GREEN CONCRETE IN DEVELOPING ECONOMIES: ASSESSING THE POTENTIAL FOR USING LOW COST CEMENT SUBSTITUTES

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To my father and to all those who have been struck down by cancer

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I would like to thank my family and close friends for their unwavering support over the years. I would also like to thank my professors at the M.E. Rinker, Sr. School of Building Construction at the University of Florida for imparting their knowledge of the construction industry, particularly my thesis committee chair Dr. Esther Obonyo and my thesis committee members Dr. Charles Kibert and Dr. Mang Tia in the UF Civil Engineering Department for their guidance and support of this project.

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Concrete is second only to water as the most consumed substance on earth, with nearly three tons used annually for each person on the planet. The building industry and the natural environment in developed and developing economies can benefit from building low-cost and sustainable structures with green concrete. The aim of this study is to assess the potential and structural performance of using cement substitutes that are widely available in developing economies in 'green' or environmentally sustainable concrete. Specifically, low cost cement substitutes that are renewable and locally available in the developing world will be tested for strength and durability according to American Society for Testing and Materials (ASTM) standards. The specific research objectives of the study are:

1. To review existing practices with respect to green cement substitutes in developed and developing countries.
2. To determine the potential for using animal bone char, fly ash, and volcanic ash as substitutes for portland cement in the manufacture of 'green' concrete.

3. To characterize the material properties performance of the resulting concrete based on durability, compressive strength and tensile strength tests by ASTM standards.
4. To characterize the impact of using the proposed concrete in building envelope performance against sustainability metrics using BEES (Building for Environmental and Economic Sustainability) software.

The developing economies of the world will play a key role in the future of sustainable construction practices. It is imperative that the natural resources and ecology found within these countries are preserved due to the ever increasing human impacts on resource depletion. Many economies in the developing world have natural environments that are found nowhere else on the planet and contribute to the world's climate, oxygen and weather patterns. Additionally, these countries are experiencing record population growth, growing economies, and resource depletion on a massive scale that is unsustainable under traditional building methods. These factors can lead to massive soil runoff, desertification, greenhouse gas emissions, polluted drinking water, and an overall detrimental effect on human health.

Current practices in the manufacture of both traditional and 'green' concrete in developed and developing economies will be examined. The ethical obligations of developed economies to preserve a baseline well-being of humanity and assist developing economies in building practices and alternative energy technologies will also be introduced to outline the importance of sustainability in the developing world. Following laboratory testing of 'green' cement substitutes, recommendations for further study and research will be made for use in future sustainable building projects.

CHAPTER 1
INTRODUCTION

Background

In recent years, projected changes in the earth's climate have been viewed as an unavoidable consequence of a combination of natural planetary warming cycles and human activities through the increased use of fossil fuels and destruction of the biosphere. The built environment has been no exception in contributing to an increase in the burning of fossil fuels for building energy needs, an increase in construction waste in landfills, an increase in negative effects on human health, as well as contamination of water resources, agriculture and natural ecosystems. It is imperative to human survival that all professionals associated with the building industry begin implementing new construction techniques and utilizing sustainable building materials that will reverse potentially catastrophic harm to future generations. At the same time, it is imperative to incorporate alternative energy technologies in power generation in the built environment to reduce energy consumption, reduce reliance on a finite supply of fossil fuels and to mitigate the human contribution to climate change and pollution.

Developed economies have a moral and ethical obligation to the developing economies of the world that lack infrastructure, resources and technical applications to share knowledge of sustainable building practices and technologies. Any delay in sharing this information will have potentially irreversible effects on future generations and will increase the risk of further degrading the earth's environment due to the depletion of natural resources and potential poisoning of natural ecosystems which are crucial to human survival.

This introduction presents an overview of the objectives of this thesis study. Some of the information to be presented in this study will be the following: a definition of environmentally sustainable or ‘green’ concrete; current research on sustainable cement substitutes; a review of current unsustainable cement manufacturing processes; the need for ‘green’ concrete in developing economies; cost considerations in producing sustainable cement substitutes; and an overview the ethical framework of sustainable construction. This study will then test the structural performance of organic cement substitutes in a laboratory setting and present the data obtained.

Aims and Objectives

The aim of this study is to assess the potential and structural performance of using cement substitutes that are widely available in developing economies in ‘green’ or environmentally sustainable concrete. The specific research objectives of the study are:

1. To review existing practices with respect to green cement substitutes in developed and developing economies.
2. To determine the potential for using animal bone char, fly ash, and volcanic ash as substitutes for portland cement in the manufacture of ‘green’ concrete.
3. To characterize the material properties performance of the resulting concrete based on durability, compressive strength and tensile strength tests.
4. To characterize the impact of using the proposed concrete in building envelope performance against sustainability metrics using BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) software.

Outline of the Remainder of the Thesis

The remainder of this thesis will present the methodology and research data results that were conducted to determine the materials properties and environmental performance of using sustainable cement substitutes in developing economies.

A literature review has been conducted on these issues and the results are discussed in Chapter 2. Chapter 3 provides the methodology used to conduct this research. Chapter 4 provides the results of the laboratory experiments performed on the concrete specimens with regard to compressive strength, tensile strength and durability (water absorption) testing as well as environmental performance with BEES software. The final Chapter 5discusses and analyzes the laboratory results, provides a conclusion of the research and results, and provides opportunities for further research in the field of sustainable construction.

CHAPTER 2
LITERATURE REVIEW

Introduction

This literature review presents an overview of the current information available about sustainable concrete. Green concrete will be defined as a sustainable building material that contains locally available, renewable, and low cost cement substitutes. Organic, animal based materials of bone char and bone meal will be defined and current studies reviewed in terms of current applications as water filtration sources. The potential applications of bone char and bone meal as cement substitutes will be presented in terms of their mineral composition. The traditional manufacturing process of concrete and portland cement will be presented in terms of materials content and energy consumption. The need for green concrete in developing economies will then be defined with respect to current trends in the building industry and projected effects on climate change. An overview of climate change in developing economies will be presented with respect to projected increases in carbon emissions and projected increases in the need for traditional concrete for building projects. The sustainable industries currently being employed to combat carbon emissions and to improve local economies will be presented. Particular attention will be paid to developing Central American economies which contain different economic scenarios while at the same time sharing much potential for sustainable building practices. Finally, the underpinning reasons for producing green concrete will be discussed in terms of an ethical framework of sustainability and its effects on future generations.

What is 'Green' Concrete?

In order to define green concrete and its material properties, one must first consider the general definition of 'green' building materials in the construction industry (note: the use of the word 'green' is meant in terms of sustainable building practices not the typical construction industry term to describe new or uncured concrete). Most sustainable building materials can be classified into five separate categories and are best for the environment if they contain characteristics of all five, of which green concrete is included. These categories are (1) materials made with salvaged, recycled, or agricultural waste content; (2) materials that conserve natural resources; (3) materials that avoid toxic or other emissions; (4) materials that save energy or water; (5) materials that contribute to a safe, healthy, built environment (Lazarus, 2002).

Green concrete is typically made from recycled aggregate that reduces the need for mining and extracting virgin aggregate and reduces toxic contamination of water supplies from leaching (Lazarus, 2002) . The use of recycled aggregate as well as organic cement substitutes requires less cement in the concrete mixtures, which reduces the embodied energy and carbon footprint of green concrete due to less need for quarried materials extraction and fossil fuel processing. This in turn reduces the amount of greenhouse gas emissions into the atmosphere. Additionally, the use of 'green' concrete can offer significant sustainability benefits in the life cycle of buildings and structures. Its thermal mass is highly efficient in reducing the energy needed to heat and cool buildings, and it also contains a high level of air tightness. Green concrete is highly durable, needs minimal maintenance, and has a long lifespan which leads to lower life cycle costs. This durability means that a building can preserve its concrete foundation or concrete exterior while replacing less durable parts like windows, insulation and plumbing. Its mass and damping qualities allow good acoustic performance while minimizing movement and reducing floor vibration. Green concrete is also non-combustible, has a slow rate of heat transfer making it a highly effective fire barrier, and is resilient to flood damage (The Concrete Centre, 2009).

Both traditional and green concrete are second only to water as the most consumed substance on earth, with nearly three tons used annually for each person on the planet. Cement is the critical ingredient in green concrete, locking together the sand and gravel cement substitutes in an inert matrix. Both traditional and green concrete are a critical part of meeting society's needs for housing and basic infrastructure and have been used extensively for over 2000 years (World Business Council For Sustainable Development, 2002). Cement used in traditional and green concrete is made by heating limestone with small quantities of other materials (such as clay) to 1450°C in a kiln. The resulting hard substance called 'clinker' is then ground with a small amount of gypsum into a powder to make Ordinary Portland Cement (OPC), the most commonly used type of cement (Figure 2-1).

Many users require cement with particular properties, and these can be made by grinding additional constituents with the clinker. Typical green cement substitutes include slag and fly ash, by-products from blast furnaces and power generation. Another is pozzolan, a type of finely ground volcanic slag that is mixed with lime and acts like OPC and will set underwater. Due to its use in construction, green cement is made to strict standards. These standards can vary by region and may limit the type and amount of additive materials used (World Business Council For Sustainable Development, 2002).

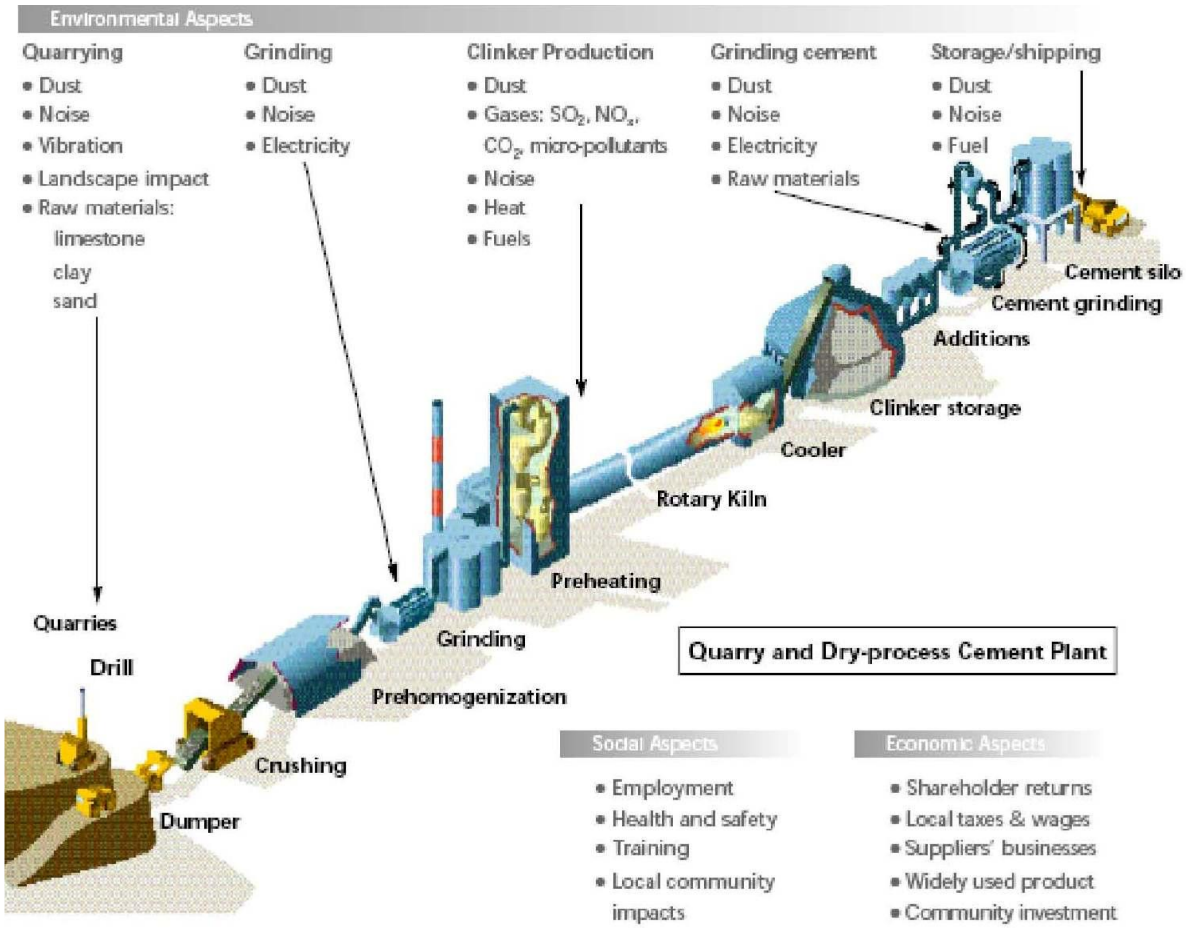


Figure 2-1. Quarry and dry-process cement plant with environmental, social and economic impacts (World Business Council For Sustainable Development, 2002).

Green concrete is also beneficial to the environment because the raw materials to produce it are prevalent in most parts of the world, which means it can be locally sourced and reduce CO_2 emissions from transportation while employing nearby workers in concrete factories. The cement, aggregates, and reinforcing steel used to make green concrete and the raw materials used to manufacture cement are usually obtained from sources within 300 miles of the concrete plant (Jeffries, 2009). Green concrete can be recycled as fill or road base, can be reused to protect shorelines in seawalls, and can be reused as aggregate in new concrete. However, its recyclability can be limited because its chemical properties degrade over time (Jeffries, 2009).

Review of Existing Trends in Green Concrete

Developed economies are taking steps to reduce the amount of carbon in the production of concrete and its transport to the construction site, which developing economies can emulate. According to the UK's Concrete Industry Sustainability Report, concrete has a high thermal mass and can reduce heating energy consumption by 2 – 15%. Well-designed combinations of heating, natural ventilation, solar shading and building design can reduce energy use for cooling and related CO_2 emissions by up to 50%. The UK concrete industry claims to recognize its "key role in delivering innovative construction solutions" and in "providing information to enable the development of CO_2 efficient designs of buildings and other infrastructure" (The Concrete Centre, 2009). In the UK, the embodied CO_2 associated with the production and transport of an average ton of concrete is 95kg of CO_2. When the total CO_2 emitted by the UK concrete industry is considered, cement is estimated to account for around 85% of these emissions. The rest arises from the production and transport of the other raw materials and from the mixing of concrete and its transport to the construction site. During cement production about 60% of the CO_2 emissions arise from the chemical reaction which takes place in the kiln; the other 40% come from the combustion of fuels. Through a significant investment in energy efficient technologies and by using biomass and other waste-derived fuels, the UK cement sector has reduced its CO_2 emissions by 27% since 1990, which has lowered CO_2 emissions by over 3.7 million tons since 1990 (The Concrete Centre, 2009).

The UK concrete industry has also been successful in reducing the embodied CO_2 of concrete through the extensive use of fly ash in concrete mixes and through the use of factory-made composite cements. The use of these materials can lower the embodied CO_2 of a concrete mix by up to 40%. Carbon emissions from sites manufacturing precast and ready-mixed concrete have also been reduced by 6.4% between 1990 and 2006. This has resulted in a 27% overall reduction in CO_2 emissions achieved by the cement industry in the UK and has greatly contributed to the government's goal of reducing carbon emissions by a minimum of 80% by the year 2050 (The Concrete Centre, 2009). However, global cement production will be increasing through 2050 and will lead to an increase in CO_2 emissions if developing nations are not included in carbon reduction policies (Figure 2-2).

Even with the current steps taken to promote energy efficiency and carbon reduction in the production of typical concrete mixes in developed countries, further research and emphasis should be placed on locally available and organic cement. New technologies may be able to achieve a carbon-negative manufacturing process. For example, the California-based company Calera has been able to filter carbon dioxide emissions through seawater to create a carbonate byproduct that is then mixed with aggregate and water to create concrete, lowering carbon emissions and avoiding the need to heat the ingredients (Jeffries, 2009). But these sustainable concrete mixes won't be affordable or accessible in the developing parts of the world, particularly China and India, which are consuming concrete at unprecedented levels on large building projects (Figure 2-3). And worldwide CO_2 reductions won't be possible without heavily subsidizing the industry in poor countries (Jeffries, 2009). Concrete plants in the developing world, where the industry continues to expand and develop new sites, may be cleaner and more efficient than those in the developed world which were built ten, twenty or even thirty years ago. In many developed countries, market growth is slow or even stagnant. In developing markets, growth rates are more rapid and a large fraction is sold as a bagged product to individual customers.

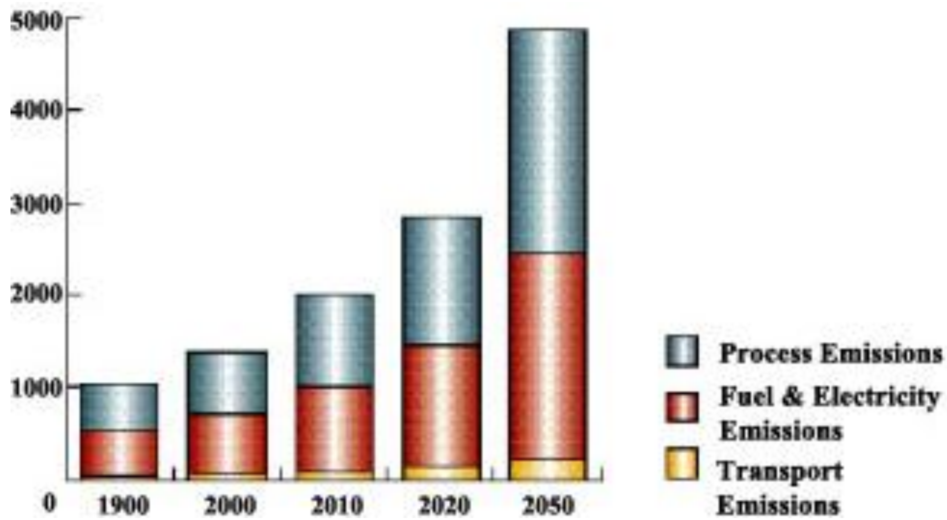


Figure 2-2. Projected CO_2 emissions (in millions of metric tons) from the global cement industry through 2050, assuming no change in current practices (World Business Council For Sustainable Development, 2002).

