

Recycled Materials Resource Center
University of Wisconsin-Madison
Madison, Wisconsin 53706 USA

Principal Investigators
C. Benson
T. Edil

Contributors
J. Lee
S. Bradshaw

This report describes research sponsored by the Electric Power Research Institute (EPRI).

This publication is a corporate document that should be cited in the literature in the following manner:

Quantifying the Benefits of Using Coal Combustion Products in Sustainable Construction. EPRI, Palo Alto, CA 1020552.

DRAFT DECEMBER 5, 2009

EXECUTIVE SUMMARY

Life cycle analysis programs were used to quantify the benefits of using coal combustion products (CCPs) from electric power production in sustainable construction. The analysis focused on the most ubiquitous CCPs (fly ash, bottom ash, and flue gas desulphurization (FGD) gypsum) and their most common applications (concrete production, wallboard manufacturing, and geotechnical applications) as identified through an analysis of industry CCP use data for 2007. Comparisons were made between energy consumption, water use, and greenhouse gas (GHG) emissions associated with conventional materials and procedures and those employing CCPs.

The analysis showed remarkable benefits are obtained by using CCPs in sustainable construction. Energy consumption is reduced by 162 trillion Btu, water consumption is reduced by 32 billion gallons, GHG emissions are reduced by 11 million tons CO_2e, and $5-10 billion is saved. The reduction in energy consumption is commensurate with the energy consumed by 1.7 million homes (a large US city), the water saved is equal to 31% of the annual domestic water use in California, and the reduction in GHG emissions is comparable to removing 2 million automobiles from the roadway. The financial savings can also provide the average income for approximately 200,000 Americans.

The greatest environmental benefits in sustainable construction are currently being realized by using CCPs (mainly fly ash) in concrete production. Use of fly ash as a cement substitute annually saves more than 55 trillion Btus of energy (≈equivalent to 600,000 households) and reduces GHG emissions by 9.6 million tons CO_2e (≈equivalent to 1.7 million passengers cars). Using FGD gypsum in wallboard manufacturing results in more energy savings (98.2 trillion Btu annually) and greater reduction in water consumption (31 billion gal, or approximately three times the annual water use in Arizona or Nevada), but a smaller reduction in GHG emissions (0.74 million tons CO_2e or 100,000 passenger cars). Smaller savings in energy consumption, water consumption, and GHG emissions are realized from geotechnical applications at current usage rates. The greatest financial benefits are obtained by using FGD gypsum in wallboard manufacturing, followed by use of fly ash in concrete, and geotechnical applications. The financial benefits are closely aligned with the reductions in energy consumption and GHG emissions and the total amount of CCPs used.

Benefits are also achieved by avoiding disposal; 3.7 trillion Btu of energy is saved (≈ 38,600 households) and CO_2e emissions are reduced by 0.3 million tons (≈ 46,300 automobiles) by not disposing CCPs in landfills. The financial savings obtained by avoiding disposal ranges between $0.5-5.3 billion/yr depending on the disposal approach (on-site vs. commercial) and the type of disposal facility (Subtitle D vs. Subtitle C).

DRAFT DECEMBER 5, 2009

ACKNOWLEDGMENTS

This report was prepared by the Recycled Materials Resource Center using financial support from the Electric Power Research Institute (EPRI). Ken Ladwig was the project manager for EPRI. The following persons provided valuable input to the study: Jeff Daniels and Jessica Sanderson (United Gypsum Company); Jim Johnson and Keith Bargaheiser (Headwaters Resources); Mike MacDonald, Tom Adams, and Dave Goss (American Coal Ash Association); Lyn Luben (U.S. Environmental Protection Agency); Jack Gibbons (CSRI); Tony Fully (National Gypsum Company); John Foster (Boral Material Technologies, Inc.); and Paul Koziar (Koziar Consulting LLC).

DRAFT DECEMBER 5, 2009

CONTENTS

1 **INTRODUCTION** **1-1**

2 **LIFE CYCLE ANALYSIS MODELS** **2-1**

BEES Model 2-1

SimaPro Model 2-1

PaLATE Model 2-2

Methodology For Determining Benefits 2-2

3 **RESULTS** **3-1**

Fly Ash Use in Concrete 3-1

FGD Gypsum in Wallboard Manufacturing 3-3

Fly Ash and Bottom Ash in Geotechnical Applications 3-4

Benefits of Avoided CCP Disposal 3-7

Cumulative Benefits 3-11

4 **SUMMARY AND CONCLUSIONS** **4-1**

5 **REFERENCES** **5-1**

A **SENSITIVITY ANALYSIS FOR TRANSPORTING CEMENT AND FLY ASH** **A-1**

LIST OF FIGURES

Figure 1-1 Historical production and use of CCPs (adapted from ACAA 2009)........................1-1
Figure 1-2 Uses of fly ash, bottom ash, and FGD gypsum by application 1-4
Figure 3-1 System boundary for 4 ksi concrete production without fly ash (adapted from EPA 2008). Replacement of cement by fly ash adds an additional branch in the tree parallel to the cement branch...3-2
Figure 3-2 Life cycle system boundaries for landfilling (adapted from EREF 1999) 3-8

DRAFT DECEMBER 5, 2009

LIST OF TABLES

Table 1-1 CCP production and use in 2007 (adapted from ACAA 2008). 1-3
Table 3-1 Benefits obtained by replacing 15% of Portland cement with fly ash (adapted from EPA 2008)....... 3-2
Table 3-2 Benefits profile for 100% FGD gypsum replacing 100% virgin gypsum (adapted from EPA 2008) 3-3
Table 3-3 Benefits profile for replacing a 50% sand and gravel mixture in with fly ash in a structural fill 3-5
Table 3-4 Benefits profile for replacing a 50% sand and gravel mixture with bottom ash in a structural fill 3-5
Table 3-5 Benefits profile for replacing crushed rock with fly-ash-stabilized subgrade....... 3-6
Table 3-6 Benefits profile for the substitution of bottom ash for Wisconsin Grade 2 granular fill subbase 3-6
Table 3-7 Total LCI attributable to landfill construction (data from EREF 1999)....... 3-9
Table 3-8 Total LCI attributable to landfill operations (data from EREF 1999) 3-9
Table 3-9 Total LCI attributable to landfill closure (data from EREF 1999)....... 3-9
Table 3-10 Total LCI attributable to landfill post-closure care (data from EREF 1999)....... 3-9
Table 3-11 Total LCI attributable to leachate management for 100 yr (data from EREF 1999) 3-10
Table 3-12 Benefits due to avoided landfilling of recycled CCPs (fly ash, bottom ash, and FGD gypsum) 3-10
Table 3-13 Economic benefits due to avoided landfilling of fly ash, bottom ash, and FGD gypsum currently used in sustainable construction....... 3-10
Table 3-14 National annual savings from the use of fly ash in concrete and comparisons to consumption equivalents....... 3-12
Table 3-15 National annual savings from use of FGD gypsum in wallboard manufacture and comparisons to consumption equivalents 3-12
Table 3-16 National annual savings from use of fly ash and bottom ash for geotechnical applications and comparisons to consumption equivalents 3-12
Table 3-16 National annual savings from avoided disposal of CCPs and comparisons to consumption equivalents....... 3-13
Table 3-18 Summary of environmental savings achieved by using fly ash, bottom ash, and FGD gypsum in each major application 3-14
Table 3-19 Total annual savings from using fly ash, bottom ash, and FGD gypsum in major applications and consumption equivalents....... 3-14

DRAFT DECEMBER 5, 2009

1 INTRODUCTION

Coal combustion accounts for 42% of all fossil fuel consumed for energy production in the United States, and contributes to 50% of the electrical power generating capacity of the nation (EIA 2009). Use of coal as an energy source has continually increased over time and coal will continue to be an important fuel for the foreseeable future. As a result of increased coal use and new air emissions controls, the production of coal combustion products (CCPs) as a byproduct from pollution control systems is also steadily increasing (Figure 1-1). In 2007, 131.1 million tons of CCPs were produced in the United States (ACAA 2008). Fly ash (71.7 million tons), bottom ash (18.1 million tons), and gypsum from flue gas desulphurization (FGD) operations (12.3 million tons) constitute the majority (78%) of the CCPs produced annually. Beneficial use in construction applications consumed 47% (48.2 million tons) of the fly ash, bottom ash, and FGD gypsum that was produced in 2007. The remaining 53% (53.9 million tons) was disposed in impoundments or landfills.

