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Benefit-Cost Analysis Of Using Class F Fly Ash-Based Green Cement In Masonry Units

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BENEFIT-COST ANALYSIS OF USING CLASS F FLY ASH-BASED GREEN CEMENT IN MASONRY UNITS

by

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DISSERTATION

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DEDICATION

**I would like to dedicate my thesis
to my beloved parents, my wife, my sons, my brothers, and my sisters**

ACKNOWLEDGEMENTS

First of all, I would like to express my deep grateful thanks to ALLAH for all his bounties that cannot be countable. Then, the conducting of my dissertation came with inexhaustible support, guidance, patience, and continues encouragement of many people who I would like to thank:

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CHAPTER 1 INTRODUCTION AND OVERVIEW

1.1 Background

From 2007 to 2010, the consumption of cement has decreased, which is believed to be because of the mortgage foreclosure crisis, which decreased residential construction spending activity (ENR, Construction Economics section, 2012). However, in 2011, the consumption of cement began to increase, and in addition to this, the price of cement has been increasing as well. In December 2011, the price of cement was $101.88 /ton, $110.00/ton in December of 2012, and reached $114.49/ton in May of 2015 (ENR, Construction Economics section, 2015). Portland cement concrete is one of the most popularly used building materials around the world. However, even being as popular as it is, some disadvantages of Portland cement are still hard to overcome. In general, there are four major drawbacks associated with Portland cement: (1) Energy consumption. “Cement production is one of the most energy intensive of all industrial manufacturing processes” (Wilson, 1993). (2) Emission of greenhouse gases. About one ton of carbon dioxide (CO_2) is released into the environment for one ton of cement production (Wilson, 1993, Davidovits, 2002). (3) “Portland cement concrete may deteriorate when exposed to severe environments, such as sulfate, acid, sea water, and other chemically corrosive” (Mindess, 1981). (4) Poor high-temperature resistance (Xiao et al, 2004; Sun, 2005). Those in the Portland cement industry know that they have to find more environmentally friendly solutions that comply with sustainable development concepts. A competitor for Portland cement, green cement, is the perfect candidate for both the inherent sustainability it presents, along with being more environmentally friendly. In addition, structures made from green cement may require less maintenance than those constructed with Portland cement concrete, because of better durability and the higher temperature/fire resistance of green cement (Sun, 2005). As a result, the lifetime cost of green cement structures may be significantly less when compared with Portland cement concrete structures. A potential application of green cement is investigated in this dissertation based on the market needs and its advantages over Portland cement. Portland cement concrete has many intrinsic disadvantages that can only be overcome by replacement with new materials, such as green cement. As a case in point, fly ash-based green cement may be a very good candidate for replacing cement in the making of masonry units (Sun, 2005). Nevertheless, the cost benefits of green cement must be quantified. Therefore, a benefit-cost analysis should be considered for enhancing the use of fly ash-based green cement.

Fly ash, a waste byproduct material, can be recycled into making value-added products, in terms of both production quantity and influence on the environment. More than 70 million tons of fly ash is produced in the United States each year. Only about 40% is beneficially utilized, and over 40 million tons of fly ash goes to waste, filling up the nation's landfills (American Coal Ash Association 2005). Therefore, using fly ash-based green cement masonry units, rather than concrete masonry units for infrastructure, has at minimum the following advantages: lower energy consumption, environmental protection, and better durability. The raw materials and mix used in this study were selected from a previous study (Wu et al. 2010). The materials include class F fly ash, silica fume, metakaolin, sodium hydroxide (NaOH) flakes, water, and fine sand (Fly Ash-Based Green Cement).

The benefit-cost analysis is required for promoting fly ash-based green cement materials. Benefit-cost analysis is simply rational decision-making. However, there is a need for formal techniques to keep our thinking clear, systematic, and rational, especially when the alternatives are too complex or the data uncertain. These techniques constitute a model for doing benefit-cost analysis. They include a variety of methods including: identifying and examining alternatives, defining alternatives in a way that allows for fair comparison, calculating and placing a dollar value on issues that regularly do not have a monetary value present, and conducting sensitivity and risk analysis on the parameters in the benefit-cost analysis model.

1.2 Objective and Scope

The objective of this study was to promote recycling fly ash into high performance construction materials by using fly ash-based green cement in the making of masonry units. Three goals took priority in this study: 1-Study the compressive strength of fly ash-based green cement mortar in order to meet the requirements of compressive strength standards for masonry units. 2-Evaluate the performance of durability present in fly ash-based green cement specimens, when subjected to weathering. Actual durability test results from a Freeze-Thaw test, and a Thermal Cycle test, are used in this research. Therefore, reliable information can be compiled and used in this study. Finally, 3- Conduct a benefit-cost analysis of using fly ash-based green cement in the making of masonry units, versus the use of Portland cement.

1.3 Need and Significance

In this section, there will be two basic concepts discussed in terms of: 1- Significance of recycling industry by-products, and 2- Significance of applying fly ash-based green cement to civil engineering.

Though Portland cement concrete is widely used in building materials around the world, Portland cement concrete has many intrinsic disadvantages that can only be overcome by being replaced with new materials such as fly ash-based green cement. In general, many of the aspects of the cement making process are potentially environmentally damaging (Xiao et al, 2004). Portland cement manufacturing can cause environmental impacts at all stages of the process. These include emissions of airborne pollution in the form of dust, gases, noise and vibration when operating machinery and during blasting in quarries, consumption of large quantities of fuel during manufacture, the release of CO_2 from the raw materials during manufacture, and damage to the countryside from quarrying (Xiao et al, 2004). In addition, Sulfur Dioxide exposure in Portland cement plants (SO_2) has a negative impact especially on those who work at Portland cement facilities (Mindess, 1981). Furthermore, Portland cement has poor high-temperature resistance (Xiao et al, 2004) and it may deteriorate when exposed to severe environments (Mindess, 1981).

According to the U.S. Energy Information Administration, almost one half of our nation's electricity is generated by burning coal (US EIA, 2012). Fly ash is discharged from coal-burning power plants throughout the world every day. Therefore, there are many good reasons to view fly ash as a resource, rather than a waste product. Recycling fly ash conserves natural resources and saves energy when it replaces raw materials through recycling. In many cases, products made with coal ash perform better than products made without it in terms of strength, durability (American Coal Ash Association, 2011). In the nearly 7 billion square feet of masonry walls produced yearly in North America (American Institute of Architects, 2008). Hence, if we were to replace concrete masonry with green cement masonry there would be a significant amount of saving energy, avoiding greenhouse gases (GHG) emissions, and reducing natural resource of raw material for cement manufacture such as limestone. By producing an average of 7 billion square feet of masonry walls using fly ash-based green cement per year, this model shows that the financial savings are large and that $5 to $10 billion is included in the monetary value of benefits (energy saving, reducing emissions of GHG, reducing consumption of raw materials, and avoiding CO_2 emissions due to avoid land filling of fly ash).

1.4 Organization of the Dissertation

This dissertation is organized into eight chapters. Chapter one provides an introduction and overview, the objective and scope of the project, and finally the need and significance of using fly ash-based green cement for building materials specially masonry units. Chapter two reviews the literature on the cement industry and its environmental implications. Chapter three discusses fly ash and its current use, environmental implications, and the impact of not recycling coal ash. Chapter four presents state-of-art issues reviews the literature on the concrete masonry industry. Chapter five experimentally studies the durability properties of fly ash-based green cement mortar, in which compressive strength and freeze-thaw experiments were carried out. Chapter six displays the literature review of benefit-cost analysis. Chapter seven studies the benefit-cost analysis model of using fly ash-based green cement as a replacement for Portland cement to make masonry units. This chapter focuses on has the results and discussions of the outcomes of this model. Finally, chapter eight represents the conclusions and suggestions for future studies.

CHAPTER 2 THE LITERATURE VIEW OF CEMENT INDUSTRY

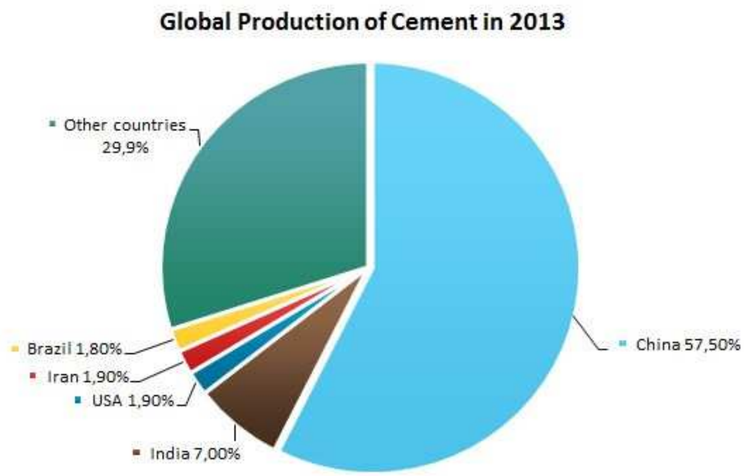
2.1 Introduction

Cement is a fine grey powder; it is an inorganic and nonmetallic substance with hydraulic binding properties. Mixed with water it forms a paste, which hardens owing to the formation of hydrates. After hardening, the cement gains its strength. The credit for its discovery is given to the Romans, who mixed lime ($CaCO_3$) with volcanic ash, (The Cement and Concrete Association of New Zealand, 1989). When the Roman Empire fell, the information on how to make cement was lost and was not rediscovered until the 16th century (The Cement and Concrete Association of New Zealand, 1989). There are numerous types of cement because of the use of different sources for calcium and different additives to regulate properties. Portland cement manufacturers produce a variety of types of cement in the United States designed to meet different requirements. The American Society for Testing Materials (ASTM) specification C-150 provides for eight types of Portland cement: five standard types (I, II, III, IV, V) and three additional types that include air-entraining properties (IA, IIA, IIIA) (PCA, 2008a).

2-2 A Brief History of Portland cement

Cement has been made since Roman times, but over time the recipes used to make cement have been refined. Lime and pozzolana (a volcanic ash containing significant quantities of SiO_2 and Al_2O_3) mixed with ground brick and water were the components of the earliest cements (The Cement and Concrete

Association of New Zealand, 1989). In 1758, the improvement of this cement began when Smeaton noticed it was 20 - 25 % clay, 75 – 80 % limestone and heating the mixture resulted in a type of cement that could harden when it is mixed with water (The Cement and Concrete Association of New Zealand, 1989). Smeaton called the new cement “hydraulic lime.” When the mixture was heated, a small quantity of it was sintered. In the 1800s, Aspdin and Johnson discovered that when the entire batch was sintered and then ground, superior cement was formed. This substance became designated Portland cement (after the region in which they were working) and is the most common cement in use today (The Cement and Concrete Association of New Zealand, 1989). The Annual cement industry shipments worldwide for 2008 was estimated at $10.0 billion, down from $15.0 billion in 2006 (Portland Cement Association, USA). Figure 2.1 shows world cement production in 2013. U.S. cement production is widely dispersed with the operation of 113 cement plants in 36 states (Portland Cement Association, USA). The top five companies collectively operate 54.4% of U.S. clinker capacity with the largest company representing 15.9% of all domestic clinker capacity. An estimated 80.0% of U.S. clinker capacity is owned by companies headquartered outside of the U.S. (Portland Cement Association, USA). Portland cement is currently defined as a mixture of argillaceous (i.e. clay-like) and calcareous (i.e. containing $CaCO_3$ or other insoluble calcium salts) materials mixed with gypsum ($CaSO_4 \cdot 2H_2O$) sintered and then pulverized into a fine powder (Portland Cement Association, USA). The precise definitions of Portland cement vary between different countries.



Source: Merchant Research and Consulting Ltd

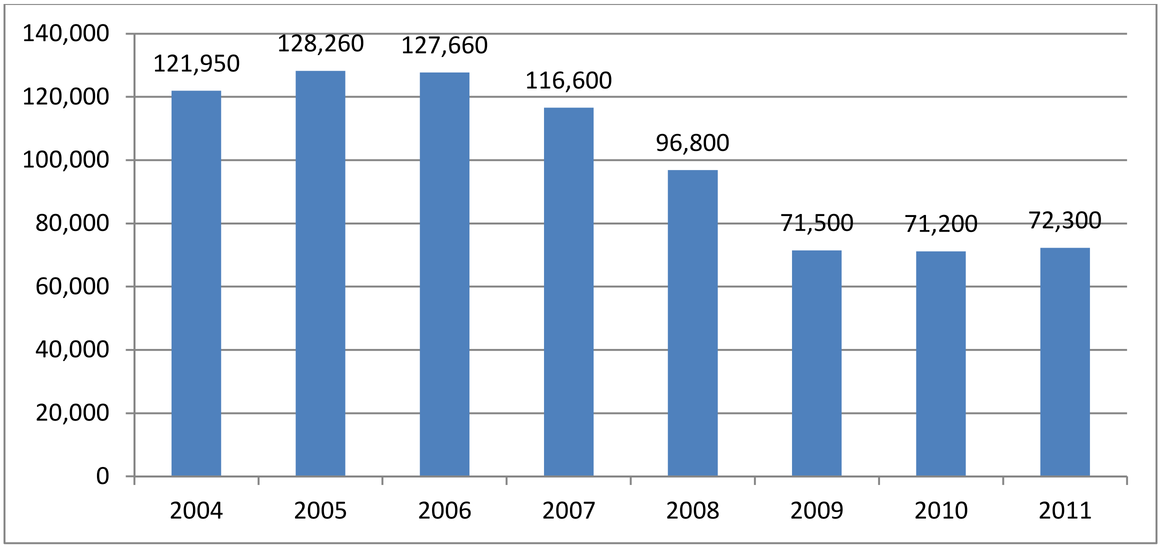
Figure 2.1: World cement production in 2013

2-3 Uses of Portland cement

The three main grades of cement are ordinary Portland cement, moderate-heat cement, and rapid hardening cement. Precast concrete and pipes are produced by using rapid hardening cement, which hydrates more quickly because it is finer ground, and it also has more gypsum than other cements. Hydroelectric dams are constructed by moderate-heat cement, as the heat produced by ordinary cement creates uneven expansion and can lead to cracking when such a large volume of concrete is used. In addition, there are special cements for special needs in different types of projects: these include blast furnace slag, fly ash blend, and sulfate resisting.