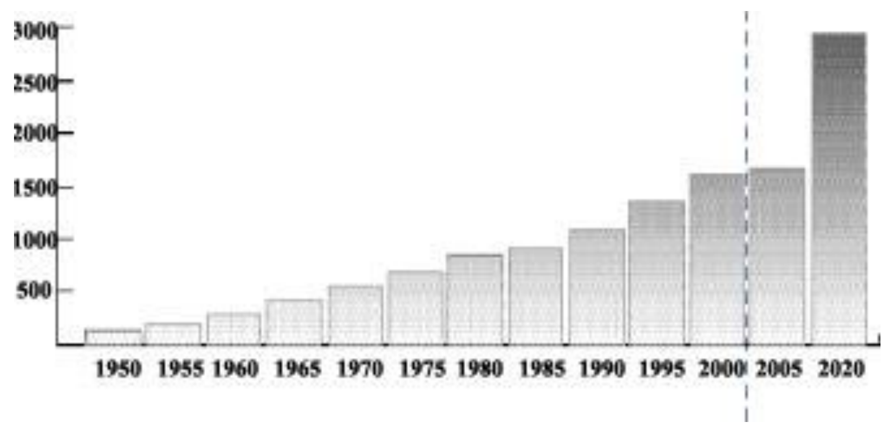


Figure 2-3. Global cement production in millions of metric tons annually. Rising cement demand will increase the need for fuels and raw materials (World Business Council For Sustainable Development, 2002).

China is the fastest growing market today (World Business Council For Sustainable Development, 2002). Existing practices in the production of concrete are not truly 'green' (Figure 2-4) without a combination of new technology, energy efficiency in the manufacturing process, and locally available, renewable additives.

Figure 2-4. A concrete industry advertisement depicting the green benefits of concrete (Jeffries, 2009).

Overview of Organic Animal Waste Materials as Potential Cement Substitutes: Bone

As the BEES data regarding environmental and economic performance of concrete shows, the amount of portland cement must be reduced and substituted with various 'green' materials in order to reduce the extraction and transportation energy and carbon footprint of concrete. In recent years, alternative materials have been added to reduce the cement content of the concrete which can reduce its overall carbon footprint without increasing cost or decreasing its structural properties. As previously mentioned in this literature review, these material cement substitutes have been thoroughly tested and used on numerous construction projects and usually consist of recycled or down-cycled industrial materials like fly ash, blast furnace slag, volcanic pumice, or recycled fiberglass. To push the limits of 'green' concrete construction, new materials that are locally available, easily renewable, environmentally friendly, and cost effective must be tested in a lab setting for their potential use in the industry.

Two such materials that have potential use as a 'green' cement substitute and have seen no significant laboratory testing are organic animal bone charcoal and bone meal. In developing countries, livestock (particularly cattle) are a widely used source of food and a significant segment of the local economy for subsistence farmers. However, once these animals are slaughtered or die of natural causes, their bones may be used for only a few small purposes like water filtration, simply composted, or not used at all.

Bone Char: Definition, Usages, Production process, Recent Studies

Meat waste management from livestock continues to be an important issue in pollution management. Large quantities of meat waste materials like blood, hair, tail, horns and bones have to be thoroughly and effectively treated through methods like composting prior to their disposal. In recent years, an emphasis has been placed in the livestock industry on reusing animal waste materials like meat and bone meal for production processes. Bone meal was widely recommended and used in animal feeds until the Small Bowel Enteroclysis (SBE) (Mad Cow disease) occurrence and micro-organism presence in the early 2000’s. The animal parts and bone were then incinerated and made into bone char to prevent any disease from spreading. However, recent studies have discovered that heavy metal absorption through the use of charred animal bones appears to be one of the most promising applications of re-using meat waste materials for pollution management and mitigation, particularly in the area of potable water filtration (Ioannis S. Arvanitoyannis, 2007).

Recent studies have also tested meat and bone char ashes obtained from specific incineration (laboratory) and from co-incineration (industrial process). In these studies, the industrial ashes contained much more heavy metals than laboratory ash and the amounts of leached elements into potential water supplies were low, especially for laboratory ash which can be classified as an inert waste. From these results, possibilities other than landfilling could be considered to give economic value to these ashes (Marie Coutanda, et al. 2008).

A recent study conducted by the Department of Chemistry at the University of Glasgow in 2002 tested animal bone charcoal as a treatment for decontaminating polluted water (J.A. Wilson, et al. 2002). This study sought to determine the use of bone charcoal as a low cost treatment for decontaminating polluted water, particularly in developing countries in Africa. In particular, its potential to remove metals like copper (Cu) and zinc (Zn) from contaminated water supplies was examined through sorption testing. This type of testing is also used to determine the water absorption rate of concrete materials.

The Case for Using Bone Char in Concrete

The 2002 University of Glasgow study provided the theoretical basis for this thesis study for testing bone meal as a potential 'green' cement substitute in developing countries. As the study states, bone charcoal is being developed as a treatment for decontaminating polluted water and it is an inexpensive yet efficient absorbent of heavy metals and aids in fluoride removal. Bone charcoal has been used to remove color from water since the early nineteenth century and it is widely used in the sugar industry to remove color and contaminants due to its mineral content (Table 2-1). However, it is difficult to recharge or reuse in the water filtration process and eventually needs disposal. Since the mineral content of bone char contains a significant amount of calcium carbonate ($CaCO_3$), a bonding agent essentially the same as limestone that is 72% of the total mass of portland cement: (see Figure 2-11), it should be tested as a cement substitute to reduce the amount of portland cement needed in the mix. If bone char is used in concrete, it can also solve the ecological problem of having to dispose of bone char that has run its useful course in filtering water for a small village or town.

Table 2-1. Mineral composition of bone charcoal (J.A. Wilson, et al. 2002).

Mineral/Material	%Content
Hydroxyapatite	70–76 wt.%
Carbon	9–11 wt.%
$CaCO_3$	7–9wt.%
$CaSO_4$	0.1–0.2wt.%
Fe_2O_3	<0.3 wt.%
Acid insoluble ash	3wt.% max

The University of Glasgow study concluded that bone charcoal has a high capacity for the removal of copper and zinc from water and further study must be completed to understand the absorption mechanisms of bone charcoal in a real-world setting. Bone charcoal may be a readily available source of cement substitutes in developing nations due to prevalent subsistence farming economies and a large availability of local livestock, particularly cattle. However, little research has been completed about its structural properties as a cement substitute in concrete.

Bone Meal: Definition, Usages, Production process, Recent Studies

Similarly, bone meal could also be a readily available, local source of cement substitutes in developing economies. Bone meal is a waste byproduct resulting from the slaughter of animals, especially beef cattle, by meat processors. It is produced by either raw or steamed animal bones that are removed of fat and dried, then ground into a white powder. Bone meal is commonly used as a fertilizer due its negligible pH effect on soils and content of approximately 20%-30% phosphorus, 2 - 4% nitrogen, 18% calcium (see Table 2-2 for bone meal mineral content), with small traces of copper, iodine, iron, manganese and zinc. It is an inexpensive form of phosphoric acid and is fed to farm animals to supply important minerals like calcium, phosphorus, iron, magnesium and zinc. It also contains a significant amount of protein due to the amount of tendon and muscle left on the ground bones (Alternative Medicine Encyclopedia, 2010). Some of the trace elements contained in bone meal can also be beneficial to human health as a dietary supplement for calcium intake. However, concerns about bone meal's high lead content and possible elevated mercury levels raise questions about using bone meal as a supplement. Typical lead content in bone meal is significantly higher than that in refined calcium carbonate (CaCO3), which is a laboratory-processed calcium.

Table 2-2. Mineral composition of bone meal (Meriter Health Services, 2009).

Mineral/Material	%Content
Calcium (Ca)	30.71
Phosphoric Acid (P_2O_5)	12.86
Nitrogen (N)	6.00
Sodium (Na)	5.69
Sulfur (S)	2.51
Magnesium (Mg)	0.33
Potassium (K)	0.19

A 2005 study conducted at the Université Paul Sabatier in Castres, France sought to determine the physical properties, chemical composition, and potential environmental effects of incinerated bone meal in response to the recent bovine spongiform encephalopathy (BSE) crisis in the European beef industry. The results of the study showed that meat and bone meal combustion residues were calcium (30.7%) and phosphate (56.3%) rich compounds, mainly a mixture of Ca10(PO4)6(OH)2 and _-Ca3(PO4)2. Significant levels of sodium (2.7%), potassium (2.5%) and magnesium (0.8%) were also observed. Ash particles were relatively small, from a few millimeters to a micrometer, with almost 90% of them smaller than 1 mm. The researchers stated the recent need for incinerating animal waste products in the meat industry for health concerns “as a result of the bovine spongiform encephalopathy (BSE) crisis in the European beef industry” and the importing of these waste products had been banned by the European Community (EU), leading to a need for the elimination or safe recycling of low risk MBM (Deydier E., et al. 2005).

The Case for Using Bone Meal in Concrete

Could low risk meat and bone meal (MBM) that is properly sterilized be safely recycled as a 'green' cement substitute in developed and developing economies? Like bone char, there is little, if any, previous research about using these organic substances as cement substitutes and further research is necessary to determine the structural and environmental properties of MBM in concrete uses. And like bone char, bone meal may be a readily available source of cement substitutes in developing nations due to prevalent subsistence farming economies and a large availability of local livestock, particularly cattle. Its high amount of calcium may aid in the concrete bonding and curing process but further research is needed.

Review of Portland Cement Manufacturing Process

This section of the literature review contains detailed economic and environmental information about the manufacturing of portland cement to make concrete that is widely used in the building industry in the developed world. This information was obtained from the materials analysis section of BEES (Building for Environmental and Economic Sustainability) software which is used in the selection of cost-effective, environmentally-preferable building products. BEES was developed by NIST (National Institute of Standards and Technology) Building and Fire Research Laboratory and is used by designers, building contractors and product manufacturers in the construction industry (BFRL: Office of Applied Economics, 2007). The following pages contain written analysis, charts and tables of information relating to portland cement concrete are excerpted from the BEES 4.0 software.

Flow diagrams (Figures 2-5 and 2-6) are an effective means of depicting the major elements of portland cement production with or without the use of cement substitutes like fly ash, slag and limestone.

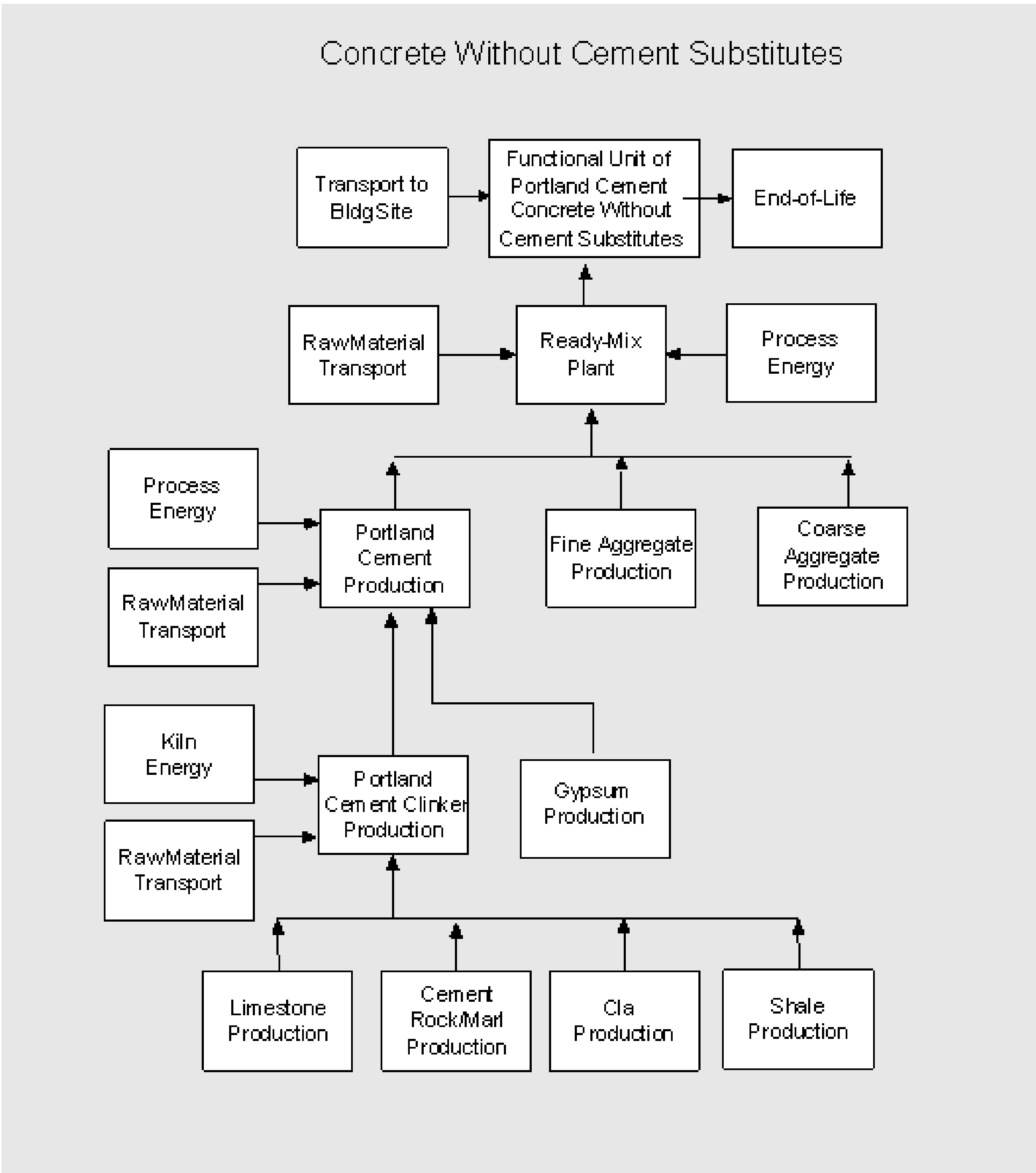


Figure 2-5. Production flow chart of typically manufactured concrete without cement substitutes (BFRL: Office of Applied Economics, 2007).

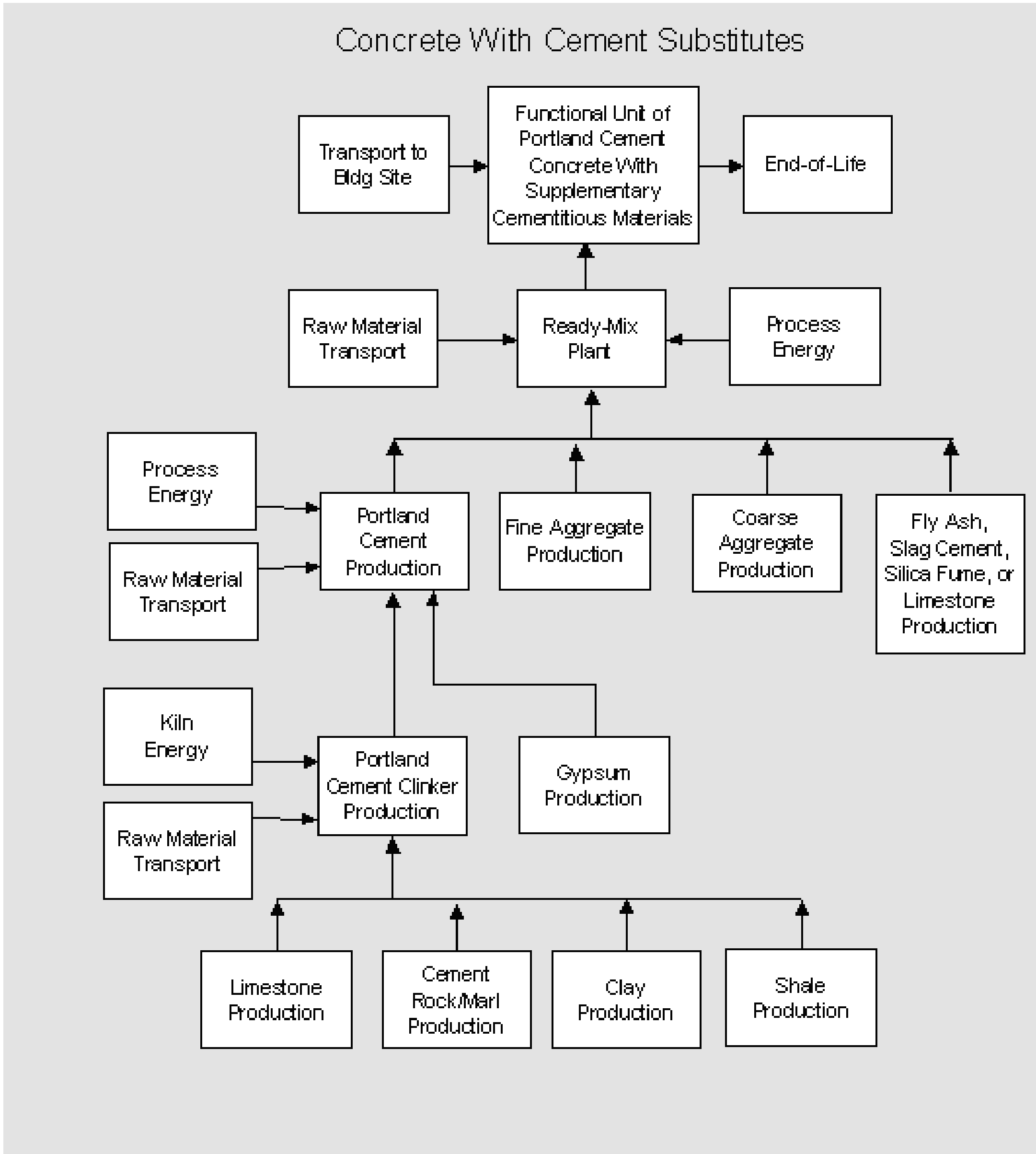


Figure 2-6. Production flow chart of typically manufactured concrete with 'green' cement substitutes (BFRL: Office of Applied Economics, 2007).