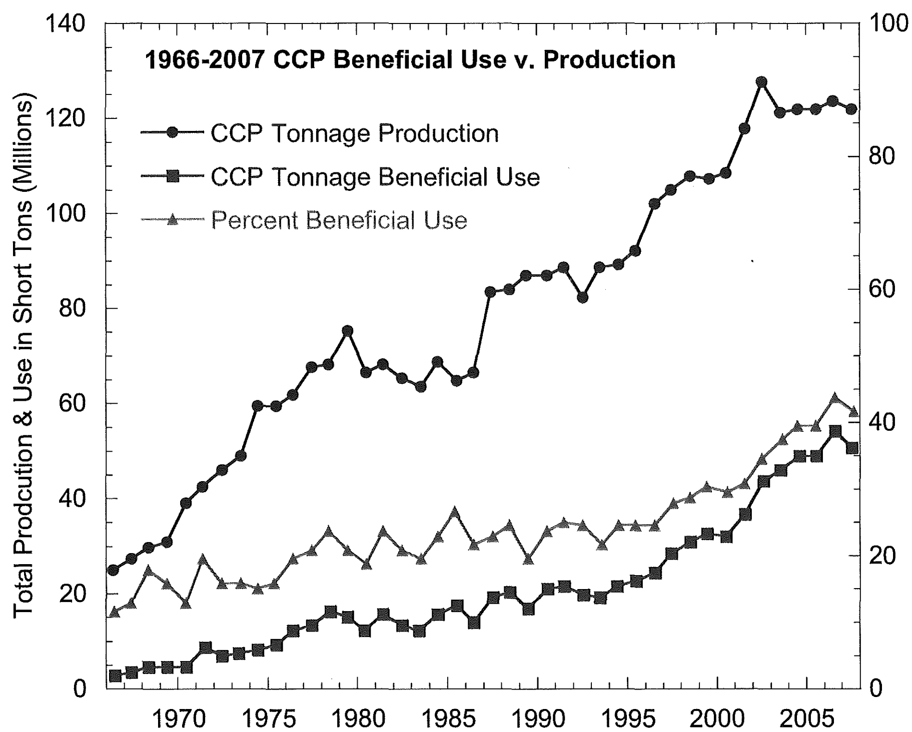

Figure 1-1
Historical production and use of CCPs (adapted from ACAA 2009).

Fly ash is a fine powdery material collected from the exhaust of a coal combustion chamber that is pozzolanic and can be cementitious. The majority of fly ash use is associated with cement and concrete (55% of total used), with partial replacement of Portland cement in concrete the most common use (43% of total used) (ACAA 2008). Geotechnical applications, which include road base and subbase, soil stabilization, and embankments/fills, are also significant uses of fly ash (28% of total used) (ACAA 2008). Bottom ash is a coarse granular residue (gravel and/or sand-size particles) from coal combustion that has similar chemical composition as fly ash (EPA 2008, FHWA 2008). Because the particles are larger, bottom ash is used as substitute for conventional aggregates (sands and gravels), primarily in geotechnical applications (55% of total used) (ACAA 2008).

FGD gypsum is a byproduct of flue gas desulphurization at coal-fired power plants that use wet scrubbers and forced oxidation to reduce SO_2 emissions. The gypsum produced by the desulphurization process is mineralogically identical to natural gypsum ($CaSO_4 \cdot 2H_2O$), making FGD gypsum an ideal replacement for mined gypsum used to manufacture wallboard. In 2007, 75% of FGD gypsum produced was used beneficially, 90% of which was used to produce wallboard. Other significant uses of FGD gypsum include agriculture and cement/concrete production (ACAA 2008).

Use of CCPs in construction materials has been steadily increasing (Figure 1-1), and in some applications (e.g., wallboard, Portland cement concrete) CCPs are now considered as standard or required materials in manufacturing and construction. The fraction of CCPs used beneficially is increasing (Figure 1-1) due to the desirable attributes of CCPs as construction materials and greater interest in sustainable construction and development. For example, production of Portland cement accounts for 5 to 8% of annual CO_2 emissions worldwide (Anderson 2008, Reiner and Rens 2006). Replacing a portion of the Portland cement with fly ash reduces the CO_2 emissions associated with production of Portland cement proportionally. Energy and water use associated with cement production are also reduced. These savings are accrued because the fly ash is used essentially "as is;" no processing or transformation is required, thereby eliminating emissions and resource consumption associated with creating a construction material.

Although the contribution of CCPs in construction to sustainability is logical, a comprehensive quantitative assessment of beneficial use of CCPs has not been conducted (past studies focused on one material, such as concrete or wallboard). The study described in this report was conducted to quantify the environmental and economic benefits of using CCPs in each of the major construction applications. The focus was on fly ash, bottom ash, and FGD gypsum because of the preponderance of these CCPs relative to other byproducts of coal combustion. The primary uses of fly ash, bottom ash, and FGD gypsum (2007 data) are summarized in Table 1-1 (ACAA 2008) and are shown graphically in Fig. 1-2. Cement and concrete, geotechnical applications, and wallboard manufacturing consume 80% of the CCPs that are used beneficially. Consequently, this study focused on these three applications for each of the three CCPs considered. The analysis focused on the benefits of using CCPs in terms of reductions in greenhouse gas (GHG) emissions, consumption of energy and water, and economic savings. Avoidance of landfill disposal costs was also considered in the analysis.

Table 1-1
CCP production and use in 2007 (adapted from ACAA 2008).

Application	Fly Ash	Bottom Ash	FGD Gypsum
	(short ton)	(short ton)	(short ton)
1. Concrete, Concrete Products, Grout	13,704,744	665,756	118,406
2. Blended Cement, Raw Feed for Clinker	3,635,881	608,533	656,885
3. Flowable Fill	112,244	0	0
4. Structural Fills and Embankments	7,724,741	2,570,163	0
5. Road Base and Sub-base	377,422	802,067	0
6. Soil Modification and Stabilization	856,673	314,362	0
7. Mineral Filler in Asphalt	17,223	21,771	0
8. Snow and Ice Control	0	736,979	0
9. Blasting Grit and Roofing Granules	0	71,903	0
10. Mining Applications	1,306,044	165,183	0
11. Gypsum Panel Products	0	0	8,254,849
12. Waste Stabilization and Solidification	2,680,348	7,056	0
13. Agriculture	49,662	2,546	115,304
14. Aggregate	135,331	806,645	70,947
15. Miscellaneous	1,025,724	530,574	11,880
Total CCP Used	**31,626,037**	**7,303,538**	**9,228,271**
Total CCP Produced	**71,700,000**	**18,100,000**	**12,300,000**