2- 4 Cement Consumption in the United States

In 2008, the United States consumed around 97 million metric tons of Portland cement, reflecting a -15.2% decrease over 2007 levels (Portland Cement Association, USA). The industry downturn was first linked to the mortgage foreclosure crisis which decreased residential construction spending activity by -18.5% in 2007 and -29.9% in 2008 (Portland Cement Association, USA). The time of year and prevalent conditions have an impact on the consumption of cement. The six months between May and October in every year account for about two-thirds of U.S. cement consumption (Portland Cement Association, USA). Ready-mix concrete operators take the majority of all cement shipments, and the rest are shipped to manufacturers of concrete related products, contractors, materials dealers, oil well/mining/drilling companies, as well as government entities. The domestic cement industry is regional in nature. The cost of shipping cement prohibits profitable distribution over long distances. As a result, customers traditionally purchase cement from local sources. Nearly 98% of U.S. cement is shipped to its customers by truck (Portland Cement Association, USA). Barge and rail modes account for the remaining distribution modes. Figure 2.2 shows cement consumption in the United States from 2004 to 2011 in (1,000 metric tons). As we see in figure 2.2, the consumption of cement decreased from 2007 to 2010 as a result of mortgage foreclosure crisis due to decreased residential construction spending activity. However, the consumption of cement increased in 2011.



Source: US Geological Survey

Figure 2.2: Apparent cement consumption in the United States from 2004 to 2011 in (1,000 metric tons)

2-5 The Chemistry of Cement Function

When water is added to concrete mix, which is a mixture of cement, aggregate, sand, and gravel, the cement undergoes a series of chemical reactions to form a "gel." The fine cement particles are broken down into even smaller particles (thus increasing the reactive surface) by crystallizing out from the super saturated solution formed (The Cement and Concrete Association of New Zealand, 1989). A series of immensely strong Si-O-Si bonds form between the particles that makes a network in which the aggregates are trapped. Bonds are also formed to the aggregates, but these are much weaker, especially for smooth, inert, hard aggregates; because they have a smaller surface area than rough aggregates, a smaller area can be involved in bonding. These reactions continue to take place for some time (depending on the exact composition of the cement). It is rare for all the cement to react completely. Usually the cement grains are only hydrated to a depth of 6-9μm after five months, while cement grains range up to 100μm in diameter (The Cement and Concrete Association of New Zealand, 1989). Table 2.1 presents the major mineral constituents of Portland cement. As we note from this table, the majority is silicate and the minority is aluminate.

Table 2.1- Major mineral constituents of Portland cement

Compound	Abbreviation	Chemical Formula	Typical concentration %
Tricalcium silicate	C_3S	$3CaO*SiO_2$	60-70
Dicalcium silicate	C_2S	$2CaO*SiO_2$	10-20
Tricalcium aluminate	C_3A	$3CaO*Al_2O_3$	5-10
Tetra calciumalumina-ferrate	C_4AF	$4CaO*Al_2O_3*Fe_2O_3$	3-8

Source: The Cement and Concrete Association of New Zealand

2-6 Cement Standards and Specifications

2-6-1 Standards Organizations

Product specifications and test methods are typically developed by national standards development organizations, such as American Society for Testing and Materials (ASTM) in the U.S. and Canadian Standards Association (CSA) in Canada. Full consensus standards are developed with the participation of all parties who have a stake in the standards' development and/or use. Table 2.2 below lists the most relevant national and international standard organizations for the concrete industry.

Table 2.2- The most relevant national and international standard organizations for the concrete industry (adopted from Portland cement Association of USA)

U.S. and Canada	
ASTM	ASTM International. Has a history of more than 100 years of standards development activities, including the first national specifications for Portland cement and other concrete materials. Uses a consensus-based standards development process. Committee C01 develops standards related to hydraulic cements and Committee C09 develops standards for concrete and other concrete materials.
AASHTO	American Association of State Highway and Transportation Officials. Develops standards for many materials through participation of state departments of transportation staff. AASHTO's Subcommittee on Materials develops concrete-related specifications, many of which are closely related to ASTM standards.
CSA	Canadian Standards Association. Develops standards for use in Canada through a consensus process, including the CSA A3000 compendium on cementations materials.
International	
ISO	International Organization for Standardization. Cement-related standards are developed by TC (Technical Committee) 74 (Cement and Lime) and concrete-related standards by TC 71 (Concrete, reinforced concrete and pre-stressed concrete).
CEN	European Committee for Standardization. EN 197 is the standard specification for cement in CEN member countries and EN 206 is the standard specification for concrete.

Product specifications and test methods are referenced in local and international building codes and specifications for ease of reference. For concrete construction projects, other organizations, such as state Departments of Transportation (DOTs) develop specifications that typically refer to ASTM or AASHTO specifications.

2-6-2 Cement specifications

Different types of cement are manufactured to meet various physical and chemical requirements. There are currently three different common hydraulic cement standards for general concrete construction in the U.S.:

1. ASTM C150 (AASHTO M 85), Specification for Portland cement.
2. ASTM C595 (AASHTO M 240), Specification for Blended Hydraulic cements.
3. ASTM C1157, Performance Specification for Hydraulic cements.

Each of these three specifications provides for several different types of cement.

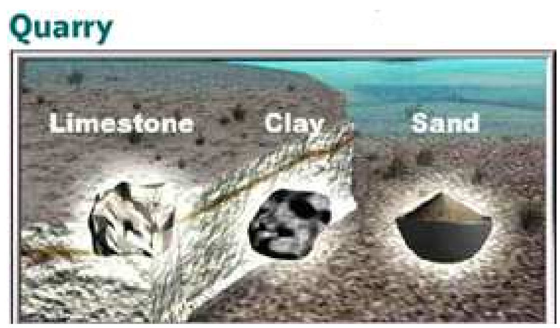
The use of ASTM C150 cements is well established, but it is interesting to note that ASTM C595 (AASHTO M 240) blended cements are broadly accepted by highway agencies throughout the country and have been effectively used for decades. ASTM C1157 cements, on the other hand, are approved by only a few State highway agencies, including in Colorado, Utah, and New Mexico, but use is expected to increase in response to a worldwide growing interest in sustainability. Major barriers to acceptance of ASTM C1157 include 1) lack of an equivalent AASHTO specification, 2) lack of experience working with these cements, and 3) uncertainty regarding the long-term durability of concrete made with ASTM C1157 cement (U.S. Department of Transportation ,2015)

2-7 The Manufacturing Process

Portland cement is made by heating raw materials rich in oxides of silicon, calcium, aluminum, and iron to temperatures of around 1200 - 1400^{o}C. The strength of cement is mainly affected by C_3S and C_3A (The Cement and Concrete Association of New Zealand, 1989). High percentages of C_3S (low C_2S) result in high early strength but also high heat generation as the concrete sets. On the other hand, high C_2S and low C_3S generate less heat and give strength more slowly (over 52 rather than 28 days). As a result of getting undesirable heat and rapid reacting properties by C_3A, $CaSO_4$ should be added to the final product to prevent that. C_3A can be converted to the more desirable C_4AF by the addition of Fe_2O_3 before heating, but this also inhibits the formation of C_3S. The resistance of cement to seawater increases with C_4AF (The Cement and Concrete Association of New Zealand, 1989). It also results in a somewhat slower reaction that evolves less heat. The balance of the formed compounds versus the performance characteristics required from the cement is a chemically controlled parameter. For this reason, considerable efforts are made during the manufacturing process to ensure the correct chemical compounds in the correct ratios are present in the raw materials before introduction of the materials to the kiln. Cement production is usually based on locally available raw materials because material transportation costs have a significant impact on final production costs. The cement manufacturing process involves four distinct stages, and these are explained in the following steps:

Step 1 - Quarrying

The raw material for cement manufacture is a rock mixture which is about 80% limestone (which is rich in $CaCO_3$) and 20% clay or shale (a source of silica, alumina and Fe_2O_3) as shown in figures 2.3 and 2.4. These are quarried and stored separately. The lime and silica provide the main strength of the cement, while the iron reduces the reaction temperature and gives the cement its characteristic grey color (The Cement and Concrete Association of New Zealand, 1989).



Source: The Portland Cement Association of USA

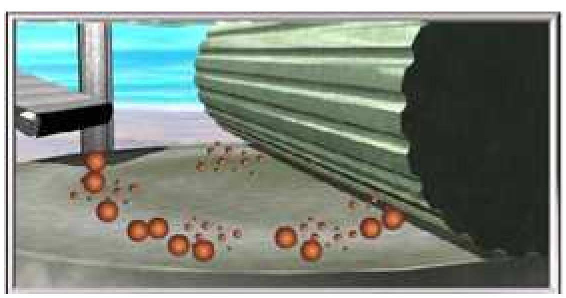
Figure 2.3: The raw material of cement

Source: The Portland Cement Association of USA

Figure 2.4: The main components of cement

Step 2 - Raw material preparation

To form a consistent product, it is essential that the same mixture of minerals is used every time. For this reason the exact composition of the limestone and clay is determined at this point, and other ingredients are added if necessary. The rock is also ground into fine particles to increase the efficiency of the reaction as shown in figure 2.5. The steps involved here depend on the process used. There are two main cement manufacturing processes currently used in the world: the dry process and the wet process. The choice of process depends on the moisture content of the available raw material. When wet raw materials (moisture content over 20%) are available, the wet process is preferred. However, in Europe, today's new cement plants are all based on the dry process as the wet process requires approximately 56 to 66% more energy (IEA ETSAP - Technology Brief I03 – June 2010 - www.etsap.org). The dry process uses more energy in grinding but less in the kiln and the wet process has lower overheads than the dry process. The two processes are discussed separately below.



Source: The Portland cement Association of USA

Figure 2.5: Proportioning, Blending & Grinding

The dry process

The quarried clay and limestone are crushed separately until nothing bigger than a tennis ball remains. Mineral analysis should be done for samples of both rocks. If necessary, minerals are then added to either the clay or the limestone to ensure that the correct amounts of aluminum, iron, etc. are present. The clay and limestone are then fed together into a mill where the rock is ground until more than 85% of the material is less than 90μm in diameter.

The wet process

The clay is mixed to a paste in a wash mill (a tank in which the clay is pulverized in the presence of water). Crushed lime is then added and the whole mixture further ground. Any material which is too coarse is extracted and reground. To ensure that it contains the correct balance of minerals the slurry should be tested, and any extra ingredients blended in as necessary.

Step 3 – Clinkering

Portland cement is characterized by this step. The finely ground material is dried, heated (to enable the sintering reactions to take place) and then cooled down again. Various chemical reactions take place to form the major mineral constituents of Portland cement while it is being heated. The powder from the dry process doesn't contain much moisture, so can be dried in a pre-heater tower. As it falls through the tower (which takes 30 seconds) it is heated from 70 to 800ºC. The moisture evaporates, up to 20% of the decarbonation (loss of CO_2) occurs (The Cement and Concrete Association of New Zealand, 1989). The mixture is then fed into the kiln. The slurry from the wet process contains too much moisture to be successfully dried in a preheated tower as showed in figure 2.6.

Instead, the slurry is fed directly into the kiln where it is formed into dry balls by the heat and rotation of the kiln. Because of this extra role of the kiln, wet process kilns are generally longer than dry process kilns. The kilns used in both processes are inclined on a shallow angle and lined with heat-resistant bricks.

Source: The Portland Cement Association of USA

Figure 2.6: Preheated Towers of cement

Step 3-1 The kiln

The kiln shell is steel, 60m long and inclined at an angle of 1 in 30. The shell is supported on 3 roller turn-ons and weighs in at over 1100 ton as shown in figure 2.7. The kiln is heated by injecting pulverized coal dust into the discharge end where it spontaneously ignites due to the very high temperatures. Coal is injected with air into the kiln at a rate of 9 - 12 T/hr. The reaction processes occurring within the kiln are not easily understood due to the wide variations in raw-mix chemistry, raw-mix physical properties and kiln operating conditions, and the physical difficulties of extracting hot materials from the process for investigation before they cool. Breaking the reaction processes into a number of simple zones as shown below means we can make some approximations about the cement formation process (The Cement and Concrete Association of New Zealand, 1989).

Source: The Portland Cement Association of USA

Figure 2.7: The Kiln

Zone 1: 35 min, 800 - 1100ºC

Decarbonation: Formation of $3CaO'Al_2O_3$ above 900oC. Melting of fluxing compounds Al_2O_3 and Fe_2O_3.

$$CaCO_3 \xrightarrow{heat} CaO + CO_2$$

Zone 2: 35-40 min, 1100-1300ºC

Exothermic reactions and the formation of secondary silicate phase as follows

$$2CaO + SiO_2 \xrightarrow{heat} 2CaO \cdot SiO_2$$

Zone 3: 40 – 50 min, 1300 – 1450 - 1300ºC

Sintering and reaction within the melt to form ternary silicates and tetra calcium alumino-ferrates

$$2CaO*SiO_2 + CaO \xrightarrow{\text{heat + time}} 3CaO*SiO2$$

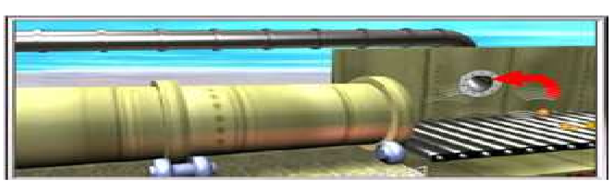
$$3CaO*Al_2O_3 + CaO + Fe_2O_3 \xrightarrow{\text{heat + time}} 4CaO*Al_2O_3*Fe_2O_3$$

<u>Zone 4: 50 – 60 min, 1300 – 1000ºC</u>

Cooling and crystallization of the various mineral phases formed in the kiln.

Step 3-2 The cooler

Immediately following the kiln is a large cooler designed to drop the temperature of the clinker from 1000ºC to 150ºC. This is achieved by forcing air through a bed of clinker via perforated plates in the base of the cooler. The plates within the cooler slide back and forth, shuffling the clinker down the cooler to the discharge point and are transported to a storage area. At this point in the process the materials have been formed into all the required minerals to make cement. Like cement, the clinker will react with water and harden, but because it is composed of 1-3 cm diameter fragments it is too coarse to be used.