As Figure 2-5 shows, concrete in developed economies is typically made from a mixture of raw materials including portland cement, fine aggregate and course aggregate. The 'green' portland cement substitutes listed in Figure 2-6 to reduce the carbon footprint of concrete are typically fly ash, slag, and 5% limestone blended cement with an equal amount of replacement by weight for portland cement. Mix designs and strength will vary depending on the aggregates and cement used and Figure 2-7 shows the typical amounts of materials used in the manufacture of portland cement.

Constituent	*Mass of inputs in kg*	*Mass Fraction*
Limestone	1.17	72.2 %
Cement rock, marl	0.21	12.8 %
Clay	0.06	3.7 %
Shale	0.05	3.2 %
Sand	0.04	2.5 %
Slag	0.02	1.2 %
Iron/iron ore	0.01	0.9 %
Fly ash	0.01	0.8 %
Bottom ash	0.01	0.6 %
Foundry sand	0.004	0.2 %
Slate	0.001	0.1 %

Figure 2-7. Materials and content used in portland cement manufacturing (BFRL: Office of Applied Economics, 2007).

Figure 2-8 shows quantities of concrete constituents for three compressive strengths (fly ash, slag, and limestone). Fly ash is a waste material that results from burning coal to produce electricity and has an environmental outflow of coal combustion with an environmental inflow of concrete production, which essentially makes it an environmentally "free" waste material. Slag cement is a waste material from steel production and is similar to fly ash with an environmental outflow of steel production and an environmental inflow of concrete production. However, slag must be processed at the steel mill and transported to a grinding facility before it can be added to concrete mixes. Other materials that are sometimes added, such as silica fume and chemical admixtures, are not shown in the table.

Constituent	Constituent Density in kg/m^3 (lb/yd^3)		
	21 MPa (3 000 lb/in^2)	28 MPa (4 000 lb/in^2)	34 MPa (5 000 lb/in^2)
Cement and Fly Ash, Slag, or 5 % Limestone	223 (376)	279 (470)	335 (564)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	141 (237)	141 (237)	141 (237)
Cement and 10 % Limestone	236 (397)	294 (496)	353 (595)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	148 (250)	147 (248)	148 (250)
Cement and 20 % Limestone	265 (447)	331 (558)	397 (670)
Coarse Aggregate	1 127 (1 900)	1 127 (1 900)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	653 (1 100)
Water	167 (281)	166 (279)	167 (281)

Figure 2-8. Concrete constituent quantities by cement blend and compressive strength of concrete (BFRL: Office of Applied Economics, 2007).

Cement plants located throughout North America at locations with ample supplies of raw materials are used in the concrete manufacturing process. Major raw materials for cement manufacture include limestone, cement rock, shale, and clay. portland cement is manufactured using one of four processes: wet, long dry, preheater, or precalciner. Figure 2-9 presents the average energy use of portland cement factories by process and fuel types. Emissions from portland cement factories include carbon dioxide (CO_2), carbon monoxide (CO), sulfur oxides (SOx), nitrogen oxides (NOx), total hydrocarbons, and hydrogen chloride (HCl). The major waste material from cement manufacturing is cement kiln dust (CKD). An industry average of 38.6 kg of CKD is generated per metric ton (93.9 lb/ton) of cement. Of this, 30.7 kg (74.6 lb) is landfilled and 7.9 kg (19.3 lb) is reused on-site. Once portland cement concrete has reached the end of its useful life, the majority of it in the United States is recycled in urban areas as fill and road base (BFRL: Office of Applied Economics, 2007).

Energy Carrier	*Cement Manufacturing Process**				
	Wet	*Long Dry*	*Preheater*	*Precalciner*	*Weighted Average*
Coal	50%	50%	70%	63%	60%
Petroleum Coke	18%	33%	11%	11%	15%
Electricity	8%	10%	12%	12%	11%
Wastes	23%	3%	2%	6%	8%
Natural Gas	1%	4%	3%	7%	5%
Liquid Fuels**	1%	1%	1%	1%	1%
All Fuels	100%	100%	100%	100%	100%
Total Energy - kJ/kg of cement (Btu/lb)	6 400 (2 749)	5 591 (2 402)	4 357 (1 872)	4 220 (1 813)	4 798 (2 061)

Figure 2-9. Energy requirements for portland cement manufacturing (BFRL: Office of Applied Economics, 2007).

Climate Change in Developing Economies

According to the Intergovernmental Panel on Climate Change, climate change refers any change in climate over time, whether due to natural variability or as a result of human activity. The planet is gradually warming, as evidenced by increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea levels. Additionally, greenhouse gas emissions due to human activity have increased 70% between 1970 and 2004 (Figure 2-10) due to growth in energy supplies, transport, industry, agriculture and particularly residential and commercial buildings. Global increases in carbon dioxide (CO_2) are also attributed to human activity through burning of fossil fuels. Atmospheric concentrations of CO_2 in 2005 far exceed the natural range measured through ice core samples over the last 250,000 years (Intergovernmental Panel on Climate Change, 2007).

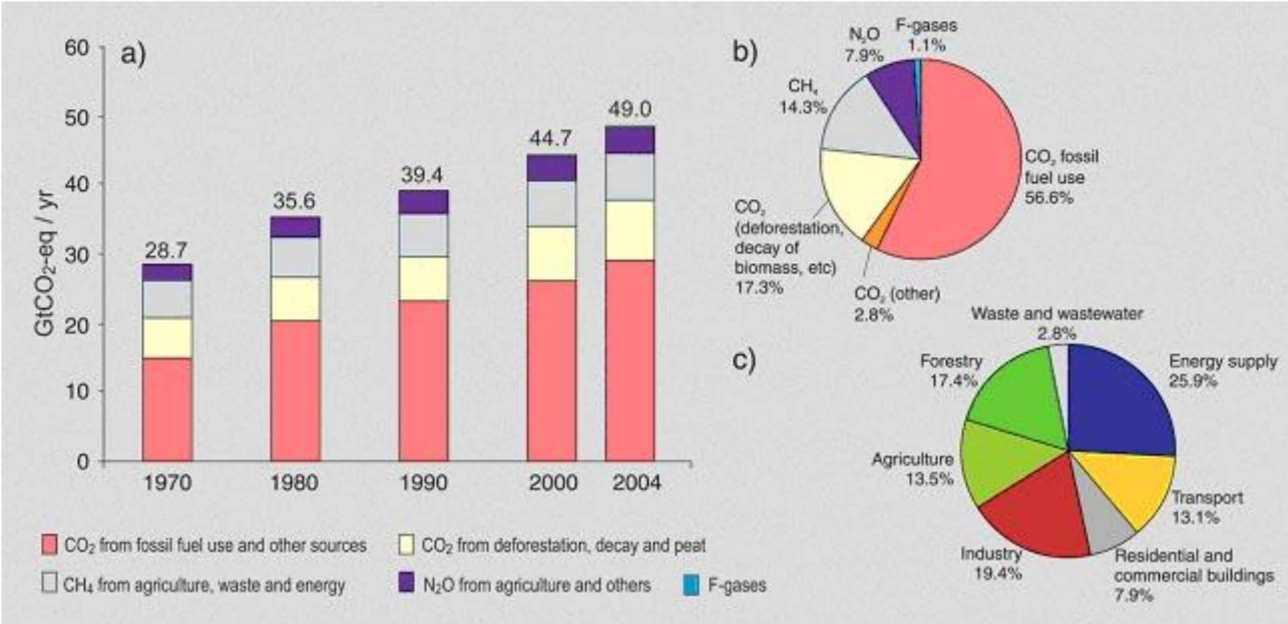


Figure 2-10. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.5 (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq. (Intergovernmental Panel on Climate Change, 2007).

Climate change will affect developing nations in the near and long term for several reasons. In Latin America, the increases in temperature and resulting decreases in soil water are projected to lead to gradual replacement of tropical forest by savanna in the eastern areas of the Amazon in Brazil, a country that has seen explosive economic growth in the last ten years. In countries like Costa Rica, Nicaragua and Panama which have tropical rainforest ecosystems, climate change poses a risk of significant biodiversity loss through species extinction. Deforestation and climate change are thought to be causing loss of significant levels of biodiversity in tropical rainforests and worldwide, with estimates over the next 20 years predicting a loss of 20% of existing species (Kibert, 2008). Rainforests are thought to contain more than 500,000 species while consisting of only 6% of the world's land mass, and a loss of biodiversity in these areas would be devastating to water and soil resources, pollution breakdown and absorption, wood products, medicinal resources and potential sources of new foods, medicines and new technologies (Kibert, 2008). In these same countries and throughout Latin America, cropand livestock productivity is expected to suffer significant declines which will lead to food shortages and an increase in the number of people at risk of hunger. Changes in precipitation patterns due to loss of glaciers are expected to cause severe water shortages for human consumption, agriculture, and energy generation. This loss of water access will severely affect Costa Rican and Nicaraguan energy production since a significant portion of energy is generated by hydroelectric dams in these countries (Intergovernmental Panel on Climate Change, 2007).

The Need for Sustainable 'Green' Concrete in Developing Economies

In the developed countries of Europe, buildings are estimated to consume roughly 50% of all energy produced. Lighting and heating buildings generates 50% of the UK's carbon dioxide emissions while the production of building materials accounts for a further 10%. The construction industry generates one-third of all waste in Britain, while 20% of new building materials on an average building site are simply thrown away at the end of the job. The greatest contribution to embodied carbon for housing comes from cement-based materials (poured concrete, concrete blocks and pre-cast concrete elements) which contribute in excess of 50% of the carbon footprint in construction (DMG World Media Dubai, 2009). This contribution is widespread and similar in all developed countries since concrete extraction and manufacturing use the same processes. In the United States, constructing to reduce the carbon footprint of the built environment is exacerbated by current unsustainable trends in which commercial and residential buildings use almost 40% of the primary energy and approximately 70% of the electricity in the United States (Annual Energy Review 2004, 2005). This massive consumption of energy leads to massive carbon emissions, and buildings account for an estimated 37% of the nation's greenhouse gas emissions (Emissions of Greenhouse Gases in the United States 2007, November 2008).

Developed countries must not continue on the same path of the developed world if true reduction or elimination of fossil fuel use combined with energy efficient buildings and alternative energy technologies is to be realized. In order for developing countries to spur economic growth through the built environment that is environmentally beneficial, sustainable materials must be extracted, produced and used in the latest building projects. Sustainable concrete that uses organic cement substitutes that reduces the amount of cement needed in the concrete mixture will produce less carbon and will be economically beneficial to local suppliers and builders.

The Need for Sustainable Industries in Developing Economies

The Intergovernmental Panel on Climate Change (IPCC) provides several reasons for the need for renewable energy technology in developing countries and how to implement it (Figure 2-11). Renewable energy like solar, wind, geothermal, biomass

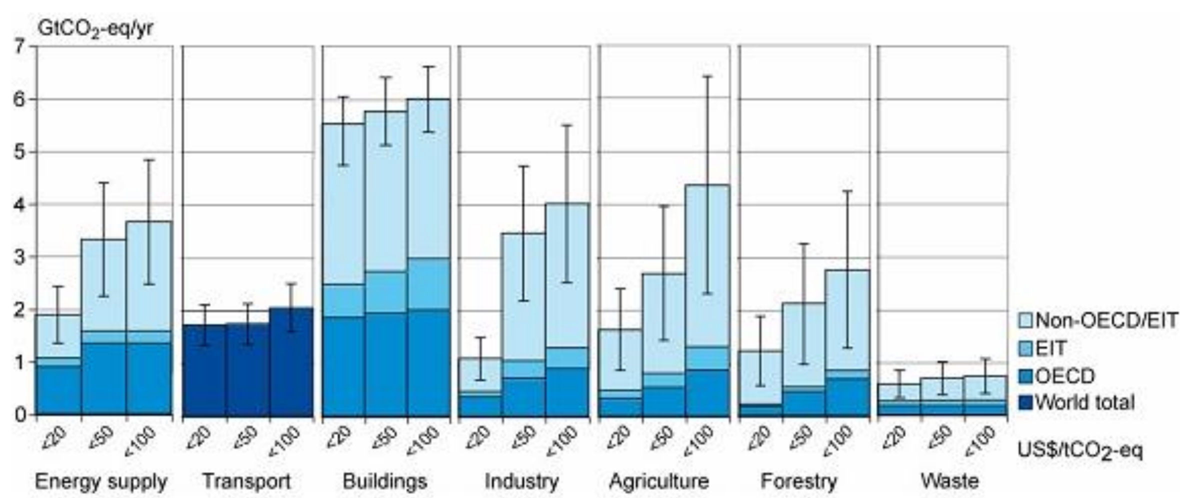


Figure 2-11. Buildings can account for a significant reduction in CO_2 emissions per year. (Intergovernmental Panel on Climate Change, 2007)

and tidal energy employed on a large scale can provide significant reductions in greenhouse gas emissions and lead to the eventual goal of complete elimination of fossil fuel use. According to the IPCC, no single technology can provide all of the carbon mitigation potential in any sector. Energy efficiency in buildings combined with utilization of renewable energy offer the best synergies with sustainable development.

In least developed countries, energy substitution can lower mortality and morbidity by reducing indoor air pollution, reduce the workload for women and children, and decrease the unsustainable use of wood for fuel and related deforestation (Intergovernmental Panel on Climate Change, 2007). The IPCC also recommends enacting governmental policies that provide a real price of carbon in order to create incentives for producers and consumers to invest in low greenhouse gas products, technologies and processes.

In developed countries, there is growing implementation of climate response options in several industrial sectors to realize synergies and avoid conflicts with other dimensions of sustainable development. Climate change policies enacted by national governments on a wide scale that are related to energy efficiency and renewable energy are often economically beneficial, improve energy security and reduce local pollutant emissions. These policies can result in reducing the loss of natural habitat and deforestation, can have significant biodiversity, soil and water conservation benefits, and can be implemented in a socially and economically sustainable manner. For example, forestation and bio-energy plantations can restore degraded land, manage water runoff, retain soil carbon and benefit rural economies (Intergovernmental Panel on Climate Change, 2007).

To illustrate the potential of sustainable technologies in developing countries, one can look to the proliferation of alternative sources of energy in the Central American nation of Nicaragua. The use of wind turbines as an alternative power source is growing rapidly in Nicaragua with a 19 turbine, $90 million project located on the shores of Lake Nicaragua, the largest lake in Central America and a direct recipient of over three hundred days of strong offshore winds per year (Figure 2-12).

Figure 2-12. These windmills, part of a $90 million project, have sprung up on the edge of Lake Nicaragua in Rivas, Nicaragua (Press, 2009).

The 410 foot high windmills, installed by Suzlon Energy Ltd. of Pune, India, were set up on the edge of Lake Nicaragua and will generate 40 megawatts or 6% of the country’s energy needs per year (Aleman, 2008). This small nation is one of the poorest countries per capita in the western hemisphere, yet its government has decided to think in bigger terms and reduce its dependence on foreign oil, of which nearly 80% is currently provided at a discount by Venezuela. Nicaragua currently produces over 35% of its energy needs from alternative sources like geothermal from volcanoes, hydroelectric generated by rivers and sugarcane based ethanol (Associated Press, 2009). Wind is part of Nicaragua's efforts to reduce its dependence on oil-based energy to just 3% by 2013 (Figure 2-13). Ernesto Martinez, executive president of the Nicaraguan Energy Company, said recently that Russia will finance and build two geothermal plants in Nicaragua with the capacity to produce 250 megawatts (Aleman, 2008).

Figure 2-13. Wind turbines on the shores of Lake Nicaragua with Ometepe Island volcano in the distance (Aleman, 2008).

Cost Comparisons Between Traditional and Green Concrete

In order for green concrete to be a viable building material, its cement substitutes will need to be low in cost and easily renewable in order to compete with traditional portland cement concrete. Traditional plain portland cement concrete with no admixtures delivered to a jobsite in the United States typically costs around $75 per cubic yard, which is about 2 cents per pound.. Portland cement itself after processing costs less than 4 cents per pound. However, using green cement substitutes in the concrete mix does not usually increase the cost of the concrete, which shows that renewable green cement substitutes are cost effective. Diluting the portland cement with a less costly waste product like fly ash typically costs only 1.5 cents per pound, which is profitable for power plants since the fly ash would be landfilled if not re-used in concrete. Ground granulated blast-furnace slag costs about 3 cents per pound, which can be mixed and combined with portland cement, fly ash, and the slag to make a cost-effective and green concrete. The total cost of an air-entrained 6-bag (564 lb) concrete mix made using gravel coarse aggregate (1800 lb) and sand fine aggregate (1250 lb) is about $75 per cubic yard, even when recycled waste materials like fly ash or ground granulated blast-furnace slag are included. Therefore, green concrete is just as cost effective as traditional concrete, while having better environmental benefits (Pistilli, 2010).

As Figure 2-14 shows, the potential for using organic animal bone char in both developed and developing economies as a potential green cement substitute shows great promise based on the sheer number of cattle processed in each of these countries.

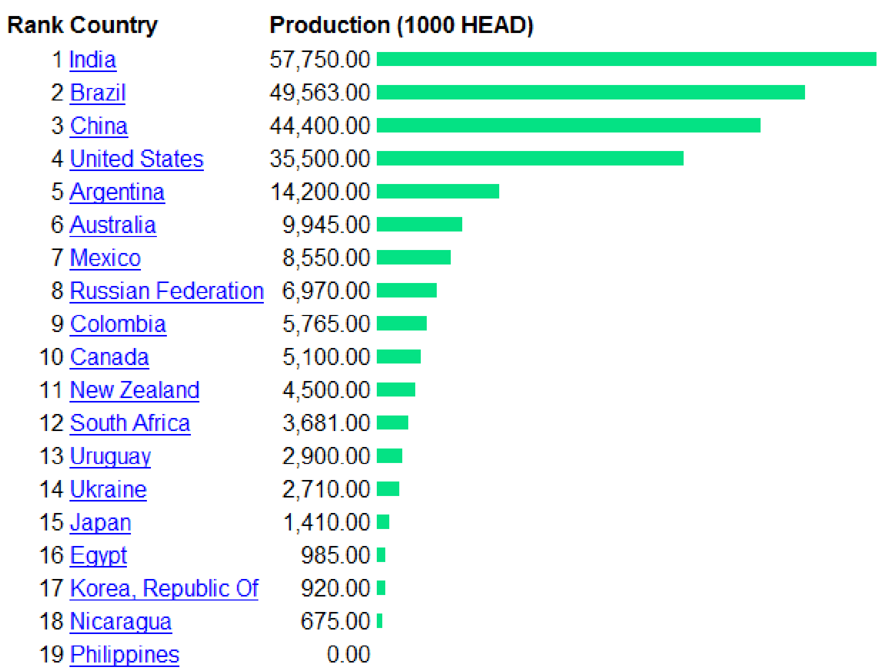


Figure 2-14. Animal Numbers, Cattle Production by Country in 1,000 HEAD (Animal Numbers, Cattle Production by Country in 1000 HEAD, 2009).