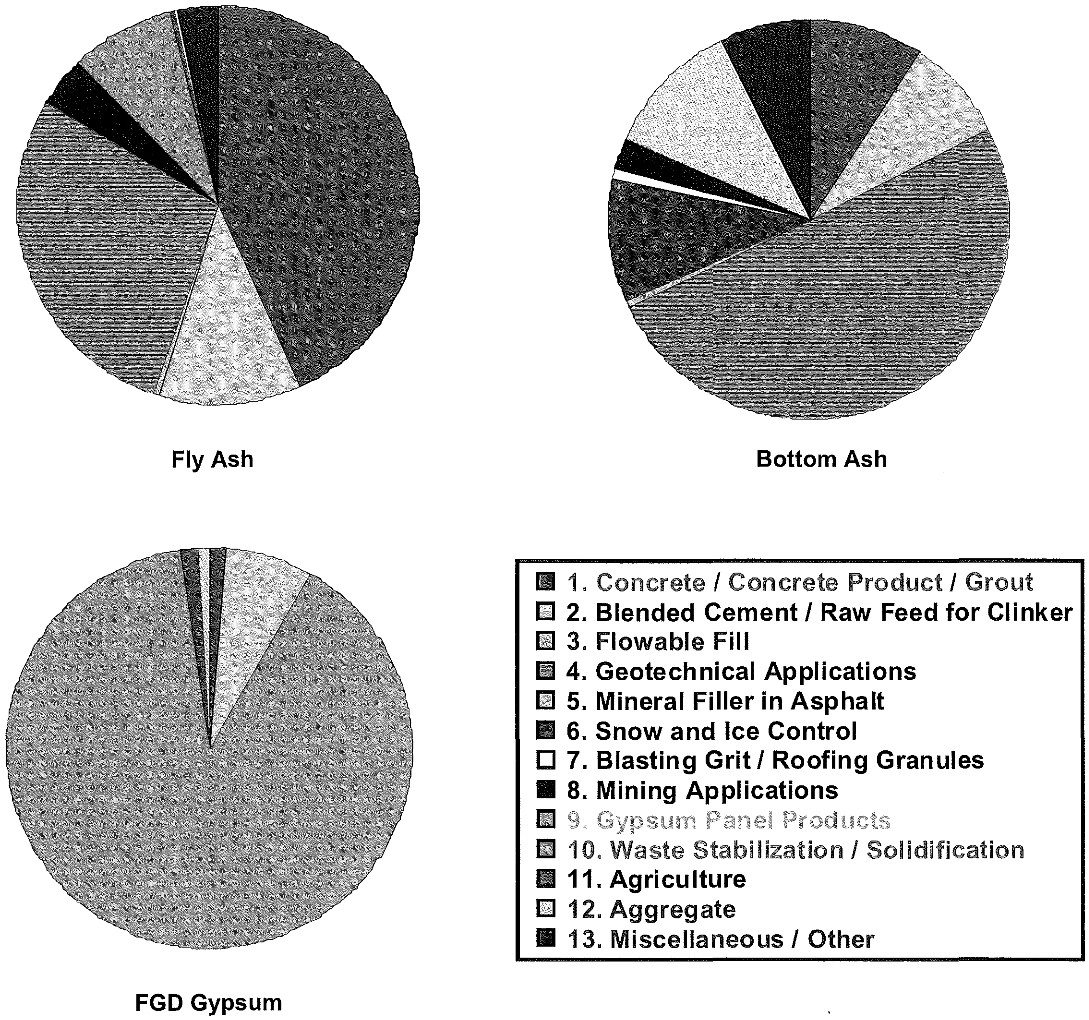

Figure 1-2
Uses of fly ash, bottom ash, and FGD gypsum by application

2
LIFE CYCLE ANALYSIS MODELS

Environmental benefits of using CCPs in sustainable construction were estimated using life cycle analysis models. Economic benefits were calculated based on the monetary value of the environmental benefits. Unit benefits (e.g., environmental benefits per ton of CCP used in the given application per year) were obtained from predictions made with the BEES (NIST, 2007), SimaPro (Pré Consultants, 2009), and PaLATE (RMRC 2004) life cycle analysis programs. Predictions with BEES and SimaPro were made by made by EPA (2008). The BEES predictions were independently verified and updated as part of this study. Independent verification of the SimaPro simulations was not possible. Predictions using PaLATE were made specifically as part of this study. Descriptions of each model are in the following sections.

BEES Model

The Building for Environmental and Economic Sustainability (BEES) model was developed by the National Institute of Standards and Technology (NIST 2007) for life cycle analysis of building construction. BEES 4.0 contains environmental data for over 230 products across a wide range of building elements including beams, columns, wall insulation, ceiling finishes, etc.

Environmental data for a variety of concrete products (e.g., concrete columns, walls, slab on grade, and beams) are included. The user can compare the environmental performance data of each of these products using different pre-determined concrete mix-designs, some of which include fly ash. A summary of the databases used to compile the information used in BEES can be found in NIST (2007).

The BEES environmental performance data serve as quantitative estimation of the energy and resource flows into a product as well as releases to the environment from the product. Total output is summed across all stages of the product life cycle for a unit product (e.g., one cubic yard of concrete). Manufacturer-specific unit environmental impact data for production of a product are obtained primarily using a unit process and facility-specific approach. Output from BEES includes energy use, water use, atmospheric emissions (e.g., (CO_2, CH_4, CO, NO_X, SO_X, particulates), waterborne waste (suspended matter, biological oxygen demand, chemical oxygen demand, Hg, Pb, Se), and nonhazardous waste.

SimaPro Model

SimaPro is a life cycle analysis program developed by the Dutch company Pré Consultants that can used to conduct detailed analyses of complex products and processes (Pré Consultants 2009). SimaPro provides a high degree of flexibility because it contains data profiles representing production, transport, energy production, product use, and waste management processes for thousands of materials. SimaPro quantifies inflows and outflows of resources, products, emissions, and waste flows during product manufacturing. SimaPro integrates all inputs (resources) and outputs (emissions and waste) by tracing all the references established on process trees from one process stage to another. Output from SimaPro includes energy and fresh water use, emissions of CO_2, CO, CH_4, N, O_3, SO_X, solid waste, particulates, suspended solids BOD and COD, Cu, Pb, Hg, and Se. Results are displayed as lifecycle inventory flows (e.g. pollutant emissions, energy use, and water use).

To use SimaPro, a process tree is constructed that describes all relevant processes in the life cycle. A network is created that identifies input and output processes and product stages are defined that describe the composition of the product, the use phase, and the disposal route. Each product stage refers to a process. Waste disposition at the end of life cycle is also defined. The computations made by SimaPro rely on information from the EcoInvent database (Pré Consultants 2009) and integrated Swiss databases (e.g. ETH-ESU 96, BUWAL250).

PaLATE Model

The Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a life cycle assessment tool that contains environmental and engineering information and data to evaluate the use of conventional and recycled materials in construction and maintenance of pavements (Horvath 2004). The user defines the dimensions of each layer in the pavement, the distance between the project site and material sources, and the density of the construction materials. These yield types and volumes of construction materials, sources and hauling distances, a set of construction activities, and a set of prescribed maintenance activities. From this information, PaLATE calculates cumulative environmental effects such as energy and water consumption; emissions of CO_2, CO, NO_X, SO_X, and PM_{10} particulate, emissions of Pb and Hg, RCRA hazardous waste, and a human toxicity potential (cancerous and non-cancerous).

Several different sources of information and analysis methods are used in PaLATE to characterize the environmental impact of road construction projects. One is based on environmentally augmented economic input-output analysis (EIO-LCA), a Leontief general equilibrium model of the entire US economy. The economy is divided into a square matrix of 480 commodity sectors. The economic model quantifies energy, material, and water use as well as emissions. Because EIO-LCA emission factors are available in metric tons per dollar of sector output, PaLATE uses average US producer prices ($/metric ton, e.g., from Means 2008) to calculate emissions per mass of material used. The databases used in PaLATE are described in Horvath (2004).