Source: The Portland Cement Association of USA

Figure 2.8: Clinker Cooler & Finish Grinding

Step 4 - Cement milling

To produce the final product the clinker is mixed with gypsum ($CaSO_4 \cdot 2H_2O$), which is added as a set retarder, and ground for approximately 30 minutes in large tube mills. The cement flows from the inlet to the outlet of the mill (a rotating chamber), being first ground with 60 mm then 30 mm diameter steel balls. The first grinding breaks up the material and the second grinding breaks it to a fine powder as shown in figure 2.9. The amount of grinding is governed by the volume of cement fed into the mill and the greater the volume, the coarser the grind. The particle size is measured by laser diffraction analysis, and the quantity of material entering the mill adjusted accordingly. Over time the charge (steel grinding balls) wear out, so when they reach a certain size they fall through a sieve and then are replaced. The cement grinding process is highly energy intensive. The rotating mill generates significant quantities of heat and water is added to both the inlet and outlet ends of the mill to cool the product and the mill itself. Cement production has several quite serious environmental hazards associated with it: dust and CO_2 emissions and contaminated run-off water (The Cement and Concrete Association of New Zealand, 1989).

Source: Portland Cement Association of USA

Figure 2.9: Finish Grinding

- The Role of the Laboratory

An on-site laboratory forms an integral part of the control systems on site with testing from raw materials to finished product. The laboratory operates a 24-hour facility in line with a continuous manufacturing facility responsible for the following aspects:

“The first step in the process is testing raw materials prior to blasting in the quarry and assisting with development of quarrying strategies. Next, analyzing rock samples from the raw mill at regular intervals during the day and night and fine-tuning the process to ensure chemical control is maintained. Then, analyzing clinker at the end of the cooler (before grinding) to ensure that the manufactured process meets specification. Next, checking that cement mills are undertaking grinding correctly and that customers receive the right product. Subsequently, checking dispatched materials for quality and compliance with standards requirements. Next, certificates of conformance are issued to customers based on these analyses. Finally, Product development. Testing work within the laboratory ranges from simple air permeability measurements to high technology X-ray fluorescence analysis" (The Cement and Concrete Association of New Zealand, 1989).

2-8 The Production Costs of Cement

Portland cement is produced using a combination of variable inputs such as raw materials, labor, electricity, and fuel. U.S. census data for the cement industry (North American Industry Classification System [NAICS] 32731: cement manufacturing) provides an initial overview of aggregated industry expenditures on these inputs (Department of Commerce [DOC], Bureau of the Census, 2010). In 2007, the total value of shipments was $10.6 billion, and the industry spent approximately $1.7 billion on materials, parts, and packaging. Total compensation for all employees (includes payroll and fringe benefits) amounted to $1.4 billion. Fuels and electricity expenditures were approximately $1.7 billion.

2-8-1 Raw Material Costs

According to the United States Geological Survey (USGS), approximately 159.7 million tons of raw materials were required to produce approximately 95.5 million tons of cement in 2005 or 1.67 tons of raw materials per ton of cement in the US. Table 2.3 summarizes the amount of raw material inputs used per ton of cement produced in the United States between 2000 and 2005. As the data shows, the amount of raw materials, limestone, and clay required to produce one ton of cement has remained essentially constant during this 6-year period. The price of these raw materials varies across regions. In 2005, the prices of raw materials were highest in Hawaii where they sold for an average of $13.34 per metric ton. The prices of raw materials were lowest in Michigan, where they sold for an average of $3.89 per metric ton (U.S. Department of the Interior, U.S. Geological Survey, 2005).

Table 2.3 - Raw Material Input Ratios for the U.S. Cement Industry: 2000 to 2005

	2000	2001	2002	2003	2004	2005
Raw material input (10^3 metric tons)	144,949	147,300	153,100	150,500	158,200	159,700
Cement production (10^3 metric tons)	85,178	86,000	86,817	89,592	94,014	95,488
Metric tons of raw material input per ton of cement	1.70	1.71	1.76	1.68	1.68	1.67

Sources: U.S. Department of the Interior, U.S. Geological Survey. 2002–2007. 2001–2005 Minerals Yearbooks, cement. Table 6. Washington, DC: U.S. Department of the Interior. U.S. Department of the Interior, U.S. Geological Survey. 2002–2007. 2001–2005 Minerals Yearbooks, cement. Table 3. Washington, DC: U.S. Department of the Interior.

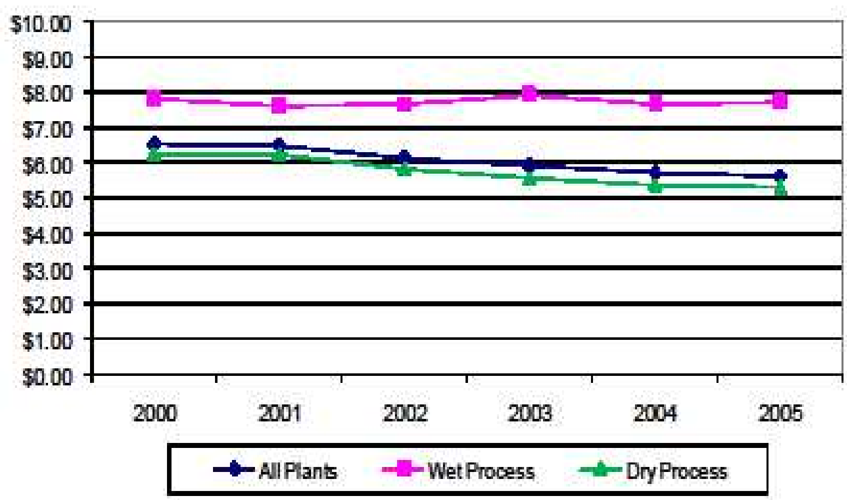
2-8-2 Labor Costs

In 2005, the Portland Cement Association (PCA) reported labor productivity measures (in terms of metric tons of cement per employee hour) for 2000 to 2005 in its U.S. and Canadian Labor-Energy Input Survey. Using these data, they computed a measure of labor hour requirements to produce cement as shown in table 2.4. It shows that a worker spent less than 1 hour to produce 1 ton of cement. As these data show, wet process plants are typically more labor intensive, requiring approximately 45% more labor hours to produce a metric ton of cement than dry process plants. In addition, labor productivity has been improving more quickly in dry process plants than in those using a wet manufacturing process. Between 2000 and 2005, labor requirements decreased by 15% in dry process plants, while in wet process plants labor requirements remained constant. As a result, labor costs for the wet process relative to labor costs for dry process plants have risen in recent years. Figure 2.10 shows labor costs per metric ton of cement in $2005. The labor costs reported in Figure 2.10 were calculated by first multiplying the number of employee hours per metric ton of cement reported in Table 2.4 by the average hourly earnings of production workers for each year (BLS, 2007). Next, these cost estimates were adjusted for inflation and expressed in 2005 dollars by using the consumer price index (CPI) (DOC, BLS, 2008).

Table 2.4 - Labor Productivity Measures for the U.S. Cement Industry by Process Type: 2000 to 2005 (employee hours per metric ton)

Year	2000	2001	2002	2003	2004	2005
All plants	0.394	0.388	0.360	0.347	0.338	0.338
Wet process	0.469	0.457	0.450	0.465	0.452	0.463
Dry process	0.376	0.375	0.342	0.328	0.318	0.318

Source: Portland Cement Association. December 2005. U.S. and Canadian Labor-Energy Input Survey 2005. Skokie, IL: PCA's Economic Research Department

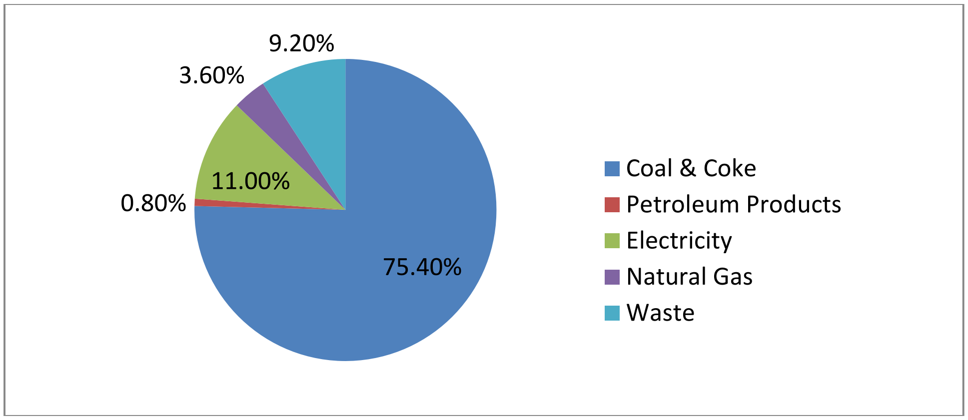


Sources: Portland Cement Association. December 2005. U.S. and Canadian Labor-Energy Input Survey 2005. Skokie, IL: PCA's Economic Research Department.

Figure 2.10: Labor Costs per Metric Ton of Cement (2005 value of dollars)

2-8-3 Energy Costs

Figure 2.11 shows a detailed breakdown of U.S. energy consumption in cement plants in 2005. As this figure explains, the vast majority of energy in U.S. cement plants is derived from coal and coke (75%). The remaining 25% of energy consumption is derived from electricity, waste, natural gas, and petroleum products. PCA also reported energy consumption data by the type of U.S. cement plant (in terms of millions of BTUs per metric ton of cement) as shown in table 2.5. As these data show, wet process plants are typically more energy intensive, consuming approximately 44% more energy per ton of cement than dry process plants. In addition, the trends in energy consumption continue to show that dry plants have become more energy efficient than wet process plants. Between 2000 and 2005, energy consumption per ton of cement in dry process plants decreased by 5%; in contrast, wet process plants' energy consumption increased slightly during this period.



Source: Portland Cement Association. December 2005. U.S. and Canadian Labor-Energy Input Survey 2005. Skokie, IL: PCA's Economic Research Department.

Figure 2.11: Distribution of Energy Consumption

Table 2.5 - Energy Consumption by Type of U.S. Cement Plant (million BTU per metric Ton)

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
All plants	4.982	4.93	4.858	4.762	4.755	4.699
Wet process	6.25	6.442	6.676	6.647	6.807	6.387
Dry process	4.673	4.655	4.498	4.433	4.407	4.433

Source: Portland Cement Association. December 2005. *U.S. and Canadian Labor-Energy Input Survey 2005*. Skokie, IL: PCA's Economic Research Department.

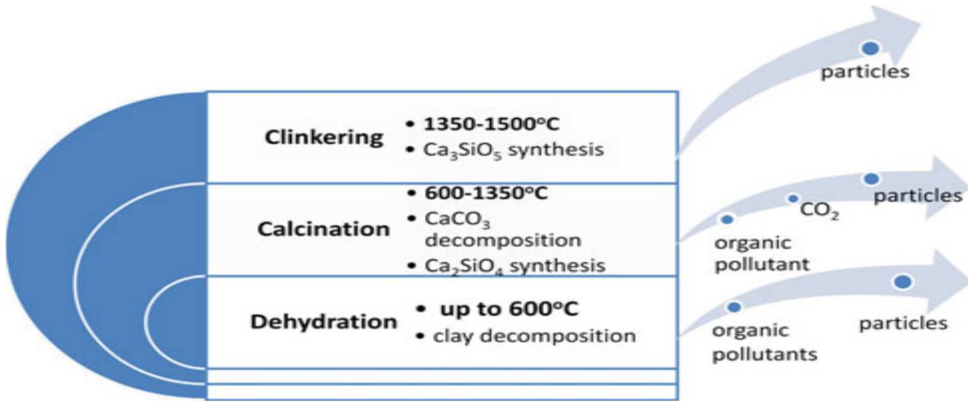
The price shown in table 2.6 is the Cement Price for Portland cement using the latest published price, in dollars per ton (U.S.) for Portland cement (Type I) quoted for Boston, U.S.A. in the Engineering News-Record (ENR), and in the Construction Economics section at ENR website http://www.enr.com.

Table 2.6 Cement Prices

Publication Date	ENR Published Price($/ton)	Market Change
August 8, 2012	$ 105.95	$4.07
July 2, 2012	$ 101.88	$0.00

2-9 Environmental Implications

Many of the aspects of the cement making process are potentially environmentally damaging. Portland cement manufacture can cause environmental impacts at all stages of the process. These include emissions of airborne pollution in the form of dust, gases, noise, and vibration when operating machinery and during blasting in quarries, consumption of large quantities of fuel during manufacture, release of CO_2 from the raw materials during manufacture, and damage to the countryside from quarrying (Portland Cement Association, USA 2008). In addition, Sulfur Dioxide Exposure in Portland Cement Plants (SO_2) has a negative impact especially on those who work at Portland cement facilities(Portland Cement Association, USA 2008). Figure 2.12 shows the release of pollutants into atmosphere.



Source: Cement industry: sustainability, challenges and perspectives

Figure 2.12: Environmental map for cement production: the release of pollutants into atmosphere

The areas of potential concern are listed below:

2-9-1 Dust Emissions

Large quantities of dust are generated during the manufacture of cement. These must be prevented (both at the environmental and economic level) from escaping to the atmosphere. The two areas where dust has the potential to escape are via air streams that have been used to carry cement (e.g. the mills or kiln) and directly from equipment used to transport cement. Thus, to prevent dust emissions all transport equipment is enclosed, and the air from both of these enclosures and from the kiln and mills is treated in an electrostatic precipitator to remove its load of dust. Here dust-laden air passes between an electrode carrying 50,000 volts and an earthed collection plate. The electrostatic discharge between the electrode and the plate forces the dust onto the plates, from which it is removed. In the United States, regulations concerning the cement industry are given in Title 40 (Protection of Environment), Part 60 (Standards of Performance for New Stationary Sources) in Subpart F- Standards of Performance for Portland Cement Plants. Emission limit values are given as:

For kilns:

(1) 0.15 kg per metric ton of feed (dry basis) to the kiln.

(2) Gases may not exhibit greater than 20 percent opacity.

For clinkers:

(1) 0.050 kg per metric ton of feed (dry basis) to the kiln.

(2) Gases may not exhibit 10 percent opacity, or greater.