Developing economies in India and Brazil are leading producers of cattle and may be able to use the processed cattle bones in green concrete instead of discarding them. And the previously mentioned developing economy of Nicaragua is a leading producer of cattle as the graph shows, so bone char made from processed cattle bones could also be a low cost and local material for green cement production for concrete building projects. The unit cost of processed cattle bones varies by each country, so more cost research would be needed to determine the exact price for using cattle bone char in green concrete.

Ethics and Sustainability

In terms of sustainable development, ethical principles provide a set of rules of acceptable conduct so that the needs of the present will be met “without compromising the ability of future generations to meet their needs” (World Commission on Environment and Development, 1987). This set of ethical principles is also referred to as *intergenerational justice* and must be applied more widely in terms of sustainable development since values must be applied across generations to be effective (Kibert, 2008). The choices of the present generation will affect future generations through availability of resources, biodiversity, and environmental quality. Present decisions about how to develop sustainably must be determined through “(1) an ethical framework that represents society’s general moral attitudes toward life and future generations; (2) an understanding of and willingness to accept risk; and (3) the economic costs of implementation and resulting impacts” (Kibert 2008).

With regard to developing countries, the ethical principle of *protecting the vulnerable* applies. People in poorer countries may be vulnerable to the decisions of wealthier and influential countries that have economic and governmental influence. This power arrangement places developing countries in a subordinate position to wealthier, developed countries and those in power have a moral obligation to protect the vulnerable and dependent population. Additionally, future generations are vulnerable to the actions of present generations and sustainble steps must be taken to ensure their existence and quality of life. This ethical principle places an “enormous responsibility” on the current generation and is made more difficult by global poverty in developing countries (Kibert, 2008).

The ethical challenges presented by climate change and the destruction of the natural environment by human activity are vast. Specifically, developing nations are increasingly dependent on the actions of developed nations to act in an ecologically sound manner and to share the knowledge necessary to negate the harmful effects of the built environment on earth’s ecosystems. The national science academies of the G8 nations and Brazil, China and India signed a statement in 2005, outlining the reality of global climate change and calling on world leaders at the G8 Summit in July 2005 to enact specific and far-reaching changes to reverse the effects. This report called attention to the fact that over the next 25 years world primary energy is expected to increase by almost 60% and fossil fuels are expected to provide 85% of this demand (Joint Science Academies, 2005). The report concluded that even with lowered emission rates targeted by developed nations through agreements like the Kyoto Protocol, humans will be experiencing the impacts of climate change throughout the 21st century and beyond. Failure to implement “significant reductions” in net greenhouse gas emissions now, will cause even further hardship for future generations trying to make significant changes in fossil fuel emissions (Joint Science Academies, 2005). The most important point made by this report is that any developing nations that lack the infrastructure or resources to respond to the impacts of climate change will be the most affected and will have to rely solely on the goodwill of developed nations, with little opportunity to make meaningful change on their own behalf.

The world's poorest people in developing nations will be the most affected and will suffer the most. Since the problem of climate change is well defined, the science academies report goes on to provide a list of suggested actions for world leaders to take to begin adapting and reversing its effects. Leaders worldwide must devise and implement strategies to adapt to its consequences with "worldwide collaborative inputs from a wide range of experts, including physical and natural scientists, engineers, social scientists, medical scientists, those in the humanities, business leaders and economists" (Joint Science Academies, 2005).

The Joint Academies report provides the following steps for developed and developing nations to adapt toand reverse the detrimental effects of climate change. Steps number three and four are particularly relevant to ethical principles of sustainability in developing countries:

1. Identify cost-effective steps that can be taken now to contribute to substantial and long-term reduction in net global greenhouse gas emissions.
2. Recognize that delayed action will increase the risk of adverse environmental effects and will likely incur a greater cost.
3. Work with developing nations to build a scientific and technological capacity best suited to their circumstances, enabling them to develop innovative solutions to mitigate and adapt to the adverse effects of climate change, while explicitly recognizing their legitimate development rights.
4. Show leadership in developing and deploying clean energy technologies and approaches to energy efficiency, and share this knowledge with all other nations.

5. Mobilize the science and technology community to enhance research and development efforts, which can better inform climate change decisions.

As evidenced by these steps, developing nations have the most to gain from sharing knowledge of sustainable technologies and building techniques that are best suited to their local ecology and climates and may have the greatest impact on climate change and applying the ethical principle of protecting the vulnerable.

The ultimate problem to be solved by ethical principles and sustainability is to figure out how all inhabitants of the planet can have a decent quality of life without destroying the planet's resources and biodiversity. If developed countries can dramatically reduce resource and energy consumption, particularly in the built environment that is materials and energy heavy, then developing countries may be able to progress their people's quality of life beyond "mere survival" (Kibert, 2008).

Summary

The world has a finite supply of natural resources, particularly fossil fuels, and mankind will not survive if it does not find new ways to reduce its energy consumption and to use renewable sources of energy. One way to achieve this is to use organic, locally available renewable cement substitutes in concrete manufacturing in both developed and developing economies. Animal waste materials, particularly in the form of bone char, may provide a promising new substitute.

CHAPTER 3
METHODOLOGY

Introduction

The aims and objectives of the study, as listed in Chapter 1, to be followed through the course of the laboratory experimentation were as follows:

1. To review existing practices with respect to green cement substitutes in developed and developing countries.
2. To determine the potential for using animal bone char, fly ash, and volcanic ash as substitutes for portland cement in the manufacture of ‘green’ concrete.
3. To characterize the material properties performance of the resulting concrete based on durability, compressive strength and tensile strength tests.
4. To characterize the impact of using the proposed concrete in building envelope performance against sustainability metrics using BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) software.

This thesis provided the ethical underpinnings for researching and providing alternative building materials technologies to developing countries. It was determined through the course of this study that in order for humanity to combat ecosystem destruction and the effects of increased amounts of carbon and toxins in the earth’s atmosphere through the burning of fossil fuels that can lead to global climate change, developing economies must preserve their natural resources and native ecosystems. These countries must use alternative sources of fuel as well as sustainable, local building materials to lower their carbon output and preserve their local resources. The key issues in promoting and utilizing sustainable building materials and practices in these countries were found to be: the availability, cost, and durability of local materials. These elements are crucial in promoting and utilizing sustainable building materials and practices in the construction of commercial buildings and residential homes. This thesis then provided further research about various types of sustainable cement substitutes including bone char and bone meal (MBM). Three sustainable cement substitutes (fly ash, volcanic ash, bone meal) were then mixed and poured into eight (8) cylinders of 4 x 8 inch size for each mix type, resulting in a total number of minimum 24 cylinders. The concrete cylinders were allowed to cure for 28 days and then tested by the American Society for Testing and Materials (ASTM) standards for compression strength, tensile strength and water absorption, and data results were obtained and analyzed. The resulting concrete material types were then tested for environmental and economic performance based on BEES (Building for Environmental and Economic Sustainability) software which measures the performance of building products by using the life-cycle assessment approach.

Scope

The methodology followed in this research was determined by the objective of the study and the hypotheses statements listed in Chapter 1. The steps taken to conduct the thesis research and to obtain quantifiable results were as follows:

1. A literature review was performed on sustainable building materials for the construction industry as well as the ethical basis for providing developing countries with the knowledge and means to employ sustainable building materials, particularly ‘green’ concrete, and practices.
2. The data needed for the analysis was identified.

3. The sources of data were identified.
4. Standard ASTM concrete testing for the three selected cement substitutes (fly ash, volcanic ash, bone meal) was identified.
5. The three concrete types were mixed and poured into 8 cylinders of 4 x 8 inch size for each mix type, resulting in a total number of 24 cylinders and tested in the laboratory by ASTM standards to obtain the data.
6. Analytical and descriptive statistics were generated to assess the significance of the laboratory results sought.
7. The concrete data for the three different cement substitutes was compared with BEES metrics according to economic performance (first cost and future costs) with a discount rate of 3%, availability in their local environments (within 300 miles of the project site), and environmental performance based on several parameters: global warming, fossil fuel depletion, ecological toxicity, human health, embodied energy by fuel renewability. Economic and environmental performance were given equal 50% weightings in the study to obtain a clear average and detailed analysis.

Experimental Approach

The following experimental specifications were taken into account when designing and testing the compressive strength of the three concrete mixtures:

1. Characteristics of the mixture
2. Maximum size aggregate
3. Minimum cement content
4. Characteristics of the cement, water aggregates and admixtures

5. Characteristics of the plastic and/or hardened concrete
6. Compressive and/or flexural strength
7. Tensile Strength
8. Water absorption coefficient

Experimental Data Entry

The following ASTM standard methods for testing concrete were conducted in the laboratory setting to make the three sustainable concrete mixtures, to determine their compressive strength, to determine their tensile strength, and to determine the water absorption coefficient of the three mixtures after twenty-eight (28) days of curing. Detailed results of the testing are contained in Chapter 4: Data Analysis. The following standard tests were used to obtain the concrete mixture data for the three samples consisting of 8 cylinders for each mix type of 4 x 8 inch size, resulting in a total number of minimum 24 cylinders:

ASTM C192: Making and Curing Concrete Test Specimens in the Laboratory

The size of the cylinder to be tested is typically 6 x 12 for 1 inch or greater max size course aggregate; 4 x 8 for ¾-inch or less size course aggregate (Figure 3-1) as used in this study. ASTM C192 provides standardized requirements for preparation of materials, mixing concrete, and making and curing concrete test specimens under laboratory conditions. The concrete cylinder specimens were mixed and rodded 20 times and vibrated for 1 minute each to ensure uniform mixing of the cement substitutes (Figure 3-2). Lab specimens were cured for 28 days in a completely saturated limewater tank (Figure 3-3).

Figure 3-1. 4in. x 8in. concrete cylinders that were used to make laboratory specimens.

Figure 3-2. Rodding and vibrating the concrete specimens in the laboratory.

Figure 3-3. The concrete specimens curing and immersed in water for 28 days.

ASTM C39: Compressive Strength of Cylindrical Concrete Specimens

This test is also known as destructive testing of hardened concrete. The strength of the concrete to be tested is affected by the length to diameter (L/D) ratio of the cylinder and the condition of the ends of the cylinder samples is noted to determine the failure mode of the concrete (Figure 3-4). The loading rate of the compression machine is typically between 20-50 psi/sec. The concrete strength testing for each class of concrete placed is conducted under the following circumstances: not less than once per day, not less than once for each 150 cubic yard (cy) of concrete placed, and not less than once for each 5000 square feet (sq. ft.) of surface area for slabs and walls (Figure 3-5). The results of this test method are used as a basis for quality control of concrete proportioning, mixing, and placing operations; determination of compliance with specifications; control for evaluating effectiveness of admixtures; and similar uses. In this study, both the wet compressive strength of the moist concrete after 28 days of curing and dry compressive strength of the hardened concrete after 28 days and 48 hours of drying in an oven were tested.

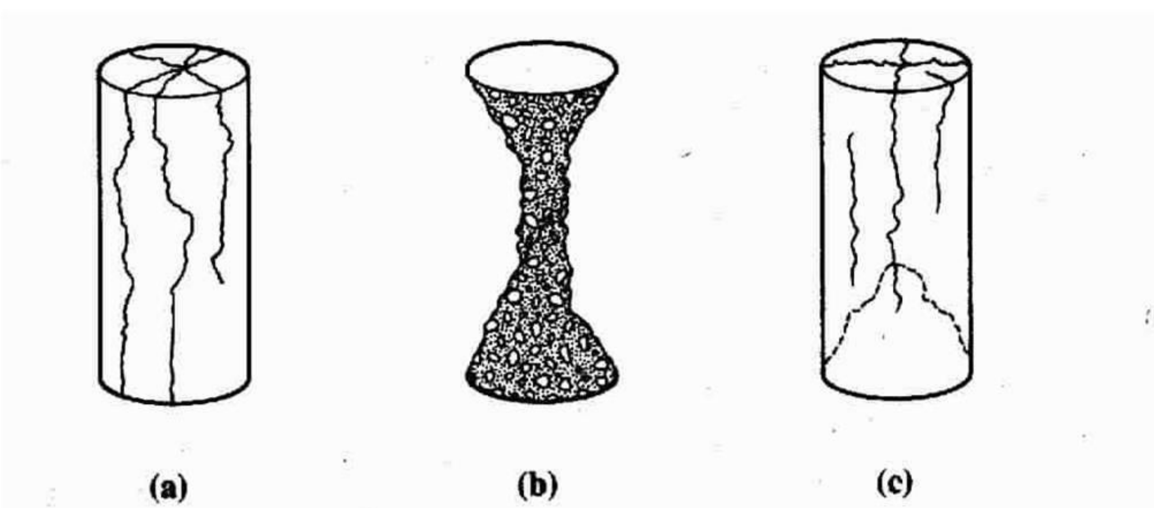


Figure 3-4. Sketch showing typical failure modes of compression testing: (a) splitting; (b) shear (cone); and (c) splitting and shear

Figure 3-5. Hardened concrete specimen failure in the compression machine after destructive testing.

ASTM C496: Splitting Tensile Strength of Cylindrical Concrete Specimens

This ASTM test method covers the determination of the splitting tensile strength of cylindrical concrete specimens. This method consists of applying a diametral compressive force along the length of a cylindrical specimen. This loading induces tensile stresses on the plane containing the applied load. Tensile failure occurs rather than compressive failure. Plywood strips are used so that the load is applied uniformly along the length of the cylinder. The maximum load is divided by appropriate geometrical factors to obtain the splitting tensile strength. The concrete cylinders were placed in the compression machine with bearing strips - 2 each, 1/8 in. thick plywood strips, 1 in. wide (the length shall be slightly longer than that of the specimens). The bearing strips were placed between the specimen and the upper and lower bearing blocks of the testing machine (see Figure 3-6).

Figure 3-6. Hardened concrete (volcanic ash) specimen failure in the compression machine after splitting tensile strength testing.

The load was applied continuously at a constant rate of 100 to 200 psi/minute of splitting tensile stress until failure occurred. The maximum load at failure in pounds was then recorded and the splitting tensile strength was calculated (Equation 3-1), where *P* is the maximum load at failure in pounds, and *l* and *d* are the length and diameter of the cylindrical specimen, respectively, in inches:

$$\mathbf{f' = 2P \,/\, \pi\, l * d} \qquad (3\text{-}1)$$

ASTM C1585 - 04e1: Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes

This test method is used to determine the rate of absorption (sorptivity) of water by hydraulic cement concrete by measuring the increase in the mass of a specimen resulting from absorption of water as a function of time when only one surface of the specimen is exposed to water. The exposed surface of the specimen is immersed in water and water ingress of unsaturated concrete dominated by capillary suction during initial contact with water is measured (Figure 3-7).

The standard method is to cure the specimens in an oven for three days, at a temperature of 50°C and relative humidity of 80%. The relative humidity is achieved using potassium bromide. As an alternative to the standard test method, potassium bromide was not used. The specimens, one sample each of fly ash, volcanic ash, bone meal concrete were cured in the oven for 2 days at a temperature of 108°C. All of the samples were kept in the same environmental condition in the laboratory at a constant temperature during the period of the testing program (Figure 3-8). All sets of samples were cured for 28 days. The properties of each are shown in Chapter 4: Data Analysis.

The readings of the test and the value of the Absorption (I) are found using Equation 3-2:

I = mt / (a* d) where mt = the change in mass in grams, at different time (t) (3-2)

a = exposed area of the specimen, in^2

d = density of water in g/in^3

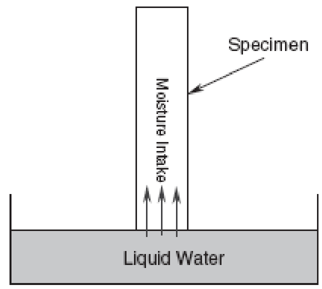


Figure 3-7. Moisture movement into concrete cylinder from surface contact with water.

Figure 3-8. The tray and chicken wire apparatus used to test the hardened concrete specimens for water absorption. Bricks were used to steady the wire base and provide an even water level across the cylinders.

Equipment Used

Concrete Mixer (Pan Type)

The Pan Concrete Mixer (Figure 3-9) is efficient for mixing quality concrete. Pan type mixer is suitable for the mixing concrete in the laboratory. It is designed to give efficient mixing of both dry and wet materials. The total effective capacity of the mixer is

56 liters. The mixer head lifts clear to provide maximum access to the pan and holds the mixing blades at a constant depth during the mixing operation. The blades can be adjusted to suit the different types and volume of materials to be mixed.

Figure 3-9. Concrete mixer and tray used to mix the batches.

Full Automatic Compression Machine

Range of 2000 kN, 3000KN and 4000 kN capacity compression machine (Figure 3-10) has been designed to meet the need for reliable and consistent testing of concrete samples. The machine features the complete automatic test cycle with a closed loop digital readout. Once the specimen parameters have been introduced, it is sufficient to press the START button to complete the test. The compression machine consists of: a frame, power pack and data acquisition control system.

Figure 3-10. Typical compression machine

Vibrating Table

The Vibrating Table (Figure 3-11) is a compact unit providing controlled vibro-compaction with fixed amplitude in the laboratory using cube or cylinder molding equipment. Vibrating tables consist of vibrating motor, control unit and clamping assembly (Concrete, 2010).