Methodology For Determining Benefits

The environmental and economic benefits of CCP use were quantified by computing differences in energy expenditure, water consumption, and global warming potential between conventional materials and those produced with CCPs, as predicted by the life cycle analysis codes. Three major applications were considered: concrete, wallboard, and geotechnical applications using fly ash, geotechnical applications using bottom ash. Total annual benefits were obtained as the product of unit benefits for energy, water, or GHG emissions and the most recent annual beneficial use quantity (in tons) provided by ACAA (2008). Unit financial savings for energy and water were generated using financial data in NPGA (2006). The market price of CO_2 was obtained from the Chicago Climate Exchange (CCX) (Chicago Climate Exchange 2009). All financial quantities were adjusted to 2009 US dollars.

DRAFT DECEMBER 5, 2009

3
RESULTS

Fly Ash Use in Concrete

Unit benefits of using fly ash as a cement substitute in concrete were obtained from the LCA modeling with BEES described in USEPA (2008). The BEES functional unit was 1 yd^3 yard of structural concrete having a compressive strength of 4 ksi and 75-yr lifespan. System boundaries for the analysis are shown in Figure 3-1. The BEES program incorporates round-trip transportation distances of raw materials from extraction sites (e.g., quarries, power plants, etc.) to ready-mix concrete plants using data provided by NIST (2007). The analysis assumed that 0.24 ton of cement was required to produce 1 ton of concrete (Lippiatt 2002). Conventional concrete was assumed to contain no CCPs. For concrete manufactured with CCPs, 15% of the Portland cement was replaced by fly ash at a 1:1 (by weight) substitution ratio. Discussions with representatives in the ready-mix concrete industry indicated that this replacement rate is conservative (i.e., higher rates are common in practice). FHWA (2003) and PCA (2009) also suggest that 15-30% of the Portland cement in concrete can be replaced by fly ash. Use of fly ash or other CCPs in manufacturing the cement used in concrete was not incorporated in the analysis.

For concrete production, transport distances for Portland cement and fly ash to the ready-mix plant were both assumed to be 60 mi. Thus no differential in benefits was considered due to differences in raw material transport. A sensitivity analysis was conducted to assess the significance of this assumption as transport distances for fly ash tend to be less than those for Portland cement (see Appendix A). Increasing the transport distance for Portland cement while keeping the fly ash transport distance fixed at 60 mi showed that the environmental benefits would only increase by only about 4% if the cement transport distance was increased to 100 mi. Thus, differences in the transport distance were considered negligible.

Unit benefits of replacing Portland cement with 15% fly ash (benefit/ton of fly ash), for energy consumption, water consumption, GHG emissions, and their corresponding financial savings are shown in Table 3-1.

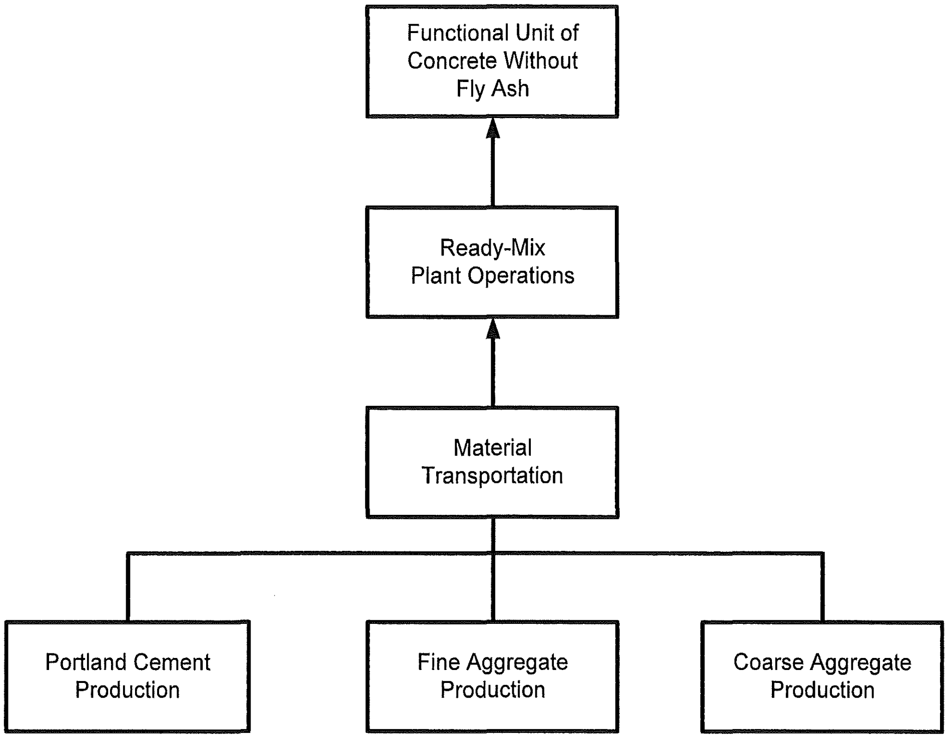

Figure 3-1
System boundary for 4 ksi concrete production without fly ash (adapted from EPA 2008). Replacement of cement by fly ash adds an additional branch in the tree parallel to the cement branch.

Table 3-1
Benefits obtained by replacing 15% of Portland cement with fly ash (adapted from EPA 2008).

Benefit		**Savings/ton fly ash**
Energy	Savings (million Btu/ton fly ash)	4.0
	Financial Savings (US$/ton fly ash)	123.5
Water Use	Savings (gal/ton fly ash)	90.1
	Financial Savings (US$/ton fly ash)	0.23
GHG Emission	CO_2e (ton/ton fly ash)	0.7
	Financial Savings (US$/ton fly ash)	2.6

FGD Gypsum in Wallboard Manufacturing

Unit benefits of using FGD gypsum as a substitute for conventional gypsum in wallboard manufacturing were obtained from USEPA (2008) analyses conducted by LCA modeling with SimaPro using the EcoInvent database. The USEPA (2008) analysis considered wallboard manufactured with 100% natural gypsum or 100% FGD gypsum. The EcoInvent data set used in the analyses incorporated the mining and grinding energies needed to extract and process natural gypsum prior to calcining (L. Luben, personal communication, 2009). Pre-drying of FGD gypsum prior to calcining is normally done using passive methods. Thus, the energy associated with pre-drying FGD gypsum was deemed negligible compared to the energy associated with extracting and processing natural gypsum prior to calcining, and was not included in the analysis.

All other factors in wallboard manufacturing using natural or FGD gypsum are essentially the same and therefore cancel out in a comparative benefits analysis. For example, calcining of natural gypsum and FGD gypsum consumes the same amount of energy per mass of gypsum that is processed. Transport of natural gypsum can require greater energy and result in greater emissions than FGD gypsum, especially as wallboard manufacturing plants are being constructed adjacent to coal-fired power plants employing wet scrubbers for FGD. However, this difference could not be adequately quantified and therefore was ignored.

Unit benefits in terms energy consumption, water consumption, and GHG emissions obtained by replacing natural gypsum with FGD gypsum (benefits/ton of FGD) and the corresponding economic savings are shown in Table 3-2.