2-9-2 CO_2 emissions

Cement manufacture is an energy intensive process. Reducing CO_2 emissions is one of the most significant challenges facing the industry as it moves into the 21st century. CO_2 is produced during the calcination phase of the manufacturing process and also as a result of burning fossil fuels. The opportunity to reduce emissions through increased energy efficiency is only possible on the latter of the CO_2 emissions. Cement manufacturing releases CO_2 in the atmosphere both directly when calcium carbonate is heated, producing lime and carbon dioxide, and also indirectly through the use of energy. The cement industry produces about 5% of global man-made CO_2 emissions, of which 50% is from the chemical process, 40% from burning fuel, and 10% from electricity and transportation (Portland Cement Association, USA, 2002). Figure 2.13 shows the distribution of carbon dioxide release during cement preparation. The amount of CO_2 emitted by the cement industry is nearly 900 kg of CO_2 for every 1000 kg of cement produced (Portland Cement Association, USA, 2002). The high proportion of carbon dioxide produced in the chemical reaction leads to a large decrease in mass in the conversion from limestone to cement. So to reduce the transport of heavier raw materials and to minimize the associated costs, it is more economical for cement plants to be closer to the limestone quarries rather than to the consumer centers (Portland Cement Association, USA, 2002).

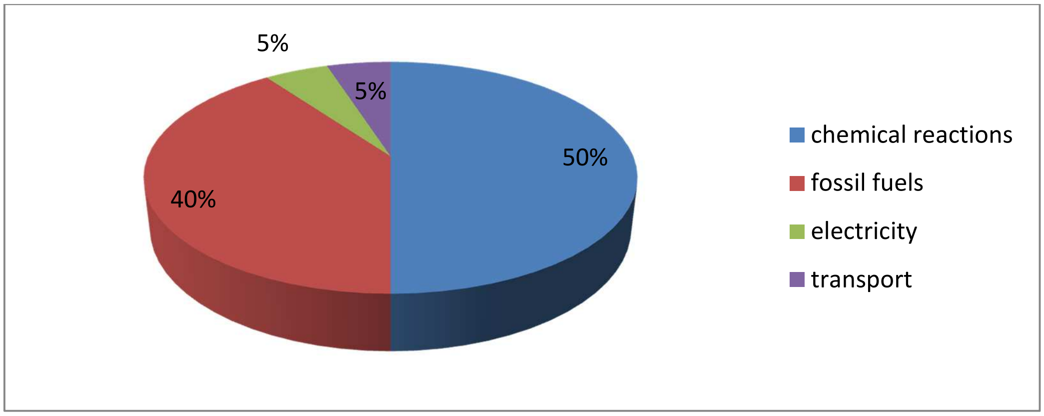


Figure 2.13: Distribution of Carbon Dioxide release during Cement preparation

The CO_2 associated with Portland cement manufacture falls into three categories:

Source 1: CO_2 derived from decarbonation of limestone

Source 2: CO_2 from kiln fuel combustion

Source 3: CO_2 produced by vehicles in cement plants and distribution.

2-9-3 Cement and Nitrogen Oxides

Nitrogen in the atmosphere is very stable. It takes a very hot flame to disrupt it. Nitrogen oxides are therefore generally produced only by processes involving high temperature combustion. The cement industry is responsible for about 1.5% of all nitrogen oxides emissions (US Environmental Protection Agency- EPA, 1995).

2-9-4 Cement and Global Warming

The cement industry affects the global warming issue in two major ways:

- The conversion of limestone to clinker involves the thermal decomposition of calcium carbonate into calcium oxide and carbon dioxide (calcinations). The latter is released into the atmosphere in large quantities from the kilns during operation.
- The cement manufacturing process is a large consumer of carbon-based fuels (generally powdered coal or natural gas), whose principal oxidation product is carbon dioxide.

2-9-5 Quarry and Plant Water Runoff

Runoff of storm water and treatment of wastewater from quarries is a problem for almost all quarry operations. Usually this is trapped in wetland areas where the water is treated in a controlled manner.

2-9-6 Heavy Metal Emissions in the Air

In some circumstances, mainly depending on the origin and the composition of the raw materials used, the high-temperature calcinations process of limestone and clay minerals can release in the atmosphere gases and dust rich in volatile heavy metals, thallium, cadmium and mercury are the most toxic (Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process, World Business Council for Sustainable Development, 2005). Heavy metals are often found as trace elements in common metal sulfides (FeS_2), zinc blend (ZnS), galena (PBS) present as secondary minerals in most of the raw materials. Environmental regulations exist in many countries to limit these emissions. As of 2011 in the United States, cement kilns are "legally allowed to pump more toxins into the air than are hazardous-waste incinerators" (Berkes et al, 2011).

2-9-7 Use of Alternative Fuels and by-products Materials

A cement plant consumes 3 to 6 GJ (GJ, or Giga-Joule, a unit of energy equal to 10^9 joules) of fuel per ton of clinker produced, depending on the raw materials and the process used. Most cement kilns today use coal and petroleum coke as primary fuels, and to a lesser extent natural gas and fuel oil. Selected waste and by-products with recoverable calorific value can be used as fuels in a cement kiln, replacing a portion of conventional fossil fuels, like coal, if they meet strict specifications (Guidelines for the Selection and Use of Fuels and Raw Materials in the Cement Manufacturing Process, 2005).

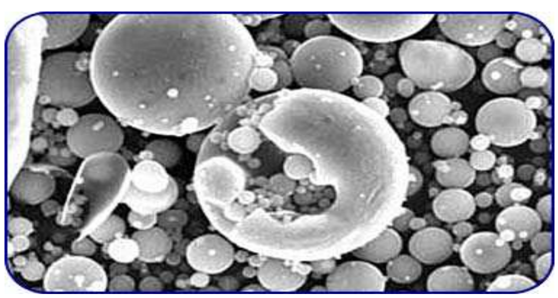
CHAPTER 3 THE LITERATURE VIEW OF FLY ASH INDUSTRY

3.1 Introduction

More than 70 million tons of fly ash is produced in the United States in a year. Only about 40% is beneficially utilized, and over 40 million tons of fly ash is for disposal (American Coal Ash Association 2005). Coal combustion products (CCPs), or coal ash, are the materials remaining after the combustion of coal. Coal is an important natural resource for our nation's economy and our energy security. According to the US Energy Information Administration, almost half of our nation's electricity is generated by burning coal (US EIA, 2012). There are many good reasons to view coal ash as a resource, rather than waste. When it replaces raw materials, recycling coal ash conserves natural resources and saves energy. In many cases, what products made with coal ash perform better than products made without it (ACAA, 2011).

3-2 What is Fly Ash?

Fly ash is a solid, fine-grained powdery material resulting from the combustion of pulverized coal in power station furnaces. Coal-fired power plants produce fly ash as a by-product of the combustion process. Fly ash is comprised of the non-combustible mineral portion of coal consumed in a coal-fueled power plant. Fly ash consists of the inorganic matter present in the coal that has been fused (melted) during the combustion of the coal, solidified while suspended in the exhaust gases and collected from the combustion air-stream as it exits the power plant. It is made up of minute glassy particles that are generally spherical in shape, usually smaller than 50 microns in size (Ash Grove Resources, L.L.C, 2006). Fly ash is a pozzolan. Pozzolanic materials have the ability to form cementitious substances when mixed with lime (Ca $(OH)_2$) and water (H_2O). The hydration reactions are similar to the reactions occurring during the hydration of Portland cement. Romans used Volcanic Ash (natural pozzolan) and lime as a mortar during the construction of Rome and other cities. Many of their structures—which used the volcanic ash and lime as a mortar or hydraulic cement—still exist today. One of the most well known is the Coliseum in Rome (Ash Grove Resources, L.L.C, 2006). The characteristics of fly ash depend upon the quality of lignite/coal and the efficiency of boilers. The combustion temperature at which the coal is fired and the rate of combustion can also affect the physical properties of fly ash (Joshi et al, 1997). Figure 3.1 shows the form of fly ash



Source: Ash Grove Resources, L.L.C

Figure 3.1: The Form of Fly Ash

3-2-1 Types of Fly Ash

Fly Ash is classified by its chemical make-up. ASTM C618 standard specification for coal fly ash and raw or natural Pozzolan has two designations for fly ash, class C fly ash and class F fly ash. Table 3.1 shows the chemical requirements for fly ash classes (from ASTM C618). Class C fly ash produces cementitious products without the need of an activator. Class C fly ash has high concentrations of calcium compounds that provide self-cementing properties. The self-cementing properties of the class C fly ash are especially useful in soil stabilization applications because it does not require an additive to achieve the desired results. Thus, class C fly ash is a hydraulic, cementitious material that has pozzolanic properties (Ash Grove Resources, L.L.C, 2006). Class F fly ash is low in lime and does not have self-cementing properties. Class F fly ash primarily consists of silica, aluminia, and iron compounds. The addition of an activator such as lime is required to produce cementitious products through a pozzolanic reaction (Ash Grove Resources, L.L.C, 2006).

Table 3.1 – Chemical requirements for fly ash class (adopted from ASTM C618)

Chemical difference	Class F	Class C
Silicon dioxide (SiO_2) + aluminum oxide (Al_2O_3) + iron oxide (Fe_2O_3), min. %	70.0	50.0
Sulfur trioxide (SO_3), max. %	5.0	5.0
Moisture content, max. %	3.0	3.0
Loss on ignition, max. %	6.0	6.0
Available alkalis (as Na_2O), max. %	1.5	1.5

3-2-2 Fly Ash Activation

Fly ash has pozzolanic properties, but its reactivity is very low in natural conditions. To date, several approaches are used to activate, or accelerate, the pozzolanic reaction of fly ash. These approaches include (1) mechanical treatment (grinding), (2) accelerated curing, hydrothermal and autoclaving, and (3) chemical activation (Wu et al, 2005).

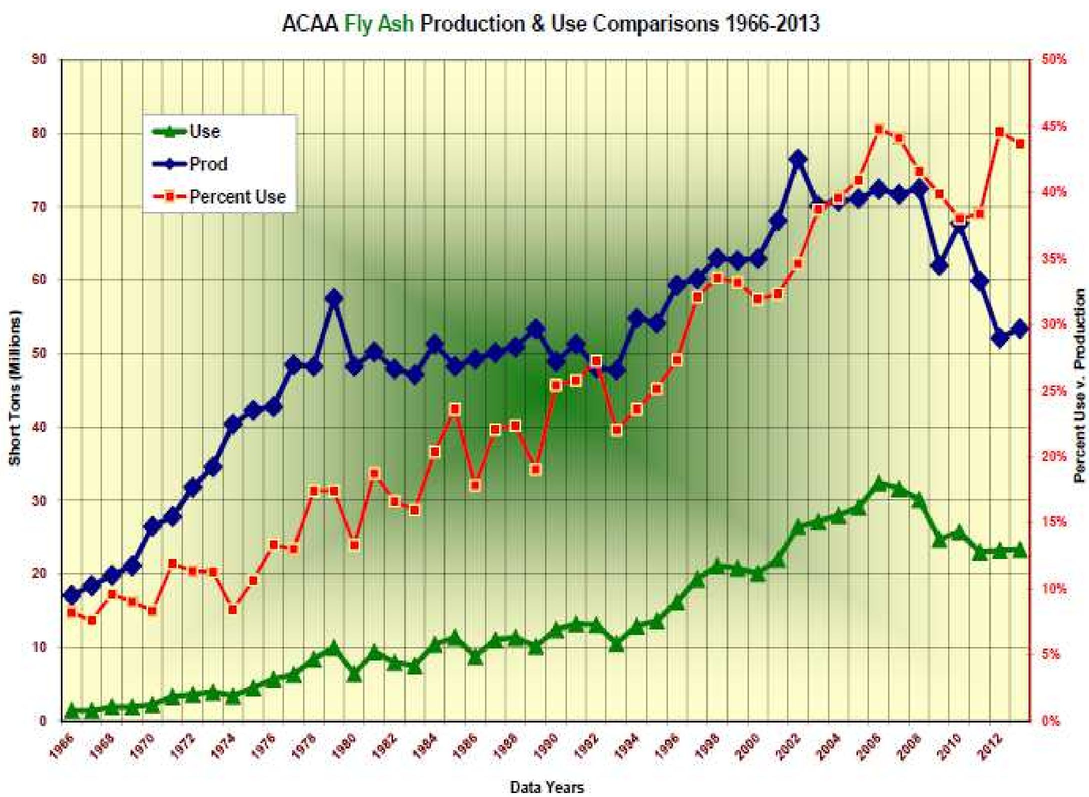
Mechanical treatment by grinding increases the fineness, the specific surface, and the specific gravity of fly ash samples (Paya et al, 1995, 1996, 1997, 2000). It has been demonstrated that the pozzolanic activity of ground fly ash is greater than that of non-mechanically treated fly ash (Paya et al, 1997; Sekulic et al, 1999), and the early strength of concrete containing ground fly ash is improved (Sekulic et al, 1999), suggesting a higher reactivity of the ground fly ash. However, it is found that the effect of mechanical treatment is less efficient compared with temperature and chemical activators (Shi et al, 2001). It is found that a synergistic use of chemical activation and hydrothermal hot pressing produces very strong fly ash samples (Wu et al, 2004). The hydrothermal process involves hot water under pressure to carry out dissolution, leaching, and precipitation reaction. Fly ash can be solidified and shows splitting tensile strengths of 0.96 to 1.24 MPa by hydrothermal hot pressing alone. With a small amount of chemical activator (sodium hydroxide), the tensile strength can reach as high as 5.4MPa (Wu et al, 2004). Many kinds of chemicals have been employed as activators for fly ash, such as sodium hydroxide, calcium hydroxide, potassium hydroxide, water glass (sodium silicate), lime, gypsum, anhydrite, sodium sulfate, calcium chloride, sodium chloride, calcium nitrate, and cement. In general, what has been discovered is that chemical activation is very efficient for increasing the activity of fly ash (Wu et al, 2005).

In summary, the following conclusions can be reached from the various activation methods mentioned above: (1) The reactivity of fly ash received from power plants with no activator added is very low; (2) The reactivity of fly ash increases with the increase of curing temperature and time; (3) Chemical activation is more efficient for increasing the reactivity of fly ash than grinding and autoclaving; (4) The combination of the use of some chemical activators shows better results than the individual constituents alone. The pH value of the chemical environment is a significant determinant for fly ash activation; (5) Class F and class C fly ash show different responses to the same chemical activator. In general, class C is more reactive than class F under the same conditions (Wu et al, 2005).