Figure 3-11. Typical vibrating table

Environmental Performance Data Entry: BEES Software

The concrete data for the three different cement substitutes was compared with BEES metrics according to economic performance (first cost and future costs) with a discount rate of 3%, availability in their local environments (within 300 miles of the project site), and environmental performance based on several parameters: global warming, fossil fuel depletion, ecological toxicity, human health, embodied energy by fuel renewability. Economic and environmental performance were given equal 50% weightings in the study to obtain a clear average and detailed analysis. Figures 3-12 through 3-18 show computer screenshots that depict the BEES process and the parameters that were chosen to obtain the computed results.

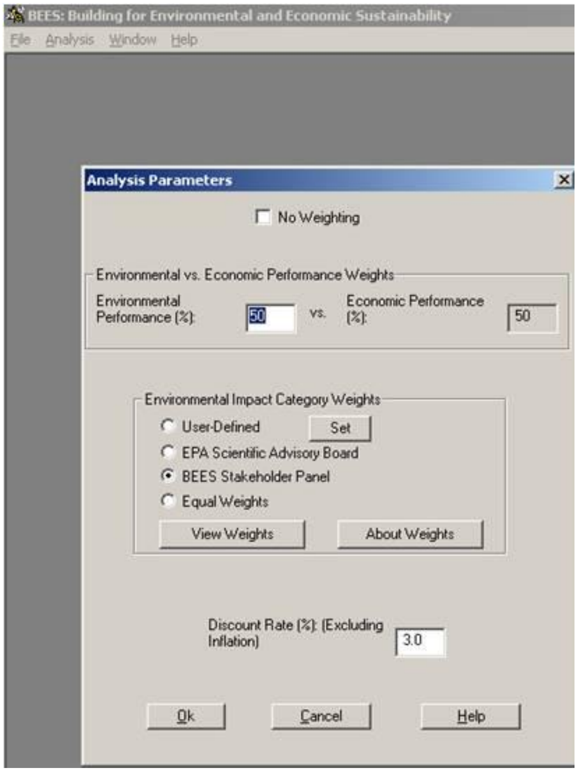


Figure 3-12. BEES screenshot showing first step of analysis: setting up performance parameters.

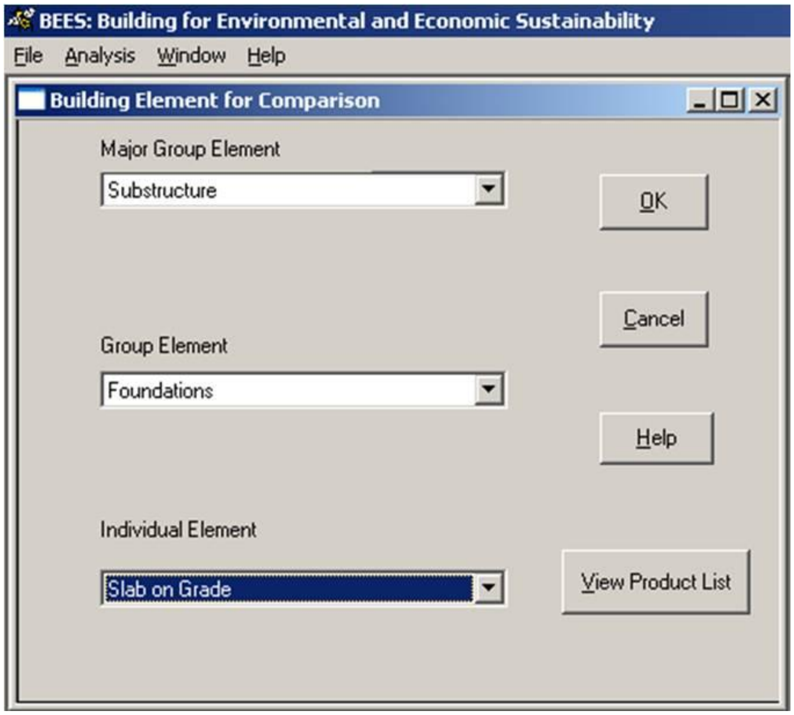


Figure 3-13. BEES screenshot showing second step of analysis: selecting building elements for comparison.

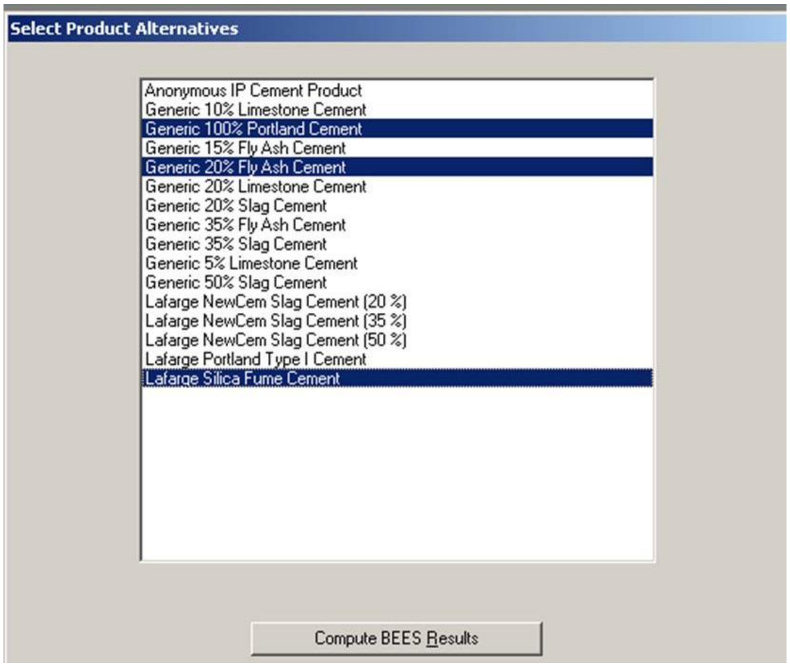


Figure 3-14. BEES screenshot showing third step of analysis: selecting product alternatives.

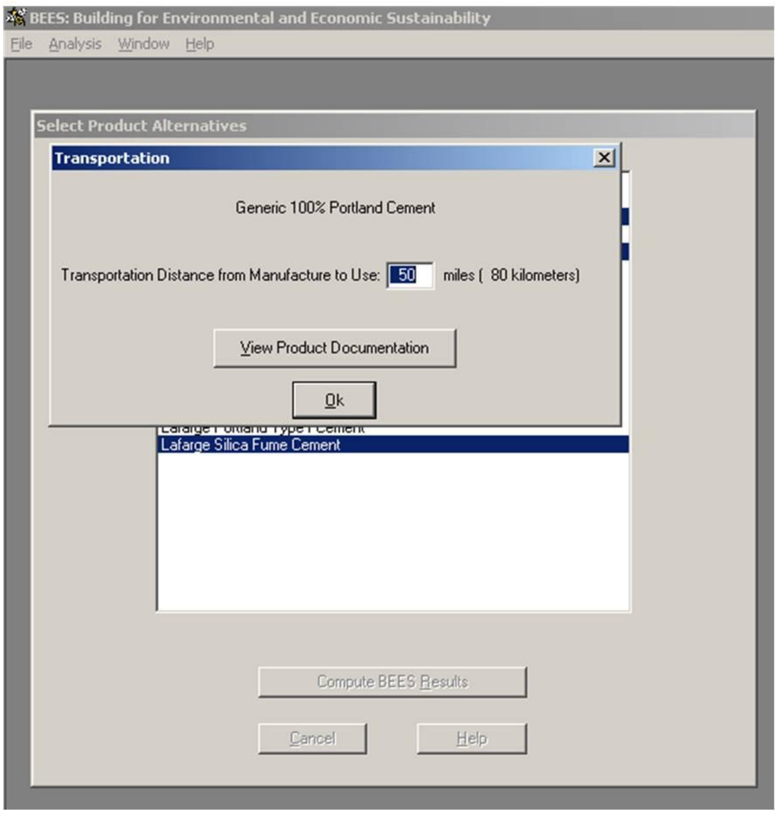


Figure 3-15. BEES screenshot showing fourth step of analysis: selecting product transportation distance.

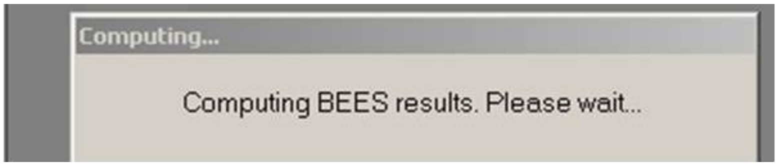


Figure 3-16. BEES screenshot showing fifth step of analysis: computing results.

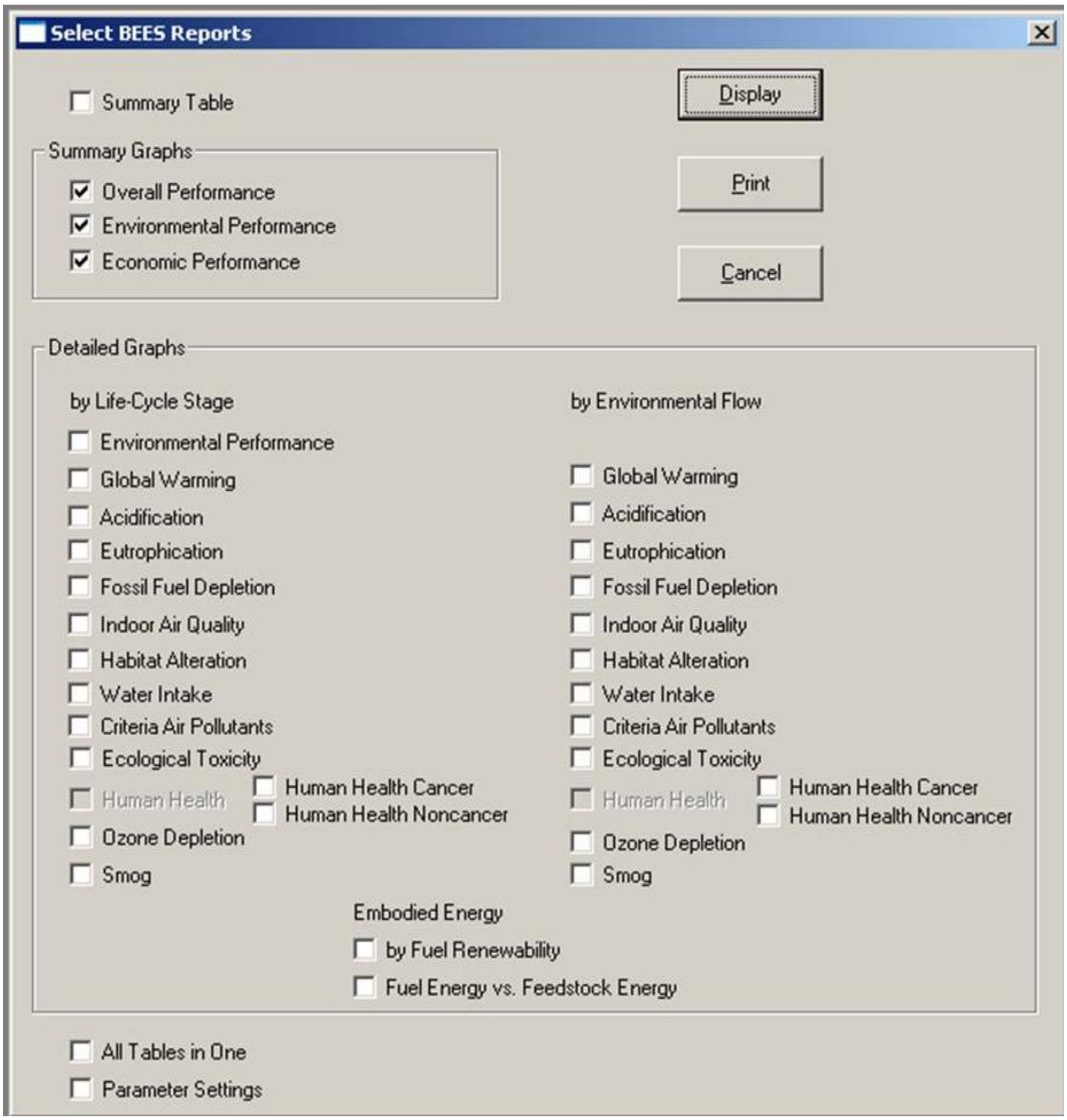
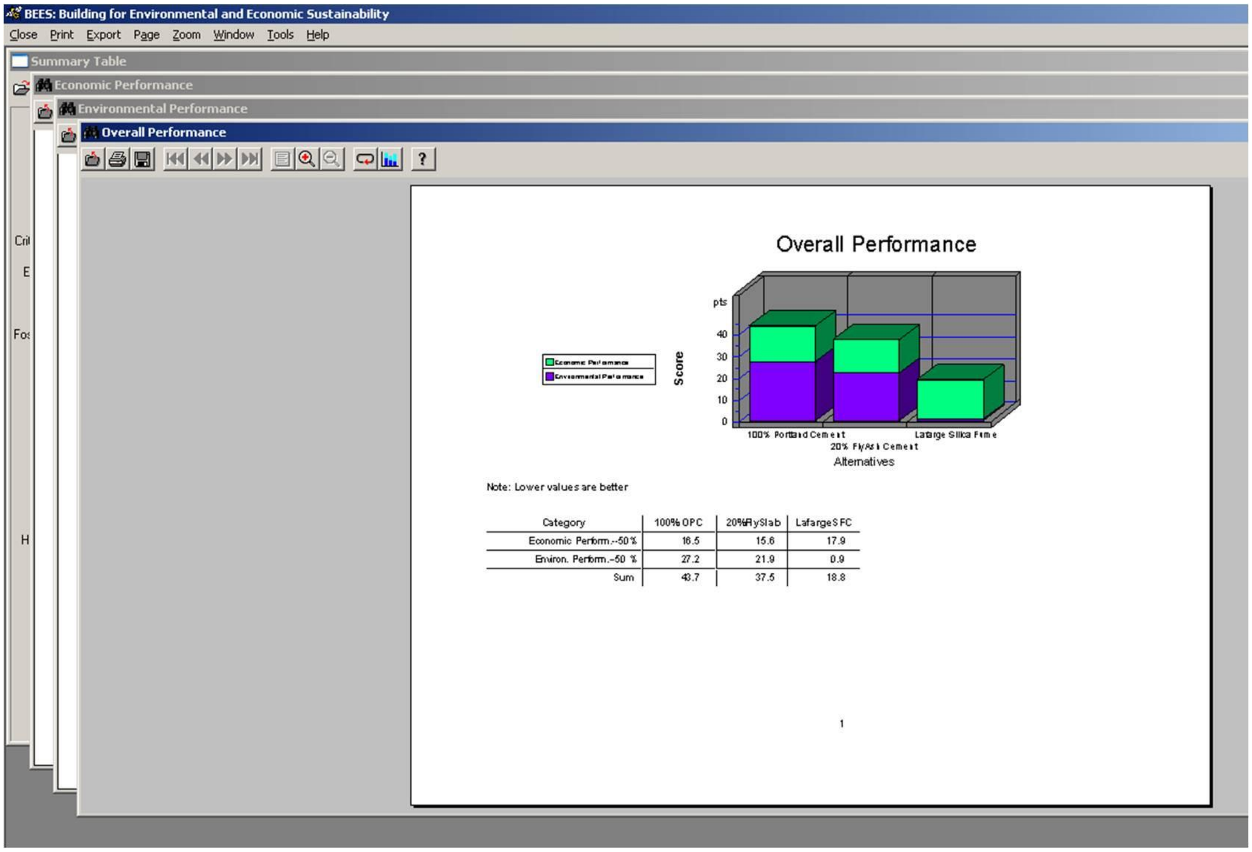


Figure 3-17. BEES screenshot showing sixth step of analysis: selecting tables and graphs to depict the product data.



Category	100% OPC	20%FlySlab	LafargeSFC
Economic Perform.–50 %	16.5	15.6	17.9
Environ. Perform.–50 %	27.2	21.9	0.9
Sum	43.7	37.5	18.8

Figure 3-18. BEES screenshot showing seventh step of analysis: final graphs and charts depicting performance of product comparisons.

CHAPTER 4
RESULTS

Introduction

The specific goals of this study were to determine an optimal mix for organic cement substitutes of fly ash, volcanic ash, and bone meal; to characterize the structural performance of the resulting concrete based on durability and compressive strength tests; and to characterize the impact of using the proposed concrete in building envelope performance against sustainability metrics and environmental performance using BEES (**B**uilding for **E**nvironmental and **E**conomic **S**ustainability) software life cycle approach. As stated in Chapter 3 Methodology, three concrete mixtures were prepared and each mix type was poured into a minimum of eight (8) cylinders of 4x8 inch size, resulting in a minimum total number of 24 cylinders. Any extra cylinders were used as potential replacements for broken test cylinders or if any problems arose during the testing.

Concrete Mix Design

A computerized mix design (Tables 4-1 and 4-2) commonly used in the concrete laboratory at the M.E. Rinker, Sr. School of Building Construction at the University of Florida was used to create the three batches yielding 2/3 cubic foot (cf) of concrete. This amount was enough concrete to pour into the required minimum of eight 4x8 inch cylinders for subsequent testing. Any extra concrete was poured into remaining cylinders as replacements. The desired compressive strength for the mix design was 3000 psi (a standard minimum in the construction industry for a laboratory setting) and the targeted air content was 2%. Standard uniform materials used in all three of the mixes were as follows: #67 coarse aggregate of 0.75 inch (85 lb/cf), fine aggregate sand with 2.09 fineness modulus, water content (W/C) ratio of 0.55, and 6.9cubic centimeters (cc) of water reducing admixture (Daracem 100) to speed up the curing process. Daracem 100 provides improved slump retention in flowable concrete and is ideal for low water/cement ratio concrete designed for high early compressive and flexural strengths with exceptional workability and flow characteristics.

Table 4-1. Computerized mix design used to create the three batches of concrete mixtures.