Table 3-2
Benefits profile for 100% FGD gypsum replacing 100% virgin gypsum (adapted from EPA 2008)

Benefit		Savings/ton FGD gypsum
Energy	Savings (million Btu/ton FGD)	11.9
	Financial Savings (US$/ton FGD)	366
Water Use	Savings (gal/ton FGD)	3,755
	Financial Savings (US$/ton FGD)	9.4
GHG Emission	CO_2e (ton/ton FGD)	0.09
	Financial Savings (US$/ton FGD)	0.34

Fly Ash and Bottom Ash in Geotechnical Applications

Unit benefits of using fly ash or bottom ash in geotechnical applications were evaluated using PaLATE (RMRC 2004). The analysis considered structural fills and embankments, roadway subbase and base course, and stabilized soil applications.

For structural fill and embankments, fly ash and bottom ash were assumed to replace conventional soils (e.g., sand and gravel) at a 1:1 (volume) replacement ratio. Placement of conventional soils and CCPs was assumed to be conducted with the same equipment and effort. Fly ash and bottom ash were assumed to be placed at a dry unit weight of 1.25 ton/yd3 (RMRC 2008), whereas conventional soils were assumed to have a dry unit weight of 1.60 ton/yd3 (Tanyu et al. 2004).

For roadway construction, fly ash was assumed to be used as a stabilizer for subgrades and base courses at a 10% dosage in lieu of excavation of soft soil and replacement with crushed rock, as described in Edil et al. (2002). The assumed dosage is conservative because fly ash dosages used for stabilization typically range between 10 and 20%. Bottom ash was assumed to be a 1:1 replacement for conventional base and subbase materials (sands and gravels) as suggested in FHWA (2008).

The analysis for fly ash stabilization compared roads constructed with equivalent structural number (i.e., 2.8) using a layer coefficient of 0.18 for conventional construction with crushed rock and 0.13 for fly ash stabilized subgrade, as suggested by Geo Engineering Consulting (2009). This resulted in a 16-inch-thick layer of crushed rock and 22-inch-thick layer of fly ash stabilized subgrade. The analysis also accounted for the differences in energy required by a reclaimer used for fly ash stabilization compared to an excavator used for crushed rock. The dry unit weight of the fly ash stabilized subgrade was assumed to be 1.38 ton/yd3, as suggested by Edil et al. (2002).

Benefits of using bottom ash were computed by comparing roads constructed with a subbase consisting of 100% bottom ash or Wisconsin Grade 2 granular fill (sand or gravel). The two granular layers were designed to have the same structural number (1.6) using a layer coefficient of 0.08 for granular backfill and 0.06 for bottom ash, as suggested by Geo Engineering Consulting (2009). This resulted in a 20-inch-thick subbase layer of conventional granular fill and a 27-inch-thick layer of bottom ash. Equipment used to install the Grade 2 granular material and the bottom ash was assumed to be the same. The bottom ash was assumed to have a unit weight of 1.25 ton/yd3, whereas the granular fill was assumed to have a unit weight of 1.60 ton/yd3.

Unit benefits of using fly ash or bottom ash in structural fills and embankments are summarized in Tables 3-3 (fly ash) and 3-4 (bottom ash). Unit benefits of replacing crushed rock with fly-ash-stabilized subgrade are summarized in Table 3-5 and unit benefits of replacing conventional granular subbase with bottom ash are summarized in Table 3-6.

Table 3-3
Benefits profile for replacing a 50% sand and gravel mixture in with fly ash in a structural fill

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	0.19
	Financial Savings (US$/ton fly ash)	5.79
Water Use	Savings (gal/ton fly ash)	0.008
	Financial Savings (US$/ton fly ash)	0.00002
GHG Emission	CO_2e (ton/ton fly ash)	0.011
	Financial Savings (US$/ton fly ash)	0.04

Table 3-4
Benefits profile for replacing a 50% sand and gravel mixture with bottom ash in a structural fill

Benefit		Savings/ton bottom ash
Energy	Savings (million Btu/ton bottom ash)	0.15
	Financial Savings (US$/ton bottom ash)	4.49
Water Use	Savings (gal/ton bottom ash)	0.005
	Financial Savings (US$/ton bottom ash)	0.0001
GHG Emission	CO_2e (ton/ton bottom ash)	0.01
	Financial Savings (US$/ton bottom ash)	0.037

Table 3-5
Benefits profile for replacing crushed rock with fly-ash-stabilized subgrade

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	1.8
	Financial Savings (US$/ton fly ash)	56.6
Water Use	Savings (gal/ton fly ash)	0.07
	Financial Savings (US$/ton fly ash)	0.0002
GHG Emission	CO_2e (ton/ton fly ash)	0.15
	Financial Savings (US$/ton fly ash)	0.56

Table 3-6
Benefits profile for the substitution of bottom ash for Wisconsin Grade 2 granular fill subbase

Benefit		Savings/ton bottom ash
Energy	Savings (million Btu/ton bottom ash)	0.17
	Financial Savings (US$/ton bottom ash)	5.28
Water Use	Savings (gal/ton bottom ash)	0.007
	Financial Savings (US$/ton bottom ash)	0.00002
GHG Emission	CO_2e (ton/ton bottom ash)	0.01
	Financial Savings (US$/ton bottom ash)	0.037

Benefits of Avoided CCP Disposal

Using CCPs in sustainable construction activities results in additional environmental and economic benefits through avoided landfill disposal. These additional savings were calculated using life cycle inventory (LCI) data generated for construction, operation, and maintenance costs for Subtitle D (non-hazardous municipal solid waste) landfills in EREF (1999). Environmental impacts associated with construction, operation, and maintenance of a Subtitle D landfills were assumed to be similar to that of Subtitle C disposal facilities. This is a conservative assumption, because Subtitle C landfills employ more sophisticated containment systems and additional restrictions on operations, waste acceptance, and disposal that increase emissions as well as consumption of energy and water. The model system boundaries for a landfill life cycle defined by EREF are shown in Figure 3-2. The major components are landfill construction, landfill operation, landfill closure, landfill post-closure care, and leachate treatment (assumed for 100 yr).

Life cycle inventory data are summarized in Tables 3-7 through 3-11 for each major component of the landfilling process shown in Figure 3-2. Any inventory information that was specific to municipal solid waste and not applicable to CCP disposal was excluded. A summary of the LCI information for all landfilling processes is shown in Table 3-12. The total economic benefits of avoided landfill disposal are summarized in Table 3-13.