3-2-3 Fly Ash Production and Its Uses

Fly ash is an important industrial by-product. It is the main residue from coal burning. As a result, millions of tons of fly ash are produced annually. However, only a limited portion (less than 35%) of fly ash is recycled at present. Figure 3.2 shows the production and use of fly ash from 1966 to 2009 in the United States (American Coal Ash Association, 2009). The majority of fly ash is disposed of at landfills, which creates environmental problems. In addition, a surcharge for landfill use is overwhelmingly required in many areas. Therefore, new recycling strategies are necessary to produce value-added products from fly ash instead of considering it as waste material that needs to be disposed of. The United State Environmental Protection Agency (EPA) issued its final regulatory determination that regulation of ash as a "hazardous waste" was not warranted (ACAA, 2011). The EPA also began actively promoting the beneficial use of coal ash products (fly Ash, bottom Ash... etc) and the rate soared to 44.5 percent in spite of steadily increasing volumes of the amount of coal ash produced. Major uses of coal ash include concrete, gypsum wallboard, structural fill, blasting grit, mineral filler, roofing granules, paving, and a variety of geotechnical and agricultural applications. Table 3.2 lists the use of fly ash in 2010 from American Coal Ash Association survey (ACAA, 2011).

Among the current limited use of fly ash, application in the field of cement and concrete accounts for a large portion—about 50% (ACAA, 2002, 2003, 2004). Fly ash has been used around the world as an ingredient in concrete for more than 60 years. When fly ash is added to the concrete mix, some of the cement can be replaced, and the concrete with fly ash is more durable and stronger than concrete made with cement alone (Wesche, 1991). The benefits of using fly ash in concrete include: 1) decreased permeability; 2) increased long term strength; 3) reduced damage from heat of hydration; and 4) increased resistance to sulfate and other chemical attack. According to research findings and practice, the replacement of 15 to 25 percent of cement in concrete were typically found to provide similar or slightly improved performance comparing to plain concrete. Further increases in replacement rates would have a detrimental effect (Berry et al, 1994; ACI Committee 211, 1993).



Source: American Coal Ash Association, 2015

Figure 3.2: The production and use of fly ash from 1966 to 2013 in the United

Table 3.2- Coal Combustion Product (CCP) Production & Use Survey Report 2010 (ACAA)

Beneficial Utilization versus Production Totals (Short Tons)	
CCP Categories	Fly Ash
2010 Total CCPs Produced by Category	67,700,000
2010 Total CCPs Used by Category	25,723,217
1. Concrete/Concrete Products /Grout	11,016,097
2. Blended Cement/ Raw Feed for Clinker	2,045,797
3. Flow- able Fill	135,321
4. Structural Fills/Embankments	4,675,992
5. Road Base/Sub-base	242,952
6. Soil Modification/Stabilization	785,552
7. Snow and Ice Control	0
8. Blasting Grit/Roofing Granules	86,484
9. Mining Applications	2,399,837
10. Gypsum Panel Products	109
11. Waste Stabilization/Solidification	3,258,825
12. Agriculture	22,220
13. Aggregate	6,726
14. Miscellaneous/Other	1,047,305
2010 Totals by CCP Type/Application	25,723,217
Category Use to Production Rate (%)	37.90%

3-2-3-1 Fly Ash Based Geopolymers

"Chemically, geopolymers consist of three-dimensionally cross-linked units of AlO_4 and SiO_4 tetrahedral, where positive ions (Na+, K+, Li+, Ca2+, Ba2+, H3O+, et al) must be present to balance the negative charges of the framework (Davidovits, 1989, 1991, 1994a). Geopolymers are formed through a chemical reaction between various aluminosilicate materials with silicates under highly alkaline conditions, yielding Si-O-Al bonds. These materials were first recognized in the Ukraine (Glukhovsky, 1994) in the 1950s. At that time, they were referred to as "soil cement". It was Davidovits (1989, 1991, 1994a) who first examined the chemistry of such material in details and coined the term "geopolymer" in the 1980s. Structural units such as sialate (-Si-O-Al-), sialate-siloxo (-Si-O-Al-O-Si-O-) and sialate-disiloxo (-Si-O-Al-O-Si-O-Si -O-) were proposed by Davidovits to envisage the chemical structure of geopolymers" (Sun, 2005; Wu et al, 2005).

3-2-3-1- a- Properties of Geopolymers

Polymers and polycondensers are considered as geopolymeric materials. At low temperatures, they take over a selected shape, like organic polymers; however, as "geo-materials," they are minerals that are hard and weather resistant and can stand with higher temperature than organic polymers (Wu et al, 2005).

Geopolymers have the properties as follows:

1- Low-energy consumption and environmental friendly. Geopolymers do not consume a lot of energy, and they can be formed at ambient temperature. Also, tons of industry by-products, such as fly ash, slag, and so on can serve as geopolymeric raw materials (Comrie, 2000; Wu et al, 2005).

2- High early-age strength and good mechanical property. Rahier et al (1996a) reached more than 60MPa of compressive strength. In addition, 70% of the final compressive strength can be developed in the first 4 hours of setting (Van Jaarsveld et al, 1997; Sun, 2005).

3- Superior chemical resistance. Geopolymers made from metakaolin possesses good chemical resistance. (Palomo et al, 1999a).

4- Superior freeze-thaw performance. Experimentally, after 180 freeze-thaw cycles, geopolymer specimens made from metakaolin showed mass loss less than 0.1%, and strength loss less than 5% (http://www.geopolymer.org; Sun, 2005).

5- Superior high-temperature resistance. Geopolymers of the sialate-disiloxoresins, harden like thermosetting organic resins, but have use-temperature range up to 1000°C (1830°F) (Davidovits et al, 1991; Sun, 2005).

6- Low permeability. The permeability of geopolymer binders is in the order of 10^{-10} m/s (http://www.geopolymer.org), (P. Sun, 2005).

3-2-3-1- b- Geopolymer and Portland cement System

There are major differences between geopolymer system and Portland cement system as follows:

1- Starting Materials. Portland cement and water are the starting materials in Portland cement system. On the other hand, the starting system materials for geopolymer system include aluminosilicate material (metakaolinite in Davidovits' system), activators such as alkali hydroxide and/or alkali silicate and water (Sun, 2005).

2- Aqueous Solution. Cement hydration uses a aqueous solution which is water and the pH starts from neutrality and gradually increases up to 12-13 with increasing solid dissolution (Mindess et al, 1981); while geopolymerisation requires a strongly alkaline solution to "activate" aluminosilicate solids dissolution and favor the production of geopolymer (Davidovits, 1982, 1991; Phair et al, 2001a, 2002a; Wu et al, 2005).

3- Reaction Products. The major reaction products between Portland cement and water are calcium silicate hydrate (CSH) and calcium hydroxide (Mindess et al, 1981). For the geopolymer system, the major reaction product is three-dimensionally networked amorphous to semi-crystalline alumino silicate materials (Sun, 2005).

4- Properties of Final Products. Geopolymer possesses better properties than Portland cement such as shorter setting and quicker strength development (Van Jarrsveld et al, 1997). Furthermore, it has lower density with good mechanical properties (Table 3.3), better chemical resistance (Table 3.4), higher temperature resistance (Table 3.5), and low shrinkage on setting compared with Portland cement system (Table 3.6) (Wu et al, 2005).

Table 3.3 - Strength and density comparison between "low-temperature synthesized aluminosilicate glasses" and Portland cement concrete (Wu et al, 2005).

Low-temperature synthesized aluminosilicate glasses (Rahier et al, 1996a)			
Composition		Compressive Strength (MPa)	Density (g/cm^3)
Sil/Mk[a]	Sand/Mk[b]		
0.8	2.4	42.7	1.691
1.0	2.6	60.2	1.717
1.2	2.7	51.5	1.724
Normal strength Portland cement concrete (Neville, 1995; Dorf, 1996; Nawy, 1990)			
Compressive strength (MPa)		Density (g/cm3)	
20-40		1.85-2.40	

a. Sodium silicate solution to metakaolin ratio

b. Sand to metakaolin ratio, average size of the sand is 240 μm

Table 3.4 - Break up in 5% acid solutions (% of matrix dissolved under identical conditions) (Van Jaarsveld et al, 1997)

Matrix	H_2SO_4	HCl
Portland cement	95	78
Portland cement/slag blend	96	15
Ca-aluminate cement	30	50
Geoplymer	7	6

Table 3.5 - Typical properties of fiber-reinforced concrete (FRC) and geopolymer-carbon fabric laminates (GCFL) (Lyon et al, 1997)

Material	Density	Tensile modulus	Flexural strength	Maximum temperature capacity
	Kg/m^3	GPa	MPa	°C
FRC	2300	30	14	400
GCFL	1850	76	245	≥ 800

Table 3.6 - Percentage shrinkage of geopolymer cement compared to Portland cement (Van Jaarsveld et al, 1997)

Matrix	7 days	28 days
Portland cement type I	1.0	3.3
Portland cement type III	1.5	4.6
Geopolymer cement	0.2	0.5

3-2-3-1- c- Applications of Geopolymer Technology

Geopolymers have advantages that make them appropriate for many applications such as the following;

1- Geopolymer cement and concrete. In 1994, Davidovits found that geopolymer cement hardens rapidly at room temperature and provides compressive strengths in the range of 20 MPa, after only 4 hour at 20º C. Also, the final 28-day compressive strength is in the range of 70-100 MPa (Sun, 2005).

2- High temperature and fire proof application. Geopolymeric materials and composites, especially those with high Al/Si ratio such as potassium polysialate (K-PS) have particular thermal stability with melting points in the range of 1400º C (Barbosa et al. 2003a, 2003b; Sun, 2005).

3-2-3-2 Fly Ash in Soil Stabilization.

3-2-3-2- a- Drying Out Wet Soils

Class C fly Ash is effective in reducing the moisture content of soils to levels suitable to achieve proper compaction, and it can reduce the moisture content of soils by up to thirty percent (30%) and sometimes even more (Ash Grove Resources, L.L.C, 2006). Class C fly Ash can accomplish this in just a few hours. Besides the speed in which these materials dry out the soil, there is an additional benefit. Once mixed with the soil and compacted, the mixed product is more resistant to moisture penetration or disturbances during the duration of the project's construction phase (Ash Grove Resources, L.L.C, 2006). Using Class C fly Ash to dry out wet soils can be a more economical and time efficient solution to the problem. Buildings, structures, highways, bridges—anything that is constructed—must be placed on a stable, dependable soil base. In order to achieve an acceptable base, soils must be compacted to the specified densities. For this to occur, the moisture content of the soils must be within a specific range. If a soil has too much moisture, it cannot be compacted to the specified density. Consequently, there are two choices. One, all of the soil can be replaced with other materials or two; the soil must be dried out. Drying out can be accomplished by either aerating the soil or by adding a drying agent to the soil. When the drying agent method is used, the construction industry gains several advantages. By using class C fly ash as the drying agent, the process becomes more time efficient and it can be less expensive than soil replacement or other methods (Ash Grove Resources, L.L.C, 2006). While the primary goal of using the drying agent is to reduce the moisture content to facilitate final compaction of the soil, a degree of stabilization also occurs validating the process (Ash Grove Resources, L.L.C, 2006).

3-2-3-2- b- Soil and Aggregate Stabilization

Stabilization applications usually address one or more of these engineering properties, Shear strength, Compressibility, Permeability, and Swell Potential. There are two categories of soil stabilization. One is mechanical stabilization. This is achieved by compacting the soil to develop the desired engineering properties. The other is a chemical stabilization that involves the addition of a substance that reacts with the soil to achieve the desired stabilization or improvement. For this chemical reaction to occur, it requires a cementitious product that alters the soil to achieve the desired changes in engineering properties.

Class C fly ash produces cementitious compounds that bind the soil particles and thereby achieve the desired stabilization. Class C Fly Ash has certain amounts of free lime (CaO) available to react with clay minerals to further stabilize or alter the soil properties (Ash Grove Resources, L.L.C, 2006). A major consideration when using Class C Fly Ash in soils is the rapid rate of hydration. When this factor is properly addressed in the mix design and construction procedures, significant benefits are improved in the four engineering properties including shear strength, compressibility, permeability, swell potential (Ash Grove Resources, L.L.C, 2006). Class C fly ash presents some good possible application uses in the construction industry for the treatment of expansive clay soils. It has been commonly used as solutions for the industry when faced with expansive clay soils. The soils can be replaced with materials having a low shrink-swell potential or the soil can be treated with lime. Lime stabilizes expansive soils by means of a chemical alteration of the clay minerals in the soil as evidenced by the reduction in Atterberg limits (Ash Grove Resources, L.L.C, 2006). Class C fly ash is also effective in stabilizing expansive clays. However, since only limited amounts of free lime are available, the stabilization is achieved by physically binding the soil particles thereby restricting the expansion and contraction of such soils to acceptable limits (Ash Grove Resources, L.L.C, 2006). Class C fly ash can be used to reduce the shrink/swell potential in expansive clay soils (Ash Grove Resources, L.L.C, 2006). There are a number of additional benefits to mixing class C fly ash in expansive clay soils (Ash Grove Resources, L.L.C, 2006). One is that the soil's strength is actually increased providing a more stable work base for construction. Another is the reduced sensitivity to additional moisture. Class C fly ash gives the construction industry an alternative solution to a wide range of issues that occur in construction projects. These clay soils no longer need to be replaced with expansive materials. Lime treatment is no longer the only chemical stabilization alternative to working with a clay soil. Using the class C fly ash to stabilize this type of soil is generally a more economical and time efficient construction procedure (Ash Grove Resources, L.L.C, 2006). Stabilization of pavement sub grade with class C fly ash can provide a significant increase in strength within the stabilized section. The stabilization can increase CBR (California Bearing Ratio) values from 3 to 5 for the untreated soils to values of 20 to 30 for the stabilized section (Ash Grove Resources, L.L.C, 2006).

3-2-3-3 Fly ash in concrete

Fly ash concrete was first used in the U.S. in 1929 for the construction of the Hoover Dam (NAHB Research Center, 2001), when engineers found that it allowed for less total cement usage. It is now used across the country. Consisting mostly of silica, alumina and iron, fly ash is defined as a pozzolan, which is a substance containing aluminous and siliceous material that forms cement in the presence of water. When mixed with lime and water it forms a compound similar to Portland cement. The spherical shape of the particles reduces internal friction thereby increasing the concrete's consistency and mobility, permitting longer pumping distances. Improved workability means less water is needed, resulting in less segregation of the mixture. Although fly ash cement itself is less dense than Portland cement, the produced concrete is denser and results in a smoother surface with sharper detail (NAHB Research Center – Tool base. http://www.toolbase.org/Technology-Inventory/Foundations/fly-ash-concrete, 2011).