Properties	Amount
Required Compressive Strength (psi)	3000
Target Air Content	2
CA	
Nominal max size (inches)	0.75
Dry rodded unit weight/bulk density (lb/cf)	85.3
Gs	2.44
NMC (%)	2.5
ABS (%)	5.5
FA	
Fineness modulus	2.09
Gs	2.63
NMC (%)	4
ABS (%)	0.5
admixture (fl oz/100lbs cement)	3
w/c ratio	0.55
slump (inches)	4
water content (lbs)	340
CA content (cf CA/cf concrete)	0.69
Fly Ash	
amount replaced (%)	20.0
Gs	2.4
Cementitious materials (lbs)	618.2

Each of the mixes contained a uniform 20% amount of sustainable cement substitute. The percentages were determined by weight derived from the 2/3 cf concrete mixture in Table 4-2 and amounted to 3.0 lbs each.

Table 4-2. Recipe used to create 2/3 cubic foot (cf) of ‘green’ concrete.

Ingredient	Content
Cement (lbs)	12.2
Water (lbs)	8.6
CA (lbs)	40.2
FA (lbs)	30.4
‘green’ cement substitute (lbs)	3.0
water reducer (cc)	6.9

Three sets of 8 concrete cylinders were produced, one set of 20% fly ash concrete, one set of 20% volcanic ash concrete, and one set of 20% bone meal (MBM) concrete. The mixes consisted of the following cement substitutes with the following properties:

1. Fly ash (Figure 4-1) obtained from the M.E. Rinker, Sr. School of Building Construction concrete laboratory and Class F type, which is produced from Eastern U.S. coal plants and commonly used in Florida. Class F greatly reduces the risk of expansion due to sulfate attack that may occur in fertilized soils or near coastal areas, and produces a dense concrete with smooth surface.

Figure 4-1. Class F fly ash used in the lab tests.

2. Volcanic pumice ash obtained from a local pet store. Manufactured by Kaytee Company (Figure 4-2) and is a high quality, natural dusting

powder used for small pets. This product was chosen due to time constraints and since it was readily available in the local area.

Figure 4-2. Volcanic pumice ash obtained from local pet store.

3. Bone meal: Due to time and cost constraints in this study, Miracle Gro Organic Choice (Figure 4-3) was chosen as a cement substitute. Bone char cement substitute was not readily available and time constraints did not allow for it to be tested as a substitute. Bone meal however, is locally available at plant nurseries and is an all-natural phosphorous supplement to promote root and flower growth. It is enriched with iron for stronger, greener plants and allows for controlled-release nitrogen for plant feeding. Three pounds of bone meal were used in the experimentation according to the computerized mix design. During the curing process, the bone meal cylinders were weaker and easily broke apart when immersed in water, which was a result of high water content and also resulted in lower compressive and tensile strengths during testing. The specific mineral content of this product is also listed in Table 4-3.

Figure 4-3. Miracle Gro Organic Choice bone meal.

Table 4-3. Mineral composition of Miracle Gro Organic Choice bone meal (Fertilizer Product Information, 2009).

Mineral	% Content	Metal	Parts per Million (ppm)	Gypsum & Liming Materials	% Content
Nitrogen (N)	6.00	Arsenic	0.26	Calcium Carbonate ($CaCO_3$)	N/A
Phosphoric Acid (P_2O_5)	9.00	Cadmium	0.26	$CaCO_3$ Equivalent	N/A
Soluble Potash	N/A	Cobalt	1.30	Magnesium	N/A
(K_2O)	N/A	Mercury	0.0050	Carbonate($MgCO_3$)	N/A
Calcium (Ca)	N/A	Molybdenu	1.80	Calcium Sulfate	
Magnesium (Mg)	N/A	m	2.73	($CaSO_42H_2O$)	
Sulfur (S)	N/A	Nickel	0.58		
Boron (B)	N/A	Lead	1.29		
Chlorine (Cl)	N/A	Selenium	167.00		
Cobalt (Co)		Zinc			

Once poured into the 4x8 in. cylinder forms, the concrete was allowed to cure for 24 hours (Figure 4-5). After 24 hours all of the cylinders were placed together in a large metal tub of water (Figure 4-6) and allowed to cure, completely immersed, for an additional 28 days as per ASTM standards listed in Chapter 3 Methodology. It was initially noted however, that the bone meal concrete cylinders were still very moist after 24 hours of curing and were very fragile when immersing them in water. During the 28 day curing process, three of the nine bone meal cylinders broke down and disintegrated in the water, which resulted in fewer testable bone meal samples (only six versus the minimum of eight needed) for the compressive strength, tensile strength and water absorption tests.

Figure 4-4. The three sets of concrete cylinders curing for 24 hours.

Figure 4-5. The three sets of concrete cylinders curing for 28 days.

Concrete Testing Results: Wet Compressive Strength

Once the concrete cylinders were cured for 28 days, they were removed from the metal tub of water and inspected for cracking and any material problems. As noted before, three of the nine bone meal cylinders disintegrated in the water while the rest of the cylinders were intact. One cylinder from each batch was tested for wet compressive strength (Figure 4-7) while the remaining cylinders were placed in an oven (Figure 4-8) at 108 degrees Celsius for 48 hours to completely dry.

Figure 4-6. A bone meal concrete cylinder being tested for wet compressive strength.

Figure 4-7. Concrete cylinders drying in oven for 48 hours.

The results of the wet compressive strength of each of the concrete cylinders were as follows with compressive strength measured in pounds per square inch (psi):

Table 4-4. Max wet compressive strength of concrete cylinders achieved after 28 days of curing.

Mix No.	Sample ID	Diameter (inches)	Area (sq. in.)	Ultimate Stress (lbf)	Ultimate Stress (psi)
1	Volcanic Ash	4.0	12.57	27500	2190
1	Bonemeal	4.0	12.57	4230	336
1	Fly Ash	4.0	12.57	42100	3350
Average				20700	1650
SD				17390	1384

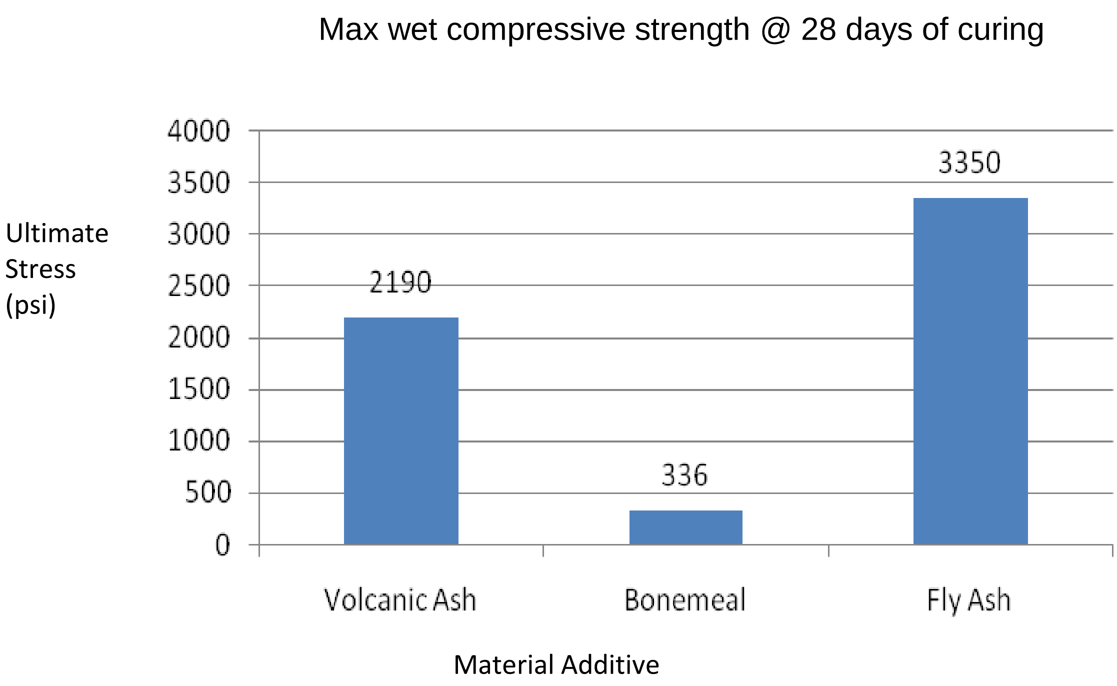


Figure 4-8. Graph of max wet compressive strength of concrete cylinders achieved after 28 days of curing.

As the graph shows, fly ash performed the best with 3350 psi, which achieved the minimum strength of 3000 psi as required by the computerized mix design. Bone meal performed the most poorly with only 336 psi. Volcanic ash performed well with 2190 psi but still did not achieve the minimum 3000 psi standard.

Concrete Testing Results: Dry Compressive Strength

After the remaining cylinders were allowed to dry for 48 hours, they were removed from the oven (Figure 4-10), allowed to cool for 2 hours, and three cylinders from each batch were tested for dry compressive strength (Figure 4-11) in the compression machine.

Figure 4-9. Concrete cylinders after removal from the oven.

Figure 4-10. A volcanic ash concrete cylinder being tested for dry compressive strength.

The results of the dry compressive strength testing are listed in the following table:

Table 4-5. Max dry compressive strength of concrete cylinders achieved after 28 days of curing.

Mix No.	Sample ID	Diameter (inches)	Area (sq. in.)	Ultimate Stress (lbf)	Ultimate Stress (psi)
1	Volcanic Ash 1	4.0	12.57	27600	2200
1	Volcanic Ash 2	4.0	12.57	29900	2380
1	Volcanic Ash 3	4.0	12.57	31700	2520
1	Bonemeal 1	4.0	12.57	16510	1314
1	Bonemeal 2	4.0	12.57	15660	1246
1	Bonemeal 3	4.0	12.57	5460	434
1	Fly Ash 1	4.0	12.57	47900	3810

1	Fly Ash 2	4.0	12.57	50800	4040
1	Fly Ash 3	4.0	12.57	52800	4200
AVG				23900	1902
SD				19170	1525

As the graph in Figure 4-11 shows, fly ash performed the best with an average compressive strength of 4017 psi and all three of the fly ash cylinders achieved the minimum strength of 3000 psi as required by the computerized mix design. Bone meal performed better than the wet compressive strength testing and achieved an average of 998 psi, but was still not close to the minimum 3000 psi desired. Volcanic ash performed well with an average compressive strength of 2367 psi but still did not achieve the minimum 3000 psi standard.

Max dry compressive strength @ 30 days of curing

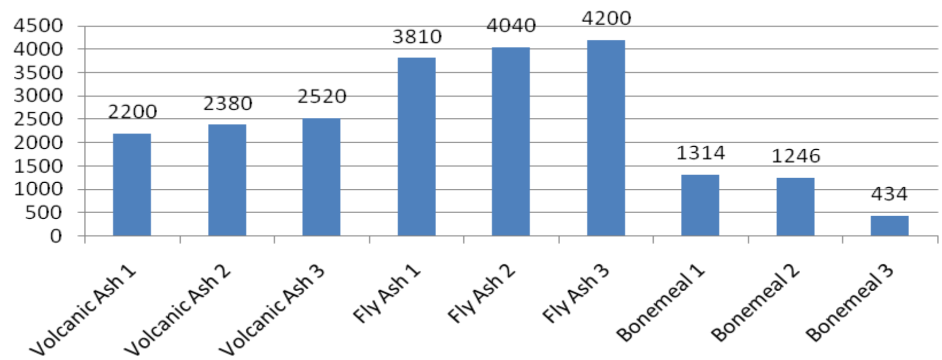


Figure 4-11. Graph of max dry compressive strength of concrete cylinders achieved after 28 days of curing.

Concrete Testing Results: Tensile Strength

After the remaining cylinders were allowed to dry for 48 hours, three cylinders from each batch were tested for tensile strength in the compression machine (Figure 4-13). However, two bone meal cylinders were not available for testing since they had disintegrated during the 28 day curing process. This allowed for only one bone meal cylinder to be tested and affected the data results

Figure 4-12. A volcanic ash concrete cylinder being tested for tensile strength.

The results of the tensile strength testing are listed in the following table:

Table 4-6. Max tensile strength (psi) and spitting tensile strength (f') of concrete cylinders achieved after 28 days of curing.

Mix No.	Sample ID	Diameter (inches)	Area (sq. in.)	Ultimate (lbf)	Ultimate Stress (psi)	f'
1	Volcanic Ash 1	4.0	12.57	12185	969	242.5
1	Volcanic Ash 2	4.0	12.57	16080	1279	320.1
1	Volcanic Ash 3	4.0	12.57	22780	1812	453.4
1	Bonemeal 1*	4.0	12.57	6940	552	138.1
1	Fly Ash 1	4.0	12.57	14105	1122	280.8
1	Fly Ash 2	4.0	12.57	25060	1994	498.8
1	Fly Ash 3	4.0	12.57	12285	977	244.5

* Only one bonemeal cylinder was available for testing due to disintegration of remaining bonemeal cylinders during curing process.

The maximum load at failure for each cylinder was recorded and listed in Table 4-6 under "Ultimate" and measured in pounds per foot (lbf). The splitting tensile strength was calculated with the formula from Chapter 3 Methodology and listed as f'. As the table shows, fly ash again performed the best with an average splitting tensile strength of 341 while volcanic ash was close behind with an average of 339. Bone meal performed the most poorly and achieved a single result of 138 since no other cylinders were available for testing.

Concrete Testing Results: Water Absorption

After the remaining cylinders were allowed to dry for 48 hours, one cylinder from each batch was tested for water absorption in the laboratory according to ASTM standards listed in Chapter 3 Methodology. The test method was used to determine the rate of absorption (sorptivity) of water by measuring the increase in the mass of the specimens as a function of time when only one surface of the specimen was exposed to water. The exposed surface of the specimen was immersed in water (Figure 4-15) with a simple mesh wire device. The density of the specimens were measured at intervals of 5 minutes, 10 minutes, 20 minutes, 1 hour and 2 hours and each time the specimens were removed from the water and weighed on an electronic scale (Figure 4-16), then returned to the water.

Figure 4-13. The tray and chicken wire apparatus used to test the hardened concrete specimens for water absorption.

Figure 4-14. Concrete cylinders after exposure to water and being weighed on electronic scale for water absorption.

The results of the water absorption testing are listed in the following table:

Table 4-7. Weight of concrete cylinders after intervals of 5 minutes, 10 minutes of water immersion.

Mix No.	Sample ID	Diameter (inches)	Area (sq. in.)	Dry Weight (g)	Weight @ 5 min (g)	Weight @ 10 min (g)
1	Volcanic Ash 1	4.0	12.57	3398	3402	3403
1	Bonemeal 1	4.0	12.57	2612	2614	2614
1	Fly Ash 1	4.0	12.57	3273	3281	3283

Table 4-8. Weight of concrete cylinders after intervals of 20 minutes, 1 hour and 2 hours of water immersion.

Mix No.	Sample ID	Weight @ 20 min (g)	Weight @ 1 hr (g)	Weight @ 2 hrs (g)	Total increase (g)	% Increase
1	Volcanic Ash 1	3405	3406	3407	9	0.26%
1	Bonemeal 1	2613	2614	2612	0	0.00%
1	Fly Ash 1	3286	3298	3312	39	1.19%

The results of the water absorption testing are depicted in the following graph:

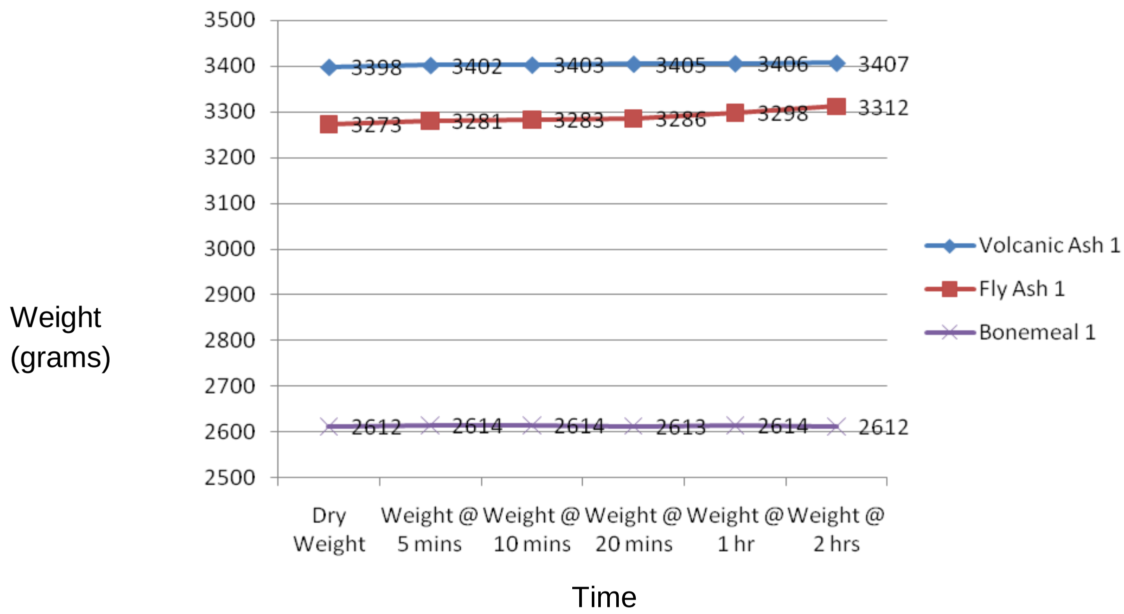


Figure 4-15. Graph depicting water absorption of concrete cylinders at specified time intervals.

The results of the water absorption testing show that fly ash had the greatest absorption and change in mass of 39 grams over the total 2 hour period. Volcanic ash followed with only 9 grams, and finally bone meal with 0 grams change in mass over the 2 hour period. The value of absorption (I) was then determined through the following equation described in Chapter 3 Methodology:

$$I = mt / (a * d) \quad \text{where } mt = \text{the change in mass in grams, at different time } (t) \qquad (4\text{-}1)$$

a = exposed area of the specimen, cm^2 (12.57 sq. in. = 81.1 sq. cm.).
d = density of water in g/cm^3 (0.999 g/cm^3 @ 65 degrees F).