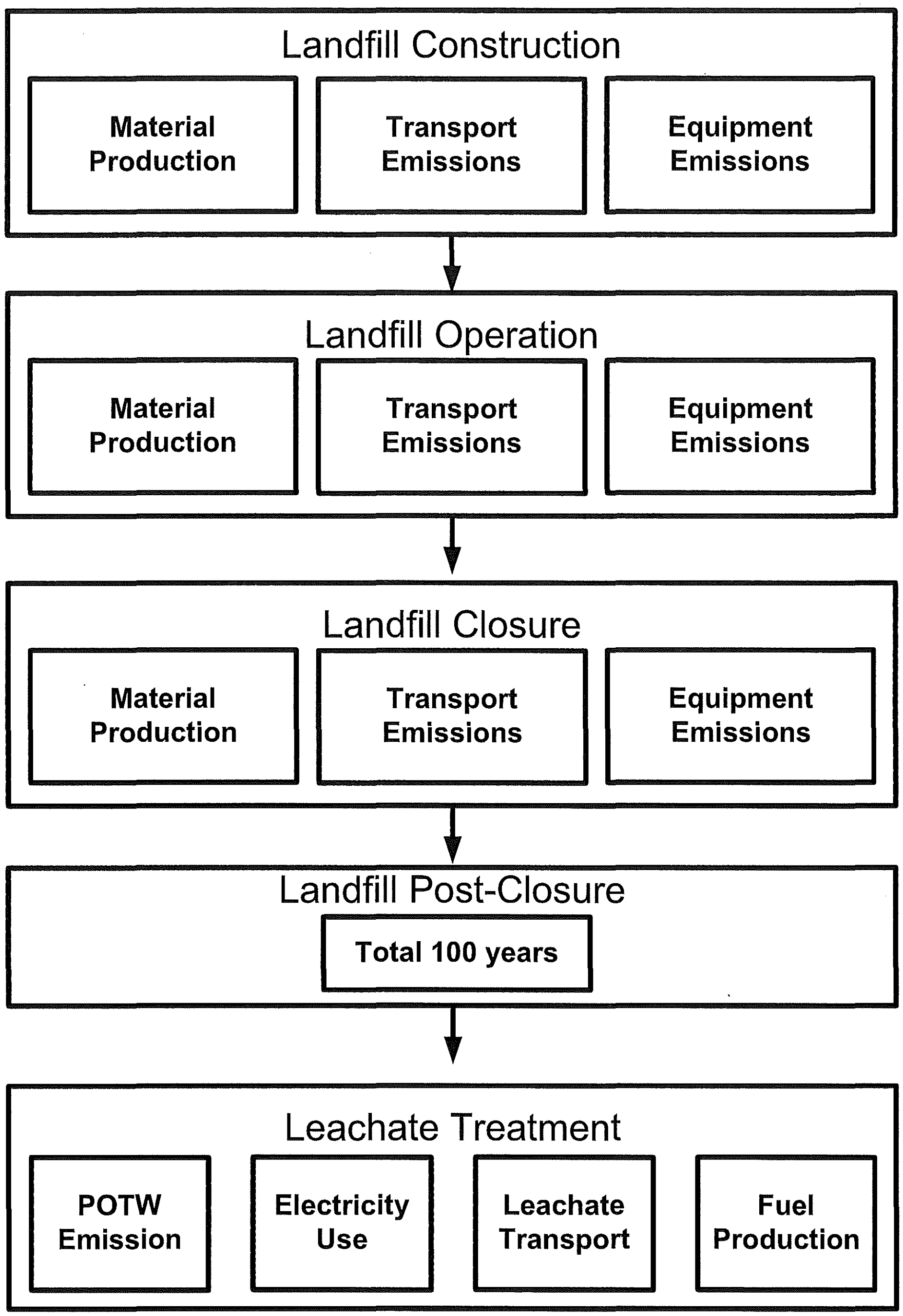

Figure 3-2
Life cycle system boundaries for landfilling (adapted from EREF 1999)

Table 3-7
Total LCI attributable to landfill construction (data from EREF 1999)

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (Btu/ton)	0	26,710.7	0	26,710.7
CO_2 (lb/ton)	1.47	0.26	1.09	2.82
Methane (lb/ton)	0.01	0.001	0.005	0.016

Table 3-8
Total LCI attributable to landfill operations (data from EREF 1999)

Parameters	Plastic	Soil	Steel	Fuel	Transport Emission	Equipment	Total
Energy (Btu/ton)	43.9	1,206.3	2,671.1	44805.1	0	0	48,726.4
CO_2 (lb/ton)	0.0017	0.194	0.49	0.734	0.048	6.176	7.64
Methane (lb/ton)	1.4 E-06	0.00008	0.0004	0.0034	-	-	0.0039

Table 3-9
Total LCI attributable to landfill closure (data from EREF 1999)

Parameters	Material Production	Transport Emissions	Equipment Emissions	Total
Energy (Btu/ton)	24,987.45	0	0	24,987.45
CO_2 (lb/ton)	2.43	0.586	0.352	3.37
Methane (lb/ton)	0.0017	-	-	0.0017

Table 3-10
Total LCI attributable to landfill post-closure care (data from EREF 1999)

Parameters	Total 100 years
Energy (Btu/ton)	2,498.75
CO_2 (lb/ton)	0.338
Methane (lb/ton)	0.00017

Table 3-11
Total LCI attributable to leachate management for 100 yr (data from EREF 1999)

Parameters	POTW Emissions	Leachate Treatment	Electricity	Fuel	Total
Energy (Btu/ton)	0	0	2,671.1	1,120.1	3,791.2
CO_2 (lb/ton)	0	0.17	0.408	0.019	0.594
Methane (lb/ton)	0	-	0.0012	0.00009	0.001

Table 3-12
Benefits due to avoided landfilling of recycled CCPs (fly ash, bottom ash, and FGD gypsum)

	Energy (Btu/ton)	CO_2 (lb/ton)	Methane (lb/ton)
Construction	26,655	2.82	0.018
Operation	48,151	7.65	0.0038
Closure	24,936	3.37	0.0017
Post Closure	2,494	0.34	0.0002
Leachate	3,787	0.59	0.0013
Total	106,023	14.77	0.025

Table 3-13
Economic benefits due to avoided landfilling of fly ash, bottom ash, and FGD gypsum currently used in sustainable construction

	Unit Cost	Quantity	Total
Construction	$311,970/ac	383 ac*	119.5 million
Operation	$6.2/ton	34.6 million tons	214.5 million
Closure	$155,985/ac	383 ac	59.8 million
Post Closure	$15,599/ac	383 ac	6.0 million
Leachate	$0.04/gal	315 million gal*	13 million
Total			0.4 billion
Commercial Landfills (Average tipping fee for subtitle D = $40/ton)			$1.4 billion
Commercial Landfills (Average tipping fee for subtitle C = $150/ton)			$5.2 billion

* EREF (1999)

Cumulative Benefits

Total annual benefits of using CCPs in construction applications are reported in Tables 3-14 through 3-16 in terms of reduced energy and water consumption and lower global warming potential (in CO_2e based on BEES global warming potential characterization factors reported in NIST 2007). Financial savings for each application were computed as the product of the annual use of each CCP in each use application (Table 1-1) and the derived unit benefits (Tables 3-1 through 3-6 and 3-12). The environmental and financial quantities in Tables 3-14 through 3-16 are also reported in terms of equivalent tangible quantities such as annual household and regional water use, percentage of national wind power generation, emissions from cars and the cement industry, and the annual salary of the average American. Conversions to these tangible quantities were based on an average American household energy use of 96.4 billion Btu per 1000 households (EIA 2009), annual domestic water consumption of the states of Nevada (8.2 billion gal in 2000) and Arizona (10.5 billion gal in 2000) (USGS 2004), annual average American shower water consumption (11.6 gal/capita) (WRF 1999), and GHG emissions from passenger cars (5.7 tons CO_2e per car) (USEPA 2009). The average annual American salary ($39,500 in 2006) was obtained from the United States Census Bureau (2006).

The greatest environmental benefits in sustainable construction are currently being accrued through the use of CCPs (mainly fly ash) in concrete production. Use of fly ash as a cement substitute annually saves more than 55 trillion Btus of energy annually (≈equivalent to 600,000 households) and reduces GHG emissions by 9.6 million tons CO_2e (≈equivalent to 1.7 million passengers cars) (Table 3-14). Using FGD gypsum in wallboard manufacturing results in even more energy savings (98.2 trillion Btu annually) and greater reduction in water consumption (31 billion gal, or approximately three times the annual water use in Arizona or Nevada), but a much smaller reduction in GHG emissions (0.74 million tons CO_2e or 100,000 passenger cars). Geotechnical applications of CCPs result in much smaller savings in energy consumption, water consumption, or CO_2 emissions at current usage rates. Financially, the greatest benefits are obtained by using FGD gypsum in wallboard manufacturing, followed by use of fly ash in concrete, and geotechnical applications. The financial benefits are closely aligned with benefits associated with reductions in energy consumption and GHG emissions.