Besides providing the critical size of fines needed to manufacture superior concrete, fly ash brings other chemical benefits and advantages to the mix design of concrete.

3-2-3-3-1- Advantages of using fly ash in plastic state concrete:

3-2-3-3-1-a- Improved workability

Because fly ash is spherical in shape it produces a paste with superior plasticity and reduces the amount of water needed in a mix (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-1-b- Reduced segregation

The improved cohesiveness of fly ash concrete provides added body to plastic state concrete, which resists segregation (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-1-c- Reduces bleed water

The lower water content required for workability in fly ash concrete reduces bleeding between cracks (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-1-d- Increased pump ability

The spherical shape of fly ash acts like tiny ball bearings, reducing internal friction, thereby producing a mix that is easier to pump (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-1-e- Reduces equipment wear

Fly ash concrete reduces wear on delivery and plant equipment because of the reduction of friction attributed to the spherical nature of fly ash (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2- Long term advantages of using fly ash in concrete:

3-2-3-3-2-a- Increases concrete strengths

Studies have indicated that fly ash concrete will continue to gain strength after 28 days with improved workability and a reduction in water needed. Fly ash concrete provides a lower water/cementitous ratio thereby producing superior strengths and longer life (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-b- Reduces drying shrinkage

By providing as much as a 10% water reduction in its plastic state. Fly ash concrete maintains workability and reduces drying shrinkage (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-c- Reduced permeability

The packing effect of the spherical fly ash particles helps to reduce permeability. The chemical reaction between fly ash and lime forms additional (C-S-H) bonds that block bleed channels and fill pore spaces (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-d- Resistance to sulphate attack

Fly ash combines with free calcium hydroxide making it unavailable to react with sulphates. In producing a less permeable structure there is increased resistance to aggressive soluble sulphate solutions resulting in longer life (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-e- Mitigates alkali aggregate

Fly ash reacts with available alkalis in the hardened cement matrix making them less likely to react with the aggregate (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-f- Reduces heat of hydration

Large masses of concrete typically produce high internal temperatures and thermal cracking. Fly ash concrete produces appreciably less heat than Portland cement concrete (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-g- Cost competitive

When used in appropriate applications fly ash concrete is cost competitive and may reduce project time with fast and easy placement of materials, less equipment, and fewer people (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-2-h- Environmental factors

Incorporating fly ash in a concrete mix design also enables cement and concrete producers to reduce the GHG emissions associated with the manufacture of Portland cement and concrete. As fly ash use in concrete increases, it leads to greater environmental sustainability through both the avoidance of landfill and the reduction resources for future use (Association of Canadian Industries Recycling Coal Ash, 2006).

3-2-3-3-3 Benefits/Costs

Fly ash does not require the energy intensive kilning process required by Portland cement. This energy expense can also be calculated in terms of fuel use. A single ton of cement requires approximately 55 gallons of oil to produce

(American Coal Ash Association, 2008). By using fly ash concrete instead, we prevent disposal, conserve virgin resources by using an industrial by-product material and we prevent the energy consumption associated with mining virgin materials. Economic gains are significant from both technical and sustainability perspectives, as well as from an aesthetic point of view. Projects that endure save taxpayers maintenance and reconstruction costs, freeing money to stimulate local economies and enhance communities. Fly ash typically costs less than Portland cement, making concrete competitive with other materials such as wood and asphalt (American Coal Ash Association, 2008). Table 3.7, which is cited from the Environmental Protection Agency in USA, shows the benefits of replacing 15 % of Portland cement with fly ash.

Table 3.7- Benefits obtained by replacing 15% of Portland cement with Fly Ash (adapted from EPA 2008).

Benefit		Savings/ton fly ash
Energy	Savings (million Btu/ton fly ash)	4.0
	Financial Savings (US$/ton fly ash)	123.5
Water Use	Savings (gal/ton fly ash)	90.1
	Financial Savings (US$/ton fly ash)	0.23
GHG Emission	CO_2 (ton/ton fly ash)	0.7
	Financial Savings (US$/ton fly ash)	2.6

The price of fly ash per ton is typically one half to one third of the price of Portland cement. As the use of Portland cement increases or decreases, the prices for fly ash follow that movement (American Coal Ash Association, 2008).

3-2-3- 4 Fly Ash in Roads and Bridges

The cost to build roads, runways, and bridges would increase by an estimated $104.6 billion over the next 20 years if coal fly ash were no longer available as a transportation construction building material, according to a new study by the American Road & Transportation Builders Association's Transportation Development Foundation (ARTBA-TDF, Alison, 2011).

The ARTBA-TDF study was conducted to forecast the potential economic impacts of the loss of fly ash availability in just one U.S. construction market – transportation infrastructure. The study identified $5.23 billion in annual direct cost increases if fly ash were unavailable for use in concrete for transportation projects. That includes a $2.5 billion increase in the price of materials and an additional $2.73 billion in pavement and bridge repair work due to the shorter pavement and service life of other Portland cement blends. To put the $5.23 billion figure in perspective, it is almost $2 billion per year more than the federal government currently invests in the Airport Improvement Program and about 13% of the federal government's annual total annual aid to the states for highway and bridge work (Alison, 2011). Without the availability of fly ash, American taxpayers would ultimately bear the burden, either paying more for the same level of transportation improvements, or dealing with the consequences of a scaled back improvement program. According to the study's findings, the estimated savings from the increased durability of various fly ash concrete life spans would be:

- $25 billion over 20 years ($1.2 billion per year average) if all concrete roadways were designed with fly ash concrete materials to last 35 years, compared to the current national average of 20 to 25 years.
- $33.5 billion over 20 years ($1.7 billion per year) if all concrete roadway repair and reconstruction work used fly ash concrete with a 40-year life span.
- $51.5 billion over 20 years ($2.6 billion per year) if all concrete roadway repair and reconstruction work used fly ash concrete with a 50-year life span.
- $65.4 billion over 20 years ($3.2 billion per year) if all concrete roadway repair and reconstruction work used fly ash concrete with a 60-year life span (Alison, 2011).

The analysis utilized bid tab data from 48 states and Washington, D.C., collected and was organized by Oman Systems, Inc., in Nashville, Tenn. The same data are used by the Federal Highway Administration (FHWA) to calculate the National Highway Construction Cost Index. Table 3.8 shows the use of concrete and estimated fly ash value ($ millions) in road construction.

Table 3.8- National Use of Concrete & Estimated Fly Ash (FA) Value ($ Millions)

Year	Total value of concrete materials	Value of total bids	Concrete cost as % of total bids	Estimated FA concrete as % of total bids	Estimated value of FA concrete
2005	$5,503	$28,822	19.1%	15%	$4,237.59
2006	$6,201	$33,284	18.6%	14%	$4,774.61
2007	$5,325	$30,230	17.6%	14%	$4,100.29
2008	$5,043	$28,120	17.9%	14%	$3,883.41
2009	$6,095	$33,873	18.0%	14%	$4,693.30
2010	$6,628	$31,717	20.9%	16%	$5,103.41
Average	$5,799	$31,008	18.7%	14%	$4,465.43

Source: Analysis of state DOT bid tab data provided by Oman Systems Inc. (2010)
Note: This table assumes an average of 77 percent of all concrete utilizes fly ash.

3-2-3-5 Fly Ash in Bricks

"Bricks whose solid ingredient is 100% fly ash have been manufactured. The manufacturing process uses techniques and equipment similar to those used in clay brick factories. The bricks produced were about 28% lighter than clay bricks. The bricks manufactured from fly ash possessed compressive strength higher than 40 MPa. This exceeds some of the best of load carrying clay bricks available by more than 25% and is several times better than acceptable commercially available common clay bricks. Other important characteristics of the fly ash bricks have been evaluated. These included absorption capacity, initial rate of absorption, modulus of rupture, bond strength and durability. The values of these characteristics for fly ash bricks are excellent and have exceeded those pertaining to clay bricks" (High Performance Bricks from Fly Ash, Obada Kayali, 2005).

As shown in figure 3.3 these bricks are similar color to cement, are uniform in shape and smooth in finish, also, they require no plastering for building work. The bricks are of dense composition, free from visible cracks, warp-edge, organic matter, pebbles and nodules of free lime. They are lighter in weight than ordinary clay bricks and less porous as well. The color of fly ash bricks can be altered with the addition of admixtures during the process of brick making. They come in various sizes, but generally are similar to the sizes of clay bricks (http://flyashbricksinfo.com/index.html)

Source :(http://flyashbricksinfo.com/index.html)

Figure 3.3: Fly Ash Bricks

3-2-3-5-a- Structural Capability

Theses bricks can provide advantages due to the fact that they are available in several load-bearing grades, through the savings in mortar plastering, and by giving smart-looking brickwork. High compressive strength eliminates breakages/wastages during transport and handling, the cracking of plaster is reduced due to lower thickness of joints and plaster and basic material of the bricks, which is more compatible with cement mortar. Due to their comparable density, the bricks do not cause any extra load for design of structures and provides better resistance for earthquake loads due to panel action with high strength bricks. Compressive strength of fly ash sand lime bricks is av. 9.00 MPa (as against 3.50 MPa for handmade clay bricks) (http://flyashbricksinfo.com/index.html).

3-2-3-5-b- Thermal properties

Thermal conductivity is 0.90-1.05 W/m² ºC (20-30% less than those of concrete blocks). These bricks do not absorb heat; they reflect heat and give maximum light reflection without glare (http://flyashbricksinfo.com/index.html).

3-2-3-5-c- Sound insulation

It provides an acceptable degree of sound insulation (http://flyashbricksinf.com/index.html).

3-2-3-5-d- Fire and vermin resistance

Fly ash bricks have a good fire rating. They are not susceptible to vermin attacks or other infestations (http://flyashbricksinfo.com/index.html).

3-2-3-5-e- Durability and moisture resistance

These blocks are highly durable, and after the proper pointing of joints, the bricks can be directly painted in dry distemper and cement paints, without a backing coating of plaster. Rectangular faced with sharp corners, solid, compact and uniformly water absorption is 6-12% as opposed to 20-25% for handmade clay bricks reducing dampness of the walls (http://flyashbricksinfo.com/index.html)

3-2-3-5-f- Toxicity and Breath-ability

There are no definite studies on the toxic fume emissions or the indoor air quality of structures built with fly ash bricks, though claims of radioactive emissions by these blocks have been made at some scientific forums (http://flyashbricksinfo.com/index.html). Fly ash as a raw material is very fine and care has to be taken to prevent it from being airborne and causing serious air pollution, as it can remain airborne for long periods, causing serious health problems relating to the respiratory system. However, blocks manufactured from fly ash have no such problems (http://flyashbricksinfo.com/index.html).

3-2-3-5-g- Build ability, availability and cost

The blocks have an easy workability and high compressive strength eliminating breakages and wastage during handling, and giving a neat finish with lower thickness of joints and plaster. The construction technique remains the same as when using regular bricks, ensuring an easy change of materials, without requiring additional training for the masons (http://flyashbricksinfo.com/index.html).

3-2-3-5-h- Applicability

Because the blocks are available in several load-bearing grades, they are suitable for use in the following:

- Load bearing external walls, in low and medium size structures.
- Non-load bearing internal walls in low and medium size structures.

• Non-load bearing internal or external walls in high-rise buildings.

(http://flyashbricksinfo.com/index.html)

3-2-3-6 Fly Ash in Other Applications

3-2-3- 6-a- Recycling Hot Mix Pavements

Many state departments of transportation (DOTs) and other entities are charged with rehabilitating existing asphalt pavements, whether streets or parking lots. With limited funds and unlimited needs, recycling the existing pavement is an economical choice. Recycling of pavements can be accomplished by pulverizing existing hot mix pavements and granular bases and then adding class C fly ash to stabilize the materials, thus producing an acceptably stabilized base section. Then, a new hot mix wearing surface is put down on top of it. Test sections have shown that the recycling process can provide a stabilized section having twice the structural capacity of a crushed aggregate base. Due to the higher structural capacity of the recycled section, the thickness of the wearing surface can be reduced, proving an even greater project savings (Ash Grove Resources, L.L.C, 2006).

3-2-3- 6-b- Structural Fill

As the lack of supply and increased cost in virgin fill materials has occurred, so has the rise in usage of class C fly ash in structural fills. Common application includes building sites, building foundations, levees or dykes, highway embankments, railways, bridges, that is, any project which needs a compacted, stable fill section. Stabilizing with class C fly ash can allow the use of steeper embankment slopes. As with other applications, control of moisture contents and compaction delay is required to achieve the full potential benefit of the stabilization process (Ash Grove Resources, L.L.C, 2006).

3-2-3- 6-c- Aggregate Base Stabilization

Stabilization with class C fly ash can provide a more economical solution for stabilizing even with poor quality aggregates. The class C fly ash serves as a cementing material increasing the strength of compacted sections. The aggregate when fully cemented by the ash has greater strength while significantly improving durability (Ash Grove Resources, L.L.C, 2006).

3-3 Environmental Implications

Using fly ash in concrete and other building products eliminates the need to dispose of the ash in landfills. In addition, when fly ash is used to replace cement in concrete, it reduces the need to manufacture cement, resulting in significant reductions in greenhouse gas emissions; for every ton of fly ash used to replace cement in concrete, approximately 0.7 tons of greenhouse gas emissions are avoided (USEPA, 2008). Based on the ACAA Production & Use Survey results (ACAA, 2011), approximately 11 million tons of greenhouse gas emissions were avoided by using coal ash to replace cement in 2010 alone (ACAA, June 2012).

In summary, the benefits of using Fly Ash in construction industry applications include:

3-3-1- Coal Combustion Products: Safe and Valuable Resources

3-3-1-a- Coal combustion products are not hazardous and are safe for human health when managed properly

- The chemical constituents of coal ash are commonly found in many everyday products and natural materials, including soil (ACAA, 2009).

3-3-1-b- Beneficial use of coal combustion products (CCPs) can result in significant societal and environmental benefits

- Coal ash can be beneficially used in a variety of applications–many of which are sustainable construction practices, as in materials such as concrete.
- Using CCPs saves the energy needed to extract and process other materials for these same uses.

  (ACAA, 2009)

3-3-1-c- Beneficial use of coal combustion products has increased steadily since the 1960s, and contributes to economic growth

- The U.S. utility and construction materials industries have nearly doubled the beneficial use of coal ash from 22 percent in 1989 to 43 percent in 2007(American Coal Ash Association, 2009).