1. For fly ash, the value of absorption I was calculated as follows:

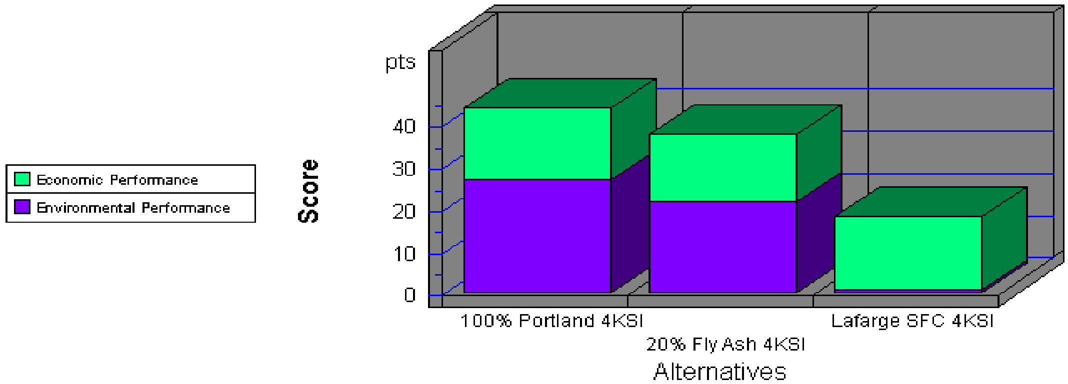
   I = (39 grams * 120 minutes) / (81.1 sq. cm. * 0.999) = 57.8
2. For volcanic ash, the value of absorption I was calculated as follows:

   I = (9 grams * 120 minutes) / (81.1 sq. cm. * 0.999) = 13.3
3. For bone meal, the value of absorption I was calculated as follows:

   I = (0 grams * 120 minutes) / (81.1 sq. cm. * 0.999) = 0

Environmental Impact Assessment: BEES Results

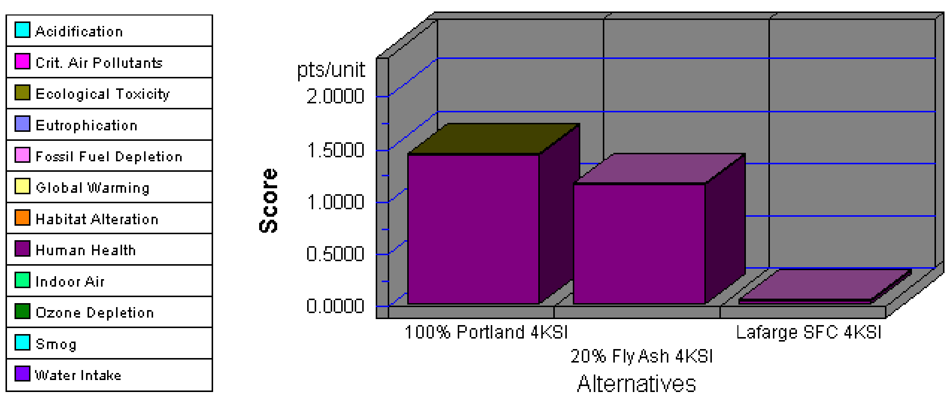
The final stage of the data analysis consisted of determining the environmental and economic performance (Figures 4-16 to 4-18) of the 20% alternative concrete materials by comparing them to typically used concrete mixes of 100% portland cement and silica fume concrete. (Silica fume is an industrial byproduct of electric furnaces and is sold as a mineral admixture in concrete. It consists primarily of silicon dioxide (SiO_2) whose particles are approximately 1/100th the size of an average cement particle. Because of its fine particles, large surface area, and the high SiO_2 content, silica fume is a very reactive pozzolan when used in concrete). The data was derived using BEES software and was entered into the program as a substructure or foundation slab material for comparison purposes. Concrete of this type would typically be used in sub-structure or foundation slabs in developing countries since many structures are no more than 2 stories in height.



Note: Lower values are better

Category	**100% OPC**	**20%FlyBeam**	**LafargeSFC**
Economic Perform.--50%	16.7	15.9	17.4
Environ. Perform.--50 %	27.1	21.8	1.0
Sum	43.8	37.7	18.4

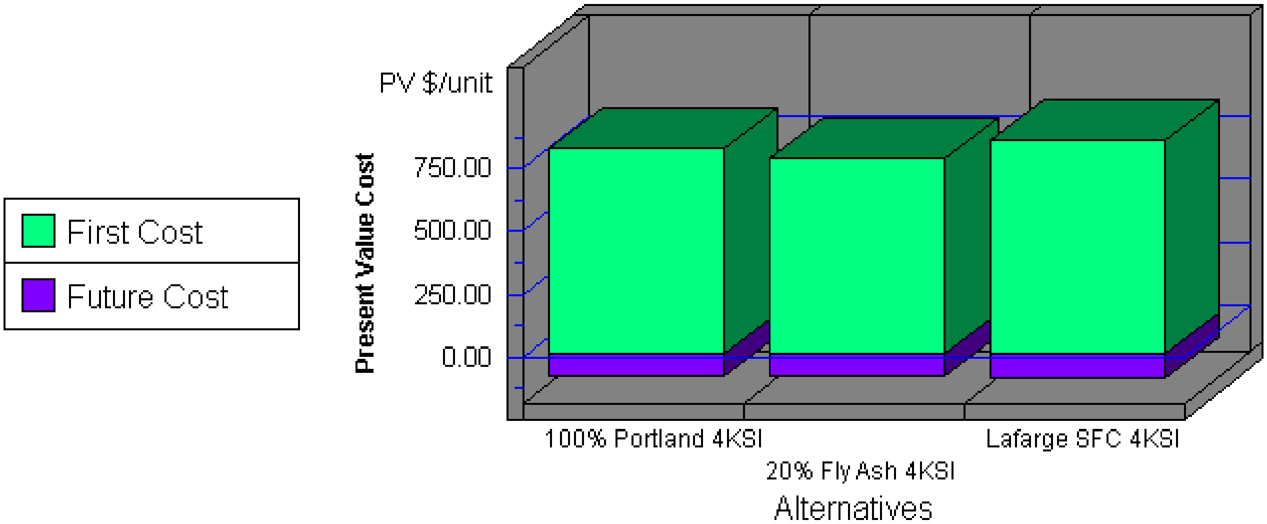
Figure 4-16. BEES overall performance results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

Category	**100% OPC**	**20%FlyBeam**	**LafargeSFC**
Acidification--9%	0.0000	0.0000	0.0000
Crit. Air Pollutants--8%	0.0017	0.0016	0.0017
Ecolog. Toxicity--8%	0.0102	0.0089	0.0091
Eutrophication--9%	0.0021	0.0020	0.0021
Fossil Fuel Depl.--9%	0.0034	0.0032	0.0034
Global Warming--9%	0.0059	0.0053	0.0083
Habitat Alteration--8%	0.0000	0.0000	0.0000

Figure 4-17. BEES environmental performance results of 100% portland cement (baseline), 20% fly Ash, and silica fume mixes.



Category	100% OPC	20%FlyBeam	LafargeSFC
First Cost	814.49	775.97	845.41
Future Cost-- 3.0%	-92.90	-88.50	-96.42
Sum	721.59	687.47	748.99

Figure 4-18. BEES economic performance results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.

CHAPTER 5
DISCUSSION AND CONCLUSIONS

Summary

It was determined through the course of this study that in order to combat ecosystem destruction and the effects of increased amounts of carbon and toxins in the earth's atmosphere through the burning of fossil fuels, developing economies must preserve their natural resources and native ecosystems. These countries must use alternative sources of fuel as well as sustainable, local building materials to lower carbon output and preserve local resources. The key issues in promoting and utilizing sustainable building materials and practices in these countries were found to be: availability, cost, and durability of local materials. Local materials are crucial to the sustainable construction of commercial buildings and residential homes. Existing practices in the manufacturing of traditional portland cement concrete and existing studies about new forms of sustainable cement substitutes were reviewed, particularly animal meat waste products like bone char and bone meal. Three sustainable cement substitutes (fly ash, volcanic ash, bone meal) were then mixed and poured into eight (8) cylinders of 4 x 8 inch size for each mix type, resulting in a total number of minimum 24 cylinders. The concrete cylinders were allowed to cure for 28 days and then tested by the ASTM standards for compressive strength, tensile strength and water absorption and data results were obtained and analyzed. The resulting concrete material types were then tested for environmental and economic performance based on BEES (Building for Environmental and Economic Sustainability) software which measures the performance of building products by using the life-cycle assessment approach.

Discussion

This discussion will refer to the aims and objectives of the study listed in Chapter 1 and determine how the aims and objectives were achieved.

Green Cement Substitutes

1. To review existing practices with respect to green cement substitutes in developed and developing countries.

This objective was reached through the extensive review of existing literature in Chapter 2. Recent studies about green cement substitutes, current practices in the manufacture of concrete in developed economies, and existing information and studies about the mineral composition and usage of animal bone char and bone meal were presented.

Potential for Bone Char, Fly Ash, and Volcanic Ash as Cement Substitutes

2. To determine the potential for using animal bone char, fly ash, and volcanic ash as substitutes for portland cement in the manufacture of 'green' concrete.

Due to time and cost constraints in this study, Miracle Gro Organic Choice bone meal was chosen as a substitute for actual bone char cement substitute. It is locally available at plant nurseries and is an all-natural phosphorous supplement to promote root and flower growth. It is enriched with iron for stronger, greener plants and allows for controlled-release nitrogen for plant feeding. However, it was also noted during the testing that this material is a porcine based product which does not use cow parts. This may have affected the mineral content of the bone meal mixture, since typical cow based bone meal contains approximately 30% calcium. The amount of minerals found in the product (listed previously in Table 4-3) were listed by the manufacturer (Miracle

Gro) and calcium, a key ingredient in the concrete curing process, was not one of the minerals listed. This may have been an oversight by the manufacturer or perhaps the actual amount of calcium in porcine-based bone meal is negligible due to the lack of cow bones in the mixture. Additionally, the manufacturer did not list calcium carbonate $CaCO_3$ as an ingredient, which would also affect the curing strength of the concrete since calcium carbonate is a key ingredient and bonding agent in portland cement. Bone char is still a very good potential cement substitute since it contains a high amount of $CaCO_3$ and its strength and durability should be tested in a laboratory setting when time and cost constraints are not a factor.

Materials Performance Testing

3. To characterize the material properties performance of the resulting concrete based on durability, compressive strength and tensile strength tests.

Three pounds of bone meal was used in the experimentation according to the computerized mix design. During the curing process, the bone meal cylinders were weaker and easily broke apart when immersed in water, which was a result of high water content. This also resulted in lower compressive and tensile strengths during testing.

Bone meal material as a cement substitute did not meet the desired targets in terms of compressive strength, tensile strength and water absorption. Bone meal failed to reach the minimum 3000 psi during wet and dry compressive strength testing, was outperformed by fly ash and volcanic ash in tensile strength testing, and had zero water absorption during testing. This is perhaps due to the high moisture content of the bone meal concrete mixture evidenced during the 28 day curing process when three of the bone meal cylinders easily broke apart when immersed in water.

Bone meal may be a desirable cement substitute with less than 20% material added to the mixture, as is the case with 5% limestone additive in portland cement. However, the lack of calcium carbonate ($CaCO_3$) in bone meal may negate any effects of reducing the material mixture since $CaCO_3$ is an effective bonding agent in the curing process. Bone char is still a very good potential cement substitute since it contains a high amount of $CaCO_3$ and its strength and durability should be tested in a laboratory setting when time and cost constraints are not a factor.

BEES Building Envelope Performance

4. To characterize the impact of using the proposed concrete in building envelope performance against sustainability metrics using BEES (Building for Environmental and Economic Sustainability) software.

Several data comparisons and graphs were obtained through the BEES software in terms of Overall Performance (Figure 4-18), Environmental Performance, and Economic Performance. Since the BEES software does not contain specific materials data on volcanic ash, bone char, and bone meal cement substitutes, the fly ash data had to be used and compared to 100% portland cement and silica fume concrete baselines with 4000 psi compressive strengths. Additional graphs and data showing more specific comparisons through BEES software in areas of global warming, ecological toxicity, fossil fuel depletion, human health and embodied energy were also obtained and are listed in Appendix A.

In terms of overall performance, 20% fly ash as an cement substitute material fared well compared to 100% portland cement and silica fume concrete. According to

BEES, silica fume concrete had by far the best environmental performance (Figure 4-19) with a score of only 1.0 (lower scores are better), while 20% fly ash scored 21.8 and 100% portland cement scored an even higher 27.1 points. Fly ash scored the best in terms of economic performance (Figure 4-20) with a rating of 15.9, while portland cement scored 16.7 and silica fume scored the worst with 17.4 points. Fly ash had lower first costs and future costs than either of its competitors.

Conclusions

A number of conclusions can be made from the results of this study. Sharing knowledge of 'green' building materials and practices, particularly with the manufacturing and usage of concrete, may have positive economic effects in developed as well as developing countries.

The standard uses of portland cement concrete in the developed world for construction projects must be replaced with alternative cement substitutes like fly ash, volcanic ash, silica fume, and other organic materials in order to minimize embodied energy, fossil fuel depletion, environmental damage and to reduce costs.

Bone meal material as a cement substitute did not meet the desired targets in terms of compressive strength, tensile strength and water absorption. Bone meal failed to reach the minimum 3000 psi during wet and dry compressive strength testing, was outperformed by fly ash and volcanic ash in tensile strength testing, and had zero water absorption during testing. This is perhaps due to the high moisture content of the bone meal concrete mixture evidenced during the 28 day curing process when the bone meal cylinders easily broke apart. Bone meal may be a desirable cement substitute with less than 20% material added to the mixture.

Twenty percent fly ash material as a cement substitute has improved environmental and economic performance compared to 100% portland cement concrete and can be considered a 'green' material for its cost effectiveness and diverting of an industrial byproduct from landfilling. However, it is far out-performed by silica fume concrete according to the BEES data comparisons in environmental impacts.

Bone char is still a very good potential cement substitute since it contains a high amount of $CaCO_3$ and its strength and durability should be tested in a laboratory setting.

Simple water absorption tests executed carefully in the laboratory can identify the effect of material cement substitutes on the water absorption of building materials, specifically 'green' concrete.

Further Research

Through the course of this study, several opportunities for further research were noted to expand the amount of data for 'green' concrete materials used in the construction industry. Specifically, further environmental impact assessment data using BEES software is needed for organic cement substitutes and alternatives to portland cement concrete. BEES data showing environmental and economic impacts of alternative cement substitutes like bone meal, fiberglass, volcanic ash is needed to aid in comparisons of 'green' building materials. The environmental performance of alternative cement substitutes can also be further studied through the Environmental Protection Agency's (EPA) (TRACI) tool. Building occupancy phase (durability and energy efficiency) performance can also be measured and predicted in terms of sustainable by using Oak Ridge National Laboratory's (WUFI) model for moisture and heat transfer through walls. The material properties of 'green' cement substitutes can also be further researched through rigorous laboratory experimentation and analysis by ASTM standards for compressive strength, moisture absorption (as used in this study) and also through studies of air tightness (pore structure analysis);

Additionally, due to the lack of research and few testing results of bone meal and bone char cement substitutes, these materials can be considered environmentally friendly in concrete mixes due to their organic and renewable content. These materials warrant further durability testing for concrete with less than 20% bone meal cement substitute and a lower moisture content. It is also recommended that further water absorption tests follow ASTM C1585 and use the device in Figure 5-1 to test ‘green’ concrete specimens.

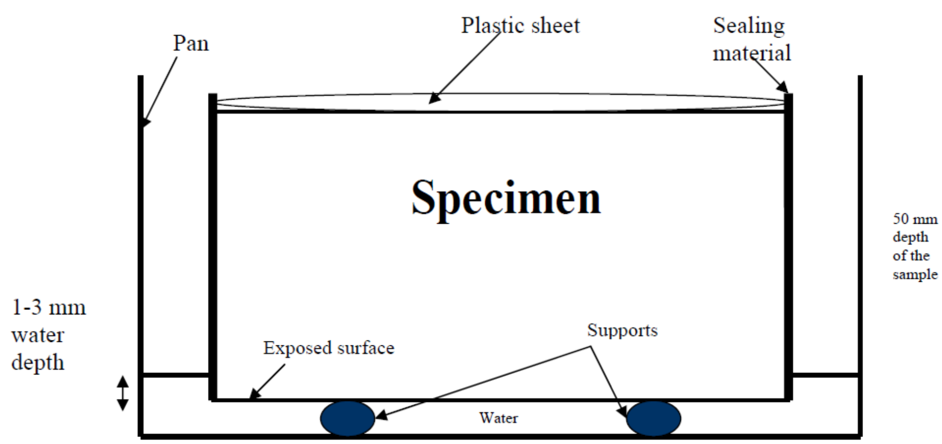
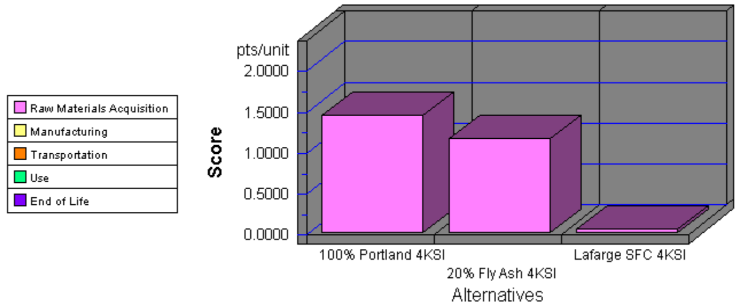


Figure 6-1. Schematic diagram of ASTM C1585 testing procedure.