The reductions in energy use, water consumption, and GHG emissions are primarily obtained by offsetting production of conventional materials (e.g., use of fly ash in concrete precludes the need to produce some Portland cement). CCPs are byproducts of energy generation and are not produced specifically, as are the construction materials they replace. Consequently, the resources embodied in their production are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

Table 3-14
National annual savings from the use of fly ash in concrete and comparisons to consumption equivalents

Point of Benefit	Annual Savings	Equivalent to
Energy (trillion Btu)	55.4	-Annual energy use for 0.6 million households (2005) -16% of annual wind power generation (341 trillion Btu in 2007)
Water (billion gal)	1.2	-11% of annual domestic use of AZ (10.5 billion gal in 2000) -15% of annual domestic use of NV (8.2 billion gal in 2000)
CO_2e (million ton)	9.59	-Equivalent to the removal 1.7 million passenger cars per year from roadways -11% of emission from cement industry (84.8 million ton in 2001)
Financial (billion $)	1.74	- Equivalent to average annual salary for 44,000 Americans ($39,500/yr)

Table 3-15
National annual savings from use of FGD gypsum in wallboard manufacture and comparisons to consumption equivalents

Point of Benefit	Annual Savings	Equivalent to
Energy (trillion Btu)	98.2	Annual energy use of 1 million households (2005) 29% of wind power generation in 2007 (341 trillion Btu)
Water (billion gal)	31	290% of domestic use of AZ in 2000 (10.5 billion gal) 380% of domestic use of NV in 2000 (8.2 billion gal)
CO_2e (ton)	742,936	Equivalent to the removal of 0.1 million passenger cars per year from roadways
Financial (billion $)	3.1	Equivalent to average annual salary for 78,000 Americans ($39,500/yr)

Table 3-16
National annual savings from use of fly ash and bottom ash for geotechnical applications and comparisons to consumption equivalents

Point of Benefit	Annual Savings	Equivalent to
Energy (trillion Btu)	4.3	Annual energy use of 45,310 households (2005)
Water (gal)	168,851	14,500 persons daily water use for shower (11.6 gal/capita)
CO_2e (ton)	306,952	Equivalent to the removal of 53,600 passenger cars per year from roadways
Financial (billion $)	0.14	Equivalent to average annual salary for 3,300 Americans ($39,500/yr)

The benefits by avoiding disposal are appreciable too, as illustrated in Table 3-17. By not landfilling CCPs, 3.7 trillion Btu of energy is saved (≈ 38,600 households) and CO_2e emissions are reduced by 0.3 million tons (≈ 46,300 automobiles). The financial savings ranges considerably, from $0.5 billion annually for a Subtitle D-style landfill operated on site by utilities to $5.3 billion annually for commercial disposal in a Subtitle C landfill. Disposal in a commercial Subtitle D landfill would likely cost $1.4 billion annually. These commercial disposal costs are based on a typical tipping fee of $40/ton for a Subtitle D landfill and $150/ton for a Subtitle C landfill (Wisconsin DNR 2009 and telephone interviews with solid waste industry representatives).

The total annual benefits obtained from using CCPs in sustainable construction applications are remarkable (Tables 3-18 and 3-19). Using CCPs results in a reduction in energy consumption of 162 trillion Btu, a reduction in water consumption of 32 billion gallons, a reduction in CO_2e emissions of 11 million tons, and a financial savings of $5-10 billion. The reduction in energy consumption is commensurate with the energy consumed by the homes in a large US city (1.7 million homes), the water saved is equal to 31% of the annual domestic water use in California, and the reduction in GHG emissions is comparable to removing 2 million automobiles from the roadway. The financial savings can also provide the average income for approximately 200,000 Americans. Moreover, these benefits may increase markedly in the future given the current interest in creating "greener" concrete by increasing the fly ash content, the increased production of FGD gypsum (and corresponding impacts on wallboard manufacturing) that is anticipated as more power plants employ wet scrubbers, and the increased use of fly ash stabilization to reduce cost and increase the service life of roadways.

Table 3-17
National annual savings from avoided disposal of CCPs and comparisons to consumption equivalents

Point of Benefit	Annual Savings	Equivalent to
Energy (trillion Btu)	3.67	-Annual energy use of 38,600 households (2005)
CO_2e (ton)	265,470	-Equivalent to the removal of 46,300 passenger cars per year from roadways
Financial (billion $)	0.5-5.3	-Equivalent to average annual salary for 12,600 - 134,000 for Americans ($39,500/yr)

Table 3-18
Summary of environmental savings achieved by using fly ash, bottom ash, and FGD gypsum in each major application

Material	Application	Energy (trillion Btu)	Water (million gal)	CO_2e (million ton)
Fly Ash	Concrete	55.4	1,200	9.6
	Embankment	1.5	0.06	0.08
	Road base	2.2	0.09	0.19
Bottom Ash	Embankment	0.4	0.01	0.02
	Road base	0.2	0.01	0.01
FGD Gypsum	Wallboard	98.2	31,000	0.7
Landfilling		3.7	Not Known	0.3
Total		161.6	32,200	11

Table 3-19
Total annual savings from using fly ash, bottom ash, and FGD gypsum in major applications and consumption equivalents

Point of Benefit	Annual Savings	Equivalent to
Energy (trillion Btu)	161.6	-Annual energy use for 1.7 million householders (EIA 2005 survey) -47% of annual wind power generation (EIA 2007 Report)
Water (million gal)	32,200	-31% of domestic water withdrawals of CA in 2000 (USGS)
CO_2e (million ton)	11	-Equivalent to the removal of 2 million passenger cars per year from roadways (EPA)
Financial (billion $)	5.5 -10.3	-Equivalent to average annual salary for 139,000–260,000 Americans ($39,500/yr)

4
SUMMARY AND CONCLUSIONS

This study has quantified the environmental and economic benefits from each major use of fly ash, bottom ash, and FGD in sustainable construction. Savings associated with reductions in energy and water consumption and lower GHG emissions are primarily accrued by offsetting the need for material production. CCPs are byproducts of energy generation and are not produced specifically as the construction materials they replace. Consequently, the resources embodied in their production are accounted for in electricity production and are expended regardless of whether CCPs are used beneficially.

The total environmental benefits obtained by replacing conventional construction materials with CCPs are remarkable. Annually, approximately 162 trillion Btu of energy is saved, 11 million tons of CO_2e emissions are avoided, and 32 billion gallons of water are not consumed. These quantities are comparable to the energy use by homeowners in a large US city and the emissions associated with approximately 2 million automobiles. The financial savings are large as well - \$5-10 billion is made available for other uses by using CCPs in sustainable construction. These quantities indicate that CCP use in construction contributes significantly to sustainability in the US, and should be nurtured and enhanced if possible.

5
REFERENCES

ACAA (2008). *ACAA 2007 CCP Survey*, American Coal Ash Association, http://www.acaa-usa.org/associations/8003/files/2007_ACAA_CCP_Survey_Report_Form%2809-15-08%29.pdf (July 6, 2009)

ACAA (2009). *1996-2007 CCP Beneficial Use v. Production*, American Coal Ash Association, http://www.acaa-usa.org/associations/8003/files/Revised_1966_2007_CCP_Prod_v_Use_Chart.pdf (July 6, 2009).

Anderson, J.. (2008). "Sustainable Cement Using Fly Ash: An Examination of the Net Role of High Volume Fly Ash Cement on Carbon Dioxide Emissions." Ecocity World Summit 2008 Proceedings.

CCX (2009). *CCX Carbon Financial Instrument (CFI) Contracts Daily Report*. Chicago Climate Exchange, http://www.chicagoclimatex.com/market/data/summary.jsf (August 31, 2009).