- Annually, the production and use of CCPs contributes more than $4 billion to the U.S. economy and provides jobs for thousands of workers (ACAA, 2009).

3-3-2- Coal Combustion Products: Environmentally and Socially Beneficial

3-3-2-a- Coal ash use is supported by the Federal government and many states as a way to reduce the impact of our industrial practices on the environment

- Using coal combustion products (CCPs) in an environmentally safe manner reduces energy consumption, saves virgin resources, and lessens greenhouse gas emissions (GHG) (ACAA, 2009).

3-3-2-b- Fly ash is more than a high performance material, it meets policy goals for sustainability

- Since the early 1950s, fly ash has been used in roadways and interstate highways. Furthermore, in 1974, the Federal Highway Administration encouraged the use of fly ash in concrete pavement with Notice N 5080.4, which urged states to allow partial substitution of fly ash for cement whenever feasible. (U.S. Department of Transportation, 2003).
- Federal concrete projects used an estimated 5.3 million metric tons of coal fly ash in 2004 and 2005 combined. This substitution yields a number of environmental benefits, including avoided energy use of approximately 25 billion mega joules; avoided water consumption of two billion liters; and

avoided carbon dioxide emissions equivalent of 3.8 million metric tons. Energy and water savings represent two significant impacts that can be monetized using market prices. Results indicate that the beneficial use of coal fly ash in 2004 and 2005 resulted in energy savings valued at approximately $700 million, and water savings valued at approximately $1.2 million. (The U.S. EPA Report to Congress, June 3, 2008).

3-3-2-c- Current green building practices encourage using recycled materials such as coal ash and other industrial byproducts

- Green building rating systems encourage the use of materials locally available, with recycled content that contributes to innovation and reduction of the consumption of other resources such as water. (U.S. Green Building Council, Leadership in Energy & Environmental Design (LEED) and Green Building Initiative Green Building Assessment Protocol for Commercial Buildings.)
- Coal combustion products used in construction practices and concrete products are required to adhere to consensus standards, such as the American Society for Testing and Materials, the American Concrete Institute, the American Association of State Highway and Transportation Officials, state departments of transportation, and others.
- The cost of one ton of ASTM C618 compliant fly ash is often half the price of Portland cement. Using fly ash instead of Portland cement can reduce

the cost of concrete in a project while improving its overall performance and durability (ACAA, 2009).

3-3-3- Coal Combustion Products: Creating Economic Sustainability

3-3-3-a- Construction project managers across America are learning that recycled-content construction products are cost-effective, reliable, easy to obtain, and environmentally friendly

- Organizations such as the Collaborative for High Performance Schools (CHPS) support the use of concrete containing fly ash in building construction. (California CHPS, November 2008; Texas CHPS, November, 2008; and Colorado CHPS February 2009)

3-3-3-b- The Federal government has taken a leadership role in encouraging and supporting sustainable practices through the use of industrial byproducts, such as coal ash, in its construction processes.

- Executive Order 13423, "Strengthening Federal Environmental, Energy, and Transportation Management," requires federal agencies to purchase green products and services, including recycled content products and environmentally preferable products and services.
- Federal Comprehensive Procurement Guidelines (CPGs), and Environmentally Preferable Purchasing (EPP), encourage and assist federal agencies in purchasing environmentally preferable products and services. The Ronald Reagan Building is cited as a case study which used

fly ash in concrete for the construction of this facility. (U.S. EPA http://www.epa.gov/epp/)

- The U.S. Army Corp of Engineers has specifications for concrete containing fly ash (www.usace.army.mil), and the Federal Aviation Administration supports the use of fly ash in many construction applications. (http://www.faa.gov/search/)
- States such as Wisconsin, Texas, Pennsylvania, Illinois, Iowa, Minnesota, and others, have state guidance pertaining to the use of coal combustion products in construction and transportation activities. Cites such as Denver, Seattle, New York City, Columbus (Ohio), and San Diego support green construction practices, including the use of coal combustion products (ACAA, 2008).

3-3-4- Some statistic data can further support the environmental benefits of using fly ash as a replacement for cement

The use of one ton of fly ash instead of cement has the following benefits:

- **Landfill space conserved**: enough for 455 days of solid waste produced by the average American.
- **CO_2 emissions reduced**: equal to 2 months of emissions from an automobile.
- **Energy saved**: enough to provide electricity to an average American home for 24 days.

- **Less water use**: concrete made with coal ash requires at least 10 percent less water to produce a long-lasting product (ACAA, coal combustion product (CCP) production use and survey, 2010).

In addition, Table 3.9 shows life cycle impacts of one ton of fly ash in concrete

Table 3.9 -Energy Savings and Life Cycle Impacts of One Ton of Fly Ash in Concrete

Metric Measurement	Amount
Avoided total CO_2 equivalent greenhouse gases (on average)	718,000 grams
Passenger cars not driven for a year	0.2 percent
Avoided gasoline consumption	310 liters or 82 gallons
Avoided oil consumption	1.7 barrels or 53.5 gallons

June 3, 2008 EPA Report to Congress (EPA530-R-08-007) Study on Increasing the Usage of Recovered Mineral Components in Federally Funded Projects Involving Procurement of Cement or Concrete to Address the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for User.

3-4- Impacts of Not Recycling Coal Ash

A review of the coal combustion products (CCP) reuse and recycling industry information for the past three years indicates the following trends as the uncertainty over regulatory issues persists (John N., 2011):

- Substantial volumes of coal ash that could have been recycled have been placed in the new lined, CCP landfills. Conservative estimates indicate the volume of re-routed and recyclable CCPs is in the range of 2 to 10 million tons over the past two years.

- There is a need for open space, and less damage of valuable natural resources, such as sand and gravel due to more landfills, and the filling up new landfills.
- Around 10 percent or 10 million tons of the coal ash has been re-routed away from construction fill material sand/or concrete the past two years. These changes resulted in:

1. 400,000 tons of additional greenhouse gases per year.
2. Over $50 million in additional energy costs per year.
3. Over 100 million gallons of additional water used for cement production or natural resources mining per year.

- Additional transportation costs and the resulting increase in greenhouse gas emissions from the burning of fossil fuels in hauling trucks and in construction equipment (John N., 2011).

CHAPTER 4 EXPERIMENTAL WORK

4.1 Introduction

For making fly ash-based green cement materials in masonry components applications, they would be exposed to different conditions of weather. Therefore, testing the ability of lasting a long time without significant deterioration is required. A durable material helps the environment by conserving resources and reducing wastes and the environmental impacts of repair and replacement. The production of replacement building materials depletes natural resources and can produce air and water pollution. Specimens have been tested for compressive strength at different ages (1-day, 3-day, 7-day, 28-day, and 90-day). The average of the 3 tests were reported. Typically, the 1-day, 3-day, 7-day, 28-day, and 90-day average compressive strengths were 25 MPa, 34 MPa, 49 MPa, 63 MPa, and 77 MPa respectively. In addition, A durability freeze-thaw test for concrete material according to ASTM C666 and hot weathering performance have been conducted to fly ash-based green cement materials in this study.

4.2 Freezing-Thawing Performance of Fly Ash-Based Green Cement Mortar

4.2.1 Experimental Program

4.2.1.1 Materials

The materials include class F fly ash, silica fume, metakaolin, sodium hydroxide (NaOH) flakes, water, and fine sand (Fly Ash-Based Green Cement).

4.2.1.1.1 Mix proportion and specimen preparation

The mix compositions of the freeze-thaw specimens are listed in table 4.1. This mix was selected from a previous study (Wu et al. 2010). Mortar prisms of 50.8mm x 50.8mm x 50.8mm are prepared for this study. Tree cubes are made per batch. Therefore, there are 15 prisms.

Table 4.1- Material mix ratios

Material	Ratio	Percentage
FA	1	28.8%
Meta	0.3	8.6%
SF	0.0975	2.8%
Sand	1.56	44.9%
NaOH	0.13	3.7%
Water	0.39	11.2%
Total	3.4775	100%

4.2.1.2 Freeze-thaw apparatus

The freezing-thawing tray consists of a mesh made from stainless steel rods and a plastic container. The clearance between specimens is 1 to 3 mm per the requirement of ASTM C666. One layer of fabric mesh (about 1 mm thick) is placed at the bottom of the container serving as the support of the specimens and preventing a direct contact of the specimens with the plastic container. Figure 4.1 shows the freeze thaw tray loaded with specimens. Distilled water is filled up to 2mm above the specimens. An ESPEC environmental chamber Figure 4.2 is used for the freeze-thaw test.

Figure 4.1: Freeze thaw tray loaded with specimens

Figure 4.2: ESPEC environmental chamber

4.2.1.3 Freeze-thaw cycle

ASTM C666 is a durability freeze-thaw test for concrete material, alternatively lowering the temperature of the specimens from 4 to –18 ° C and raising it from –18 to 4 ° C in not less than 2h no more than 5h. It is considered to be the most relevant to the durability of fly ash mortars focused here, while no standardized test procedure is available for fly ash material. Hence, it is adopted in this study, including temperature range, temperature ramp and period of cycle. Two methods are suggested in ASTM C666. Method A consists of freezing and thawing specimens in water. Method B consists of freezing specimens in air and thawing them in water. In this study, method A is employed because the process is more convenient than that of method B.

4.2.1.4 Testing and evaluation parameters

The experimental setup and procedure is described below for the following properties:

(a) Water absorption,

(b) Compressive strength.

Water absorption: A PGL 10001 digital balance (Figure 4.3, readability=0.1g, repeatability=0.1g) is employed for mass measurement. The procedure includes the following: (1) weigh each specimen before putting it into the freeze thaw tray and record M1 (dry weight, g), (2) remove the specimen from environmental chamber after reaching the number of cycles that planned for each sample and allow water to drain for 1 minute by placing it on a wire mesh, and (3) Remove visible surface water with a damp cloth, weigh and record as M2 (saturated weight, g). Then, the water absorption of each specimen is calculated as shown below:

$W (\%) = ((M2 - M1)/ M1) * 100$

Figure 4.3: Scale (readability=0.1g) is employed for mass measurement

Compressive strength: Compressive strength test is performed by using a MTS 810 machine (Figure 4.4). The loading (displacement control) rate is 0.01mm/second, and the compressive strength is calculated from the maximum applied load at the point of prism failure. Figure 4.5 shows Compression test setup of a prism specimen.

Figure 4.4: MTS 810 machine employed for compression test

Figure 4.5: Compression test setup of a prism specimen

4.2.1.5 Experimental procedures

The entire freeze-thaw test lasted 300 cycles. Per ASTM C666, the following procedure was followed before and during the test:

(1) Three specimens were tested for each batch. Therefore, there were 15 specimens totally. After being cured in air for 3 days, the group I was tested for compressive strength to be a control sample and the others were put in the ESPEC environmental chamber after being weighted.

(2) Fifteen specimens from the same composition were divided into 5 groups (I, II, III, IV, and V). Just before the freeze-thaw test started, all the specimens were measured for weight. Samples II, III, IV, and V were loaded in the freeze-thaw tray and the freeze-thaw test started.

(3) After 50, 100, 200, and 300 cycles, samples II, III, IV, and V specimens were removed respectively from the chamber machine and measured for water absorption and tested for compressive strength. The average of the 3 tests were reported. Freeze-thaw test ended after 300 cycles.

4.2.2 Results and Discussions

The average water absorption of control sample (0 cycles) was 2.56%. After 50 cycles, the average water absorption was 4.3% and increased with a small amount at 100 cycles to 4.37%. At 200 cycles, the average water absorption reached 5% and at the end of test that is after 300 cycles the average water absorption was 5.4%. Figure 4.6 shows the results of water absorption.

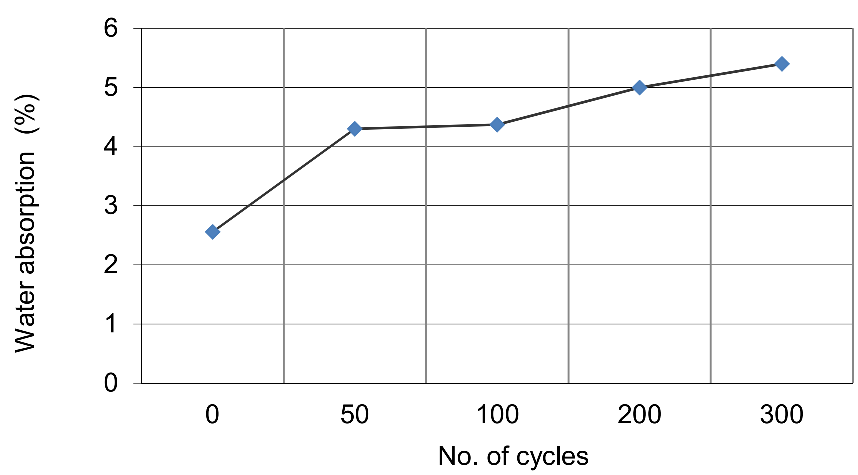


Figure (4.6) The relationship between the water absorption and number of cycles in freeze-thaw test for Green Cement

The initial average strength, of the group I specimens was 30 MPa. Specimens have been tested for compressive strength at different cycles (50, 100, 200, and 300 freeze-thaw cycles for all the specimens). It is noted that the green cement specimens did not deteriorate at all in terms of compressive strength. Moreover, the compressive strength increased to some extend with 37Mpa which is believed to be as a result of getting more cure at the end of the test.

4.2.3 Conclusions

The freeze-thaw performance of green cement mortar is investigated experimentally in this section. The freeze-thaw test is carried out in accordance with ASTM C666. The following conclusions can be reached from the test results: (1) the rate of change in water absorption was higher at the beginning of test at 50 cycles than at the end of test that is 300 cycles. (2) The green cement specimens did not lose strength even after 300 freeze-thaw cycles. (3) The dry density and the water absorption ratio of the fly ash-based green cement mortar were on average 2090 Kg/m3 and 125 Kg/m3) which were met the requirements for masonry units.

4.3 Hot Weathering Performance of Fly Ash-Based Green Cement Mortar

4.3.1 Experimental Program

4.3.1.1 Materials

The materials include Class F fly ash, silica fume, metakaolin, sodium hydroxide (NaOH) flakes, water, and fine sand (Fly Ash-Based Green Cement)

4.3.1.1.1 Mix proportion and specimen preparation

The mix compositions of the hot weathering samples are listed in table 4.1. Mortar prisms of 50.8mm x 50.8mm x 50.8mm are prepared for this study. Three cubes are made per batch. Therefore, there were 15 prisms.