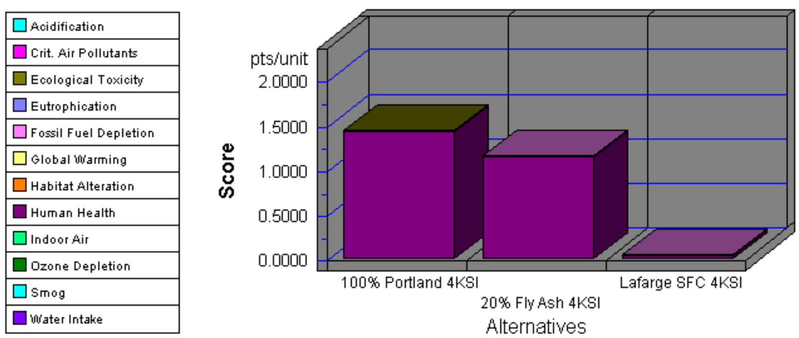
APPENDIX: ADDITIONAL BEES DATA RESULTS



Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
1. Raw Materials	1.4384	1.1568	0.0498
2. Manufacturing	0.0000	0.0000	0.0000
3. Transportation	0.0057	0.0057	0.0057
4. Use	0.0000	0.0000	0.0000
5. End of Life	0.0000	0.0000	0.0000
Sum	1.4441	1.1625	0.0555

Figure A-1. BEES environmental performance by life cycle stage results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.

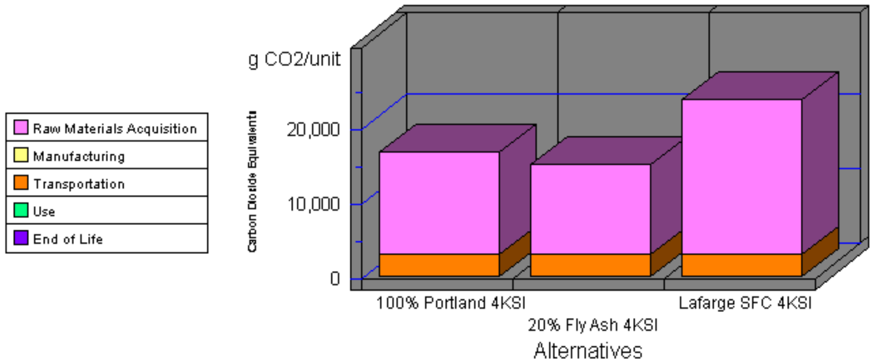


Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
Acidification--9%	0.0000	0.0000	0.0000
Crit. Air Pollutants--8%	0.0017	0.0016	0.0017
Ecolog. Toxicity--8%	0.0102	0.0089	0.0091
Eutrophication--9%	0.0021	0.0020	0.0021
Fossil Fuel Depl.--9%	0.0034	0.0032	0.0034
Global Warming--9%	0.0059	0.0053	0.0083
Habitat Alteration--8%	0.0000	0.0000	0.0000

Press PageDown for more results...

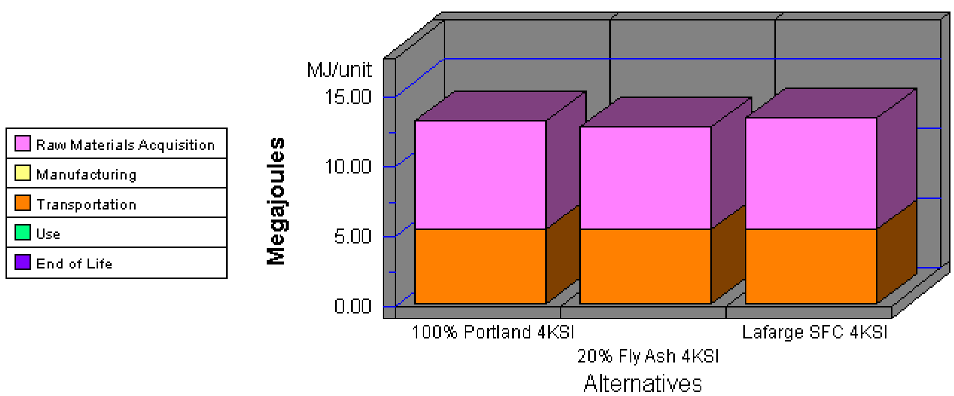
Figure A-2. BEES specific environmental performance results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
1. Raw Materials	13582	11889	20569
2. Manufacturing	0	0	0
3. Transportation	3057	3057	3057
4. Use	0	0	0
5. End of Life	0	0	0
Sum	16639	14946	23626

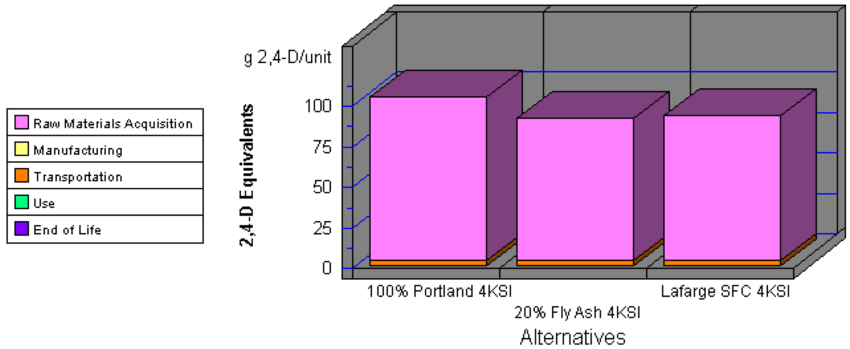
Figure A-3. BEES global warming by life cycle stage results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
1. Raw Materials	7.8240	7.3522	8.0447
2. Manufacturing	0.0000	0.0000	0.0000
3. Transportation	5.3202	5.3202	5.3202
4. Use	0.0000	0.0000	0.0000
5. End of Life	0.0000	0.0000	0.0000
Sum	13.1442	12.6724	13.3649

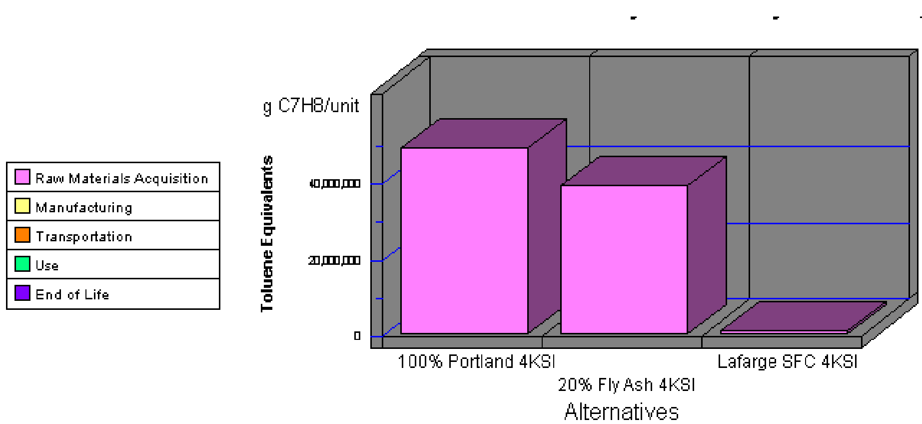
Figure A-4. BEES fossil fuel depletion by life cycle stage results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
1. Raw Materials	99.64	86.55	88.37
2. Manufacturing	0.00	0.00	0.00
3. Transportation	4.00	4.00	4.00
4. Use	0.00	0.00	0.00
5. End of Life	0.00	0.00	0.00
Sum	103.64	90.55	92.36

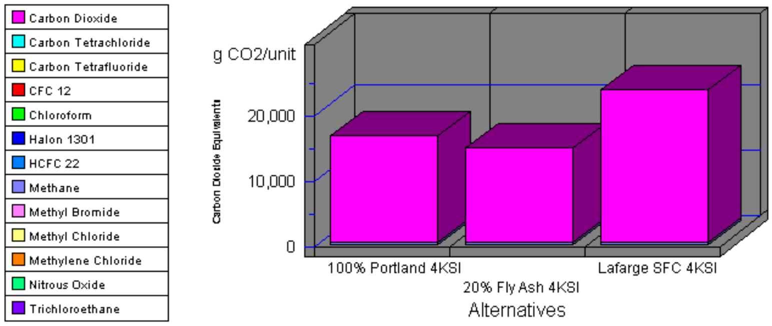
Figure A-5. BEES ecological toxicity by life cycle stage results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
1. Raw Materials	48,561,058.39	38,986,298.70	856,052.24
2. Manufacturing	0.00	0.00	0.00
3. Transportation	30,651.99	30,651.99	30,651.99
4. Use	0.00	0.00	0.00
5. End of Life	0.00	0.00	0.00
Sum	48,591,710.38	39,016,950.69	886,704.23

Figure A-6. BEES human health by life cycle stage results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.

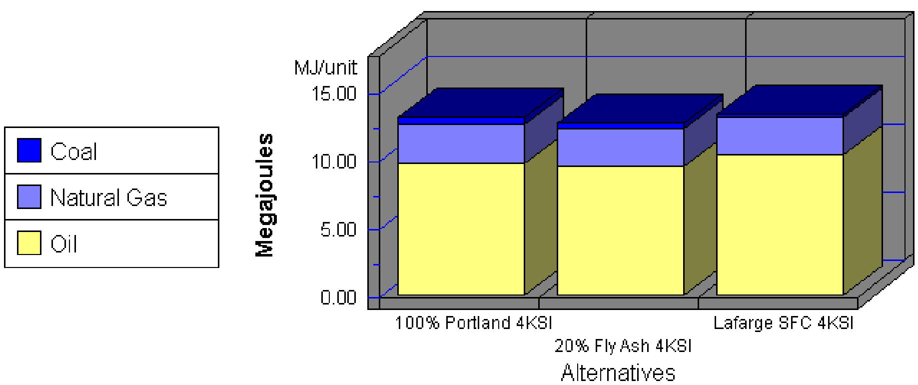


Note: Lower values are better

Category	100% OPC	20%FlyBeam	LafargeSFC
(a) Carbon Dioxide (CO2, net)	16209	14509	23209
(a) Carbon Tetrachloride (CCl4)	0	0	0
(a) Carbon Tetrafluoride (CF4)	0	0	0
(a) CFC 12 (CCl2F2)	0	0	0
(a) Chloroform (CHCl3, HC-20)	0	0	0
(a) Halon 1301 (CF3Br)	0	0	0
(a) HCFC 22 (CHF2Cl)	0	0	0
(a) Methane (CH4)	386	354	363
(a) Methyl Bromide (CH3Br)	0	0	0

Press PageDown for more results...

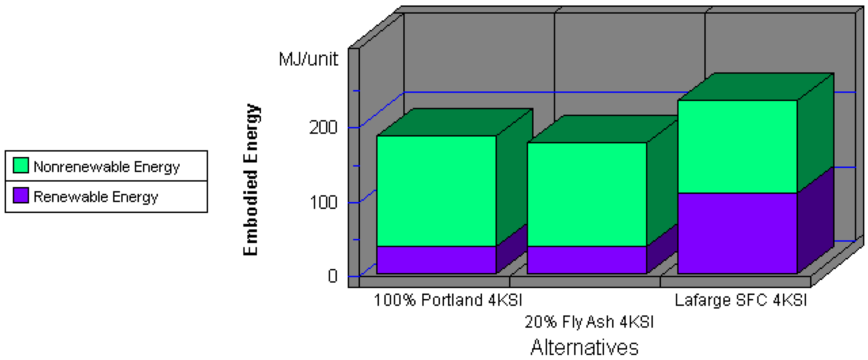
Figure A-7. BEES global warming by flow results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Note: Lower values are better

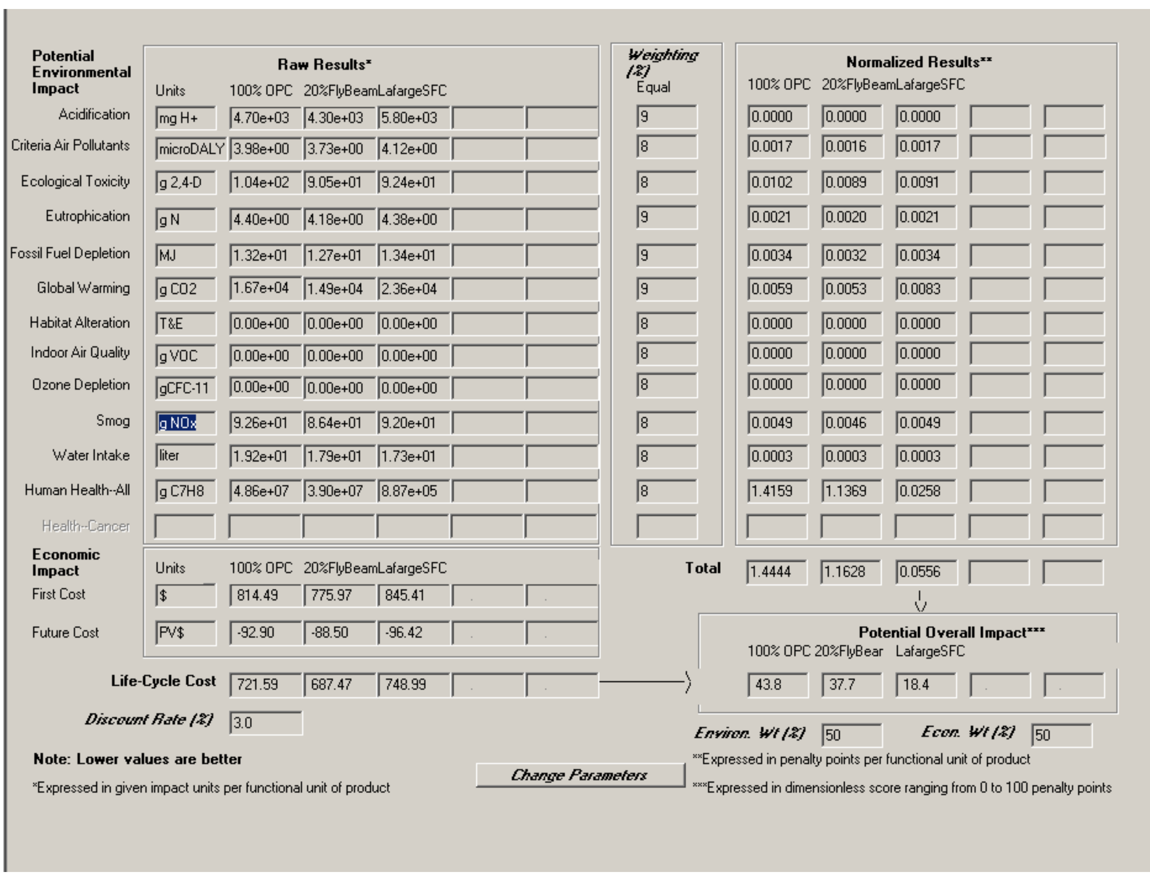
Category	100% OPC	20%FlyBeam	LafargeSFC
(r) Coal (in ground)	0.5013	0.4409	0.2773
(r) Natural Gas (in ground)	2.9098	2.7616	2.6836
(r) Oil (in ground)	9.7369	9.4738	10.4040
Sum	13.1480	12.6763	13.3649

Figure A-8. BEES fossil fuel depletion by flow results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Category	100% OPC	20%FlyBeam	LafargeSFC
Nonrenewable Energy	147.40	138.40	124.90
Renewable Energy	38.30	38.30	109.05
Sum	185.70	176.70	233.95

Figure A-9. BEES embodied energy by fuel renewability results of 100% portland cement (baseline), 20% fly ash, and silica fume mixes.



Potential Environmental Impact	Units	Raw Results* 100% OPC	20%FlyBeam	LafargeSFC	Weighting (%) Equal	Normalized Results** 100% OPC	20%FlyBeam	LafargeSFC
Acidification	mg H+	4.70e+03	4.30e+03	5.80e+03	9	0.0000	0.0000	0.0000
Criteria Air Pollutants	microDALY	3.98e+00	3.73e+00	4.12e+00	8	0.0017	0.0016	0.0017
Ecological Toxicity	g 2,4-D	1.04e+02	9.05e+01	9.24e+01	8	0.0102	0.0089	0.0091
Eutrophication	g N	4.40e+00	4.18e+00	4.38e+00	9	0.0021	0.0020	0.0021
Fossil Fuel Depletion	MJ	1.32e+01	1.27e+01	1.34e+01	9	0.0034	0.0032	0.0034
Global Warming	g CO2	1.67e+04	1.49e+04	2.36e+04	9	0.0059	0.0053	0.0083
Habitat Alteration	T&E	0.00e+00	0.00e+00	0.00e+00	8	0.0000	0.0000	0.0000
Indoor Air Quality	g VOC	0.00e+00	0.00e+00	0.00e+00	8	0.0000	0.0000	0.0000
Ozone Depletion	gCFC-11	0.00e+00	0.00e+00	0.00e+00	8	0.0000	0.0000	0.0000
Smog	g NOx	9.26e+01	8.64e+01	9.20e+01	8	0.0049	0.0046	0.0049
Water Intake	liter	1.92e+01	1.79e+01	1.73e+01	8	0.0003	0.0003	0.0003
Human Health--All	g C7H8	4.86e+07	3.90e+07	8.87e+05	8	1.4159	1.1369	0.0258
Health--Cancer								
Total						1.4444	1.1628	0.0556

Economic Impact	Units	100% OPC	20%FlyBeam	LafargeSFC
First Cost	$	814.49	775.97	845.41
Future Cost	PV$	-92.90	-88.50	-96.42
Life-Cycle Cost		721.59	687.47	748.99

Discount Rate (%) 3.0

Potential Overall Impact***	100% OPC	20%FlyBear	LafargeSFC
	43.8	37.7	18.4

Environ. Wt (%) 50   Econ. Wt (%) 50

Note: Lower values are better

Change Parameters

*Expressed in given impact units per functional unit of product

**Expressed in penalty points per functional unit of product

***Expressed in dimensionless score ranging from 0 to 100 penalty points

Figure A-10. BEES summary results of 100% portland cement (baseline), 20% fly ash, and silica fume.

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BIOGRAPHICAL SKETCH

Christian B. Terrell was born in San Francisco, California into a military family and has lived throughout the United States and in Puerto Rico. In 2001 he was awarded a Bachelor's Degree in Architecture from the University of Pennsylvania and was commissioned an officer in the U.S. Army. Christian served on active duty in the U.S. Army as an AH-64 pilot in scenic places in the United States and overseas. He has worked for international architecture firms on a variety of projects and earned a Master of Science in Building Construction from the University of Florida in May 2010. Christian plans to become a leading design-builder in the construction industry, focusing on sustainable building practices.