Edil, T., Benson, C., Bin-Shafique, M., Tanyu, B., Kim, W., and Senol, A. (2002). "Field Evaluation of Construction Alternatives for Roadways over Soft Subgrade." Transportation Research Record, 1786, pp.36-48.

EIA (2009). *Monthly Energy Review*, Energy Information Administration, http://www.eia.doe.gov/emeu/mer/ (November 2009).

EIA (2009). 2005 Residential Energy *Consumption Survey-Detailed Tables*, Energy Information Administration, http://www.eia.doe.gov/emeu/recs/recs2005/c&e/detailed_tables2005c&e.html (August 2009).

EREF (1999). *Life Cycle Inventory of Modern Municipal Solid Waste Landfill*, Environmental Research and Education Foundation.

FHWA (2008). *User Guidelines for Byproduct and Secondary Use Materials in Pavement Construction*. FHWA-RD-97-148, Federal Highway Administration.

FHWA (2003). *Fly Ash Facts for Highway Engineers*. FHWA-IF-03-019, Federal Highway Administration.

Geo Engineering Consulting (2009). *Implementation Recommendations of Equivalency of Alternative Working Platforms and Their Pavement Design Strength Contribution*. Publication

Wisconsin Highway Research Program Report 0092-06-08, Wisconsin Department of Transportation.

Horvath, A. (2004). *A Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Material for Highway Applications*. Recycled Materials Resource Center, Durham, NH.

Lippiatt, B. (2002). *BEES 3.0 Technical Manual and User Guide*, National Institute for Standards and Technology, Gaithersburg, MD.

Luben, D.. (2009). Personal Communication through an e-mail, U.S. Environmental Protecting Agency, 2009.

Mehta, P. (2004). "High-Performance, High-Volume Fly Ash Concrete for Sustainable Development," in Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China, 3-14.

NIST (2007). *Building for Environmental and Economic Sustainability Technical Manual and User Guide*, Publication NISTIR 7423, National Institute of Standards and Technology, U.S. Department of Commerce.

NPGA (2006). "2006 Representative Energy Costs." National Propane Gas Association. http://www.npga.org/i4a/pages/index.cfm?pageid=914. (Nov. 23, 2009)

PCA (2009). *Technical Brief: Green in Practice 107-Supplementary Cementitious Material*, Portland Cement Association, http://www.concretethinker.com/technicalbrief/Supplementary-Cementitious-Materials.aspx (November 2, 2009).

Pré Consultants (2009). *SimaPro LCA software*, http://www.pre.nl/simapro/. (October 26, 2009).

Reiner, M. and Rens, K. (2006). "High-Volume Fly Ash Concrete: Analysis and Application." Practice Periodical on Structural Design and Construction, pp 58-64.

Means (2008), RS *Means Building Construction Cost Data* 2008, BNI Building News, Vista, CA

RMRC (2004). *Pavement Life-Cycle Assessment Tool for Environmental and Economic Effects Version 2.0*, Recycled Materials Resource Center, www.rmrc.unh.edu/Resources/CD/PaLATE/PaLATE.htm (February 16, 2009).

RMRC (2008). *User Guidelines for Byproducts and Secondary Use Materials in Pavement Construction*, Recycled Materials Resource Center, http://www.recycledmaterials.org/tools/uguidelines/index.asp (July. 6, 2009)

Tanyu, B., Benson, C., Edil, T., and Kim, W. (2004). "Equivalency of Crushed Rock and Three Industrial By-products Used for Working Platforms during Pavement Construction." Journal of the Transportation Research Board, No. 1874, pp 59-69.

U.S. EPA (2009). *Emission Facts: Average Annual Emissions and Fuel Consumption for Passenger Cars and Light Trucks*, U.S. Environmental Protecting Agency, http://www.epa.gov/otaq/consumer/f00013.htm (August 4, 2009).

U.S. EPA (2008).*Study on Increasing the Usage of Recovered Mineral Components in Cement and Concrete Projects*, Publication EPA-530-R-08-007, U.S. Environmental Protection Agency.

U.S. EPA (2008). *Waste Materials-Flow Benchmark Sector Report: Beneficial Use of Secondary Materials – Coal Combustion Products*, Publication EPA-530-R-08-003. U.S. Environmental Protection Agency.

U.S. Census Bureau (2006). *Annual Demographic Survey*, http://pubdb3.census.gov/macro/032006/perinc/new03_028.htm (August 17, 2009)

USGS (2004). *Estimated Use of Water in the United States in 2000*, U.S. Geological Survey, http://pubs.usgs.gov/circ/2004/circ1268/htdocs/table06.html (August 17, 2009).

Wisconsin DOT (2009). "Section 210 Structural Fill," 2010 Standard Specification, Wisconsin Department of Transportation.

Wisconsin DNR (2009). *Posted Gate Landfill Tip Charges in Upper Midwest States, 2006 and 2008*. Wisconsin Department of Natural Resources, http://www.dnr.state.wi.us/org/aw/wm/solid/landfill/outofstate.htm (October 22, 2009).

WRF (1999). *Residential End Uses of Water*, Water Research Foundation, http://www.waterresearchfoundation.org/research/topicsandprojects/execSum/241.aspx (October 30, 2009).

A
SENSITIVITY ANALYSIS FOR TRANSPORTING CEMENT AND FLY ASH

A sensitivity analysis was conducted to evaluate how differences in transportation distance for cement and fly ash delivery to a ready-mix concrete plant affect energy use and GHG emissions. Transportation distances for cement tend to be longer than those for fly ash due to the more uniform distribution of coal-fired power plants compared to Portland cement productions facilities. The analysis assumed that fly ash was transported 60 mi to the plant and the cement was transported 60 to 100 mi.

The analysis showed that the difference in energy consumption and GHG emissions increases as the transportation difference increases. However, the differences were only approximately 4% at the maximum practical difference in transport distance (100 mi). Thus, the effect of difference in transportation distance was considered negligible relative to other sources of energy use and GHG emissions in this study.

Table A1. Effect of difference in transportation distance on energy consumption when transporting cement and fly ash to ready-mix concrete plants.

Distance difference = cement – fly ash (mi)	**Energy Use (billion Btu)**			**Energy savings from transportation (%) = (c/49.4) x 100**
	Cement (a)	**Fly Ash (b)**	**Difference (c) = a-b**	
0	1194.2	1345.9	-151.6	-0.3
10	1393.3	1345.9	47.4	0.1
20	1601.8	1345.9	255.9	0.5
30	1800.8	1345.9	454.9	0.9
40	1999.9	1345.9	654.0	1.3
50	2198.9	1345.9	853.0	1.7
60	2397.9	1345.9	1052.1	2.1
70	2597.0	1345.9	1251.1	2.5
80	2796.0	1345.9	1450.1	2.9
90	2995.0	1345.9	1649.2	3.3
100	3525.8	1345.9	2179.9	4.4

Table A2. Effect of difference in transportation distance on GHG emissions when transporting cement and fly ash to ready-mix concrete plants.

Distance difference = cement – fly ash (mi)	**CO_2e Emission (ton)**			**CO_2e savings from transportation difference (%) = (c/3,270,329 ton) x 10**
	Cement (a)	**Fly Ash (b)**	**Difference (c) = a-b**	
0	30,166	29,394	772	0.0
10	40,222	29,394	10,828	0.3
20	50,277	29,394	20,883	0.6
30	60,333	29,394	30,939	0.9
40	70,388	29,394	40,994	1.3
50	80,444	29,394	51,050	1.6
60	90,499	29,394	61,105	1.9
70	100,555	29,394	100,555	3.1
80	110,610	29,394	110,610	3.4
90	120,666	29,394	120,666	3.7
100	130,721	29,394	130,721	4.0