4.3.1.2 Hot weathering apparatus

Laboratory oven (figure 4.8) was used to provide high temperatures, and a timer (Figure 4.9) was used to control time.

Figure 4.7: Laboratory furnace, model # 21-350

Figure 4.8: Timer

4.3.1.3 Thermal cycle

The samples were under 2 hr for each cycle, and the maximum temperature was 180° C (356°F). The numbers of cycles were 0, 40, 100, 200, and 300. Figure 4.10 shows thermal cycle.

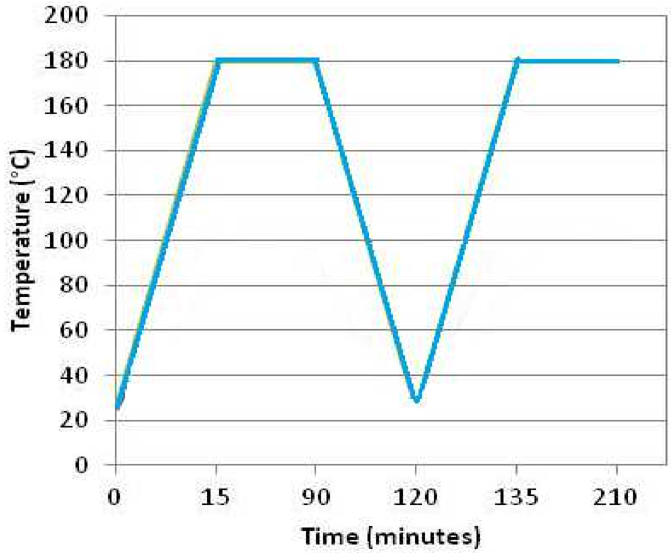


Figure 4.9: Temperature cycle 180° C (356° F)

4.3.1.4 Testing and evaluation parameters

The experimental setup and procedure is described below for the following properties:

(a) Loss of mass,

(b) Compressive strength.

Loss of mass: A PGL 10001 digital balance figure 4.3 (readability=0.1g, repeatability=0.1g) is employed for mass measurement. The procedure includes the following: (1) weigh each specimen before putting it into the oven and record M1, (2) remove the specimens from the oven after reaching the number of cycles that planned for each sample for weighing and record as M2. Then, taking the difference between M1 and M2 and calculate the percentage of loss in mass.

Compressive strength test is performed by using a MTS 810 machine (figure 4.4). The loading (displacement control) rate is 0.01mm/second, and the compressive strength is calculated from the maximum applied load at the point of prism failure. Figure 4.5 shows Compression test setup of a prism specimen.

4.3.1.5 Experimental procedures

The entire thermal cycles test lasted 300 cycles, the following procedure was followed before and during the test:

(1) Three specimens were tested for each batch. Therefore, there were 15 specimens totally. After being cured in air for 3 days, the group I was tested for compressive strength to be a control sample and the others were put in the oven after being weighted.

(2) Fifteen specimens from the same composition were divided into 5 groups (I, II, III, IV, and V). Just before the hot weathering performance test started, all the specimens were measured for weight; and the specimens of sample I were then tested for compressive strength without being in thermal cycle to be as a control sample. Samples II, III, IV, and V were loaded in the oven and the thermal cycle test started.

(3) After 40, 100, 200, and 300, group II, III, IV, and V specimens were removed respectively from the oven and measured for weight and tested for compressive strength. Thermal cycle test ended after 300 cycles.

4.3.2 Results and Discussions

The average loss of mass after 40 was -7.61%. It was stable from 100 cycles to 200 cycles and then increased up to -8.57% at the end of test (300 cycles). Figure 4.11 shows the results of loss in mass.

The initial average strength of the group I specimens was 30 MPa. Figure 4.12 shows the compressive strength retentions after 40, 100, 200, and 300 thermal cycles for all the specimens. It is noted that the green cement specimens did not deteriorate at all in term of compressive strength. However, the compressive strength increased to 271% after 100 thermal cycles and at the end of the test (300 thermal cycles) was 184 %.

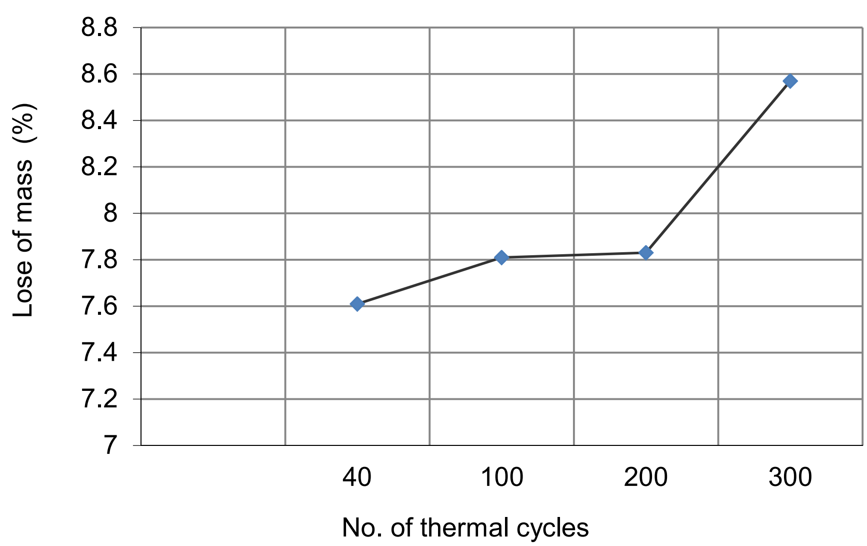


Figure (4.10) The relationship between the lose of mass and number of cycles in thermal cycles for Green Cement

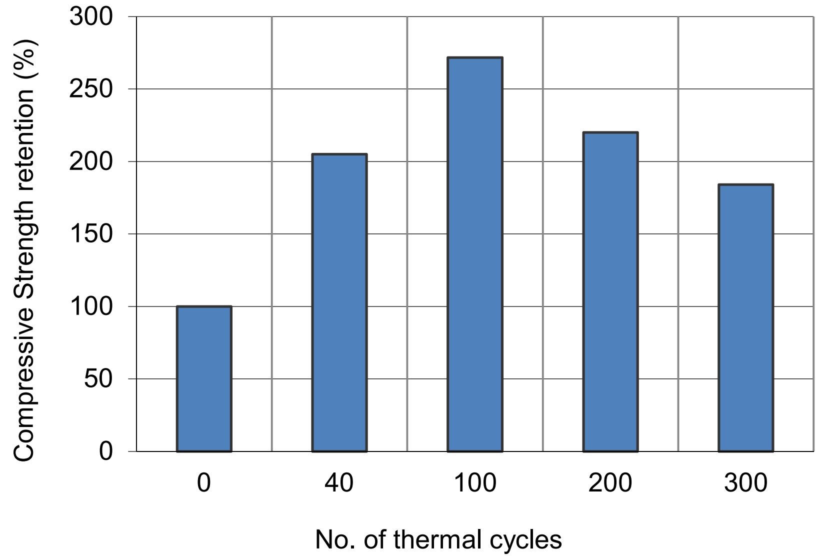


Figure 4.11: Compressive strength retention (%) for Green Cement after 0, 40, 100, 200, and 300 thermal cycles

4.3.3 Conclusions

The hot weathering performance of fly ash-based green cement mortar is investigated experimentally in this section. The following conclusions can be reached from the test results: (1) the initial mass loss was 7.61% after 40 cycles. (2) the rate of change in loss of mass was insignificant from 40 cycles to the end of the test (300 cycles). The difference between the percentage of mass loss at the beginning of test (40 cycles) and the percentage of losing mass at the end of test (300 cycles) does not exceed 1%. (3) the green cement specimens did not lose strength even after 300 thermal cycles. Moreover, the compressive strength of samples after being exposed to thermal cycles was much higher than the compressive strength of control sample (at 0 cycles).

CHAPTER 5 APPLICATION OF FLY ASH-BASED GREEN CEMENT

5.1 Introduction

The fly ash-based green cement mixture is a relatively new material. Attempting to develop a new material that is environmentally friendly for civil engineering use, fly ash has been found to be a good candidate for replacing Portland cement, partially or even completely. For applications that typically use Portland cement, green cement materials may be very good candidates for replacing cement in the making of masonry units.

5.2 Potential Application of Fly Ash-Based Green Cement Materials: Replacing Concrete Masonry Units (CMU)

5.2.1 Concrete Masonry Units (CMU)

Since 1882, when the first concrete block was molded, concrete masonry has become a standard building material (National Concrete Masonry Association, 2010). Concrete masonry unit (CMU) walls are an extremely useful framing system, capable of bearing the weight of upper floors and roofs while creating the exterior and interior walls of the building. The CMU walls can take the place of columns, beams, and drywall construction. The most common concrete masonry products are block and brick. In North America, concrete blocks are used widely in both load bearing and non-load bearing applications, whereas concrete bricks are commonly employed in non-load bearing veneers and pavers (Drysdale et al, 1994). According to the National Concrete Masonry

Association (NCMA, 1999), there are approximately 650 manufacturers of concrete masonry products in the United States, with an average service radius of 50-75 miles for each producing location. In 1999, more than 63 million tons of raw materials were consumed by the concrete masonry industry, which included 5.3 million tons of Portland cement. Nearly 7 billion square feet of masonry walls are produced yearly in North America (American Institute of Architects, 2008).

Concrete masonry units are widely used in construction. However, some drawbacks still exist and are difficult to overcome. Overall, there are five major drawbacks associated with Portland cement: (1) High-energy consumption from cement production. “Cement production is one of the most energy intensive of all industrial manufacturing processes.” (Wilson 1993), (2) Emission of greenhouse gasses from cement production. About one ton of carbon dioxide (CO_2) is released into the environment for every one-ton cement production, and it is estimated that the Portland cement industry accounts for about 8% of the total CO_2 emissions from all human activities (Wilson, 1993; Davidovits, 2002b). (3) Portland cement concrete may deteriorate when exposed to severe environments, such as sulfate, acid, and seawater (Mindess et al, 1981). (4) Portland cement concrete may deteriorate from frost damage when experiencing freezing and thawing cycles. For structures in cold areas, freeze-thaw durability is especially prevalent in cold regions (Mindess et al,1981; Sun, 2005). (5) Moderate temperature resistance. These drawbacks can only be overcome by adopting new materials, such as fly ash-based green cement. In this study, a potential application of fly ash-based green cement is investigated based on the market needs and their advantages over Portland cement.

5.2.2 Specifications and Standards of Concrete Masonry Units (CMU)

In the U.S., concrete masonry units (CMU) are manufactured to conform to ASTM C140, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. C140 and its annexes cover the standard CMU, and various other concrete masonry products such as concrete brick, segmental retaining wall units (SRWs), interlocking pavers, grid pavers, and roof pavers. This standard ensures consistent properties such as size, density (weight), water absorption, and strength. In addition, ASTM C90 and ASTM C129 specify the property requirements for load bearing and non-load bearing concrete masonry units, respectively. Table 5.1 lists the physical requirements according to ASTM C90 and C129.

Table 5.1- Physical requirements of concrete masonry units (ASTM C90 and ASTM C129)

Unit class	Compressive Strength [a], min, (MPa)		Water absorption, max, (Kg/m^3), average of 3 units		
	Average of 3 units	Individual unit	Lightweight [b]	Medium weight [c]	Normal weight [d]
Loadbearing (ASTM C90)	13.8	12.4	288	240	208
Nonloadbearing (ASTM C129)	4.14	3.45	--	--	--

(1). Sampling and testing of units according to ASTM C140;
(2). The linear shrinkage of units at delivery shall not exceed 0.0065%;
(3).
a. Compressive strength is based on average net area;
b. Oven-dry weight of concrete is less than 1680 Kg/m^3;
c. Oven-dry weight of concrete is more than 1680 but less than 2000 Kg/m^3;
d. Oven-dry weight of concrete is more than 2000 Kg/m^3.

5.3 Summary of Fly Ash-Based Green Cement properties

1- Mechanical and physical properties, and durability performance

As tested and shown in Chapter 4, typically, the 1-day, 3-day, 7-day, 28-day, and 90-day average compressive strengths were 25 MPa, 34 MPa, 49 MPa, 63 MPa, and 77 MPa respectively. These values satisfy the strength requirements of ASTM C90 and C129 for masonry walls. Also, the dry density and the water absorption ratio of the fly ash-based green cement mortar were on average 2090 Kg/m3 and 125 Kg/m3) which were met the requirements for masonry units. Moreover, fly ash-based green cement mortar presented significant durability performance.

2- Advantages of using Fly Ash-Based Green Cement masonry units rather than Concrete Masonry Units

Using fly ash-based green cement masonry units rather than concrete masonry units for infrastructures have, at minimum, the following advantages:

- Environmental protection. Fly ash, a waste byproduct material, is recycled into making value-added products. Moreover, its use minimizes concrete's carbon footprint.

- Lower energy consumption and lower CO_2 emissions. Cement production consumes an intensive energy.

- Better durability. As tested experimentally and discussed in Chapter 4, green cement specimens retain good results when exposed to freeze-thaw cycles. Therefore, its use can maximize a structure's life cycle.

- Higher early-strength. As tested experimentally and discussed in Chapter 4, green cement specimens had an average early compressive strength of 25 MPa after one day.

5.4 Summary

In this chapter, the potential application of fly ash-based green cement materials in masonry blocks is investigated based on the market needs and their advantages over Portland cement. Portland cement concrete has many disadvantages that can only be overcome by being replaced with new materials such as fly ash-based green cement materials. Furthermore, the strength requirements of ASTM C90 and C129 for masonry walls were met in this study by using fly ash-based green cement mortar. Additionally, this study showed that the durability performance for fly ash-based green cement mortar had been significant and the dry density and the water absorption ratio of the fly ash-based green cement mortar were on average 2090 Kg/m3 and 125 Kg/m3) which were met the requirements for masonry walls. Considering the nearly 7 billion square feet of masonry walls produced yearly in North America (American Institute of Architects, 2008), considerable benefits in terms of saving energy, avoiding greenhouse emissions, and reducing consumption of raw materials would be achieved by using fly ash-based green cement. Hence, fly ash-based green cement is a very good candidate for replacing Portland cement in the making of masonry units.

CHAPTER 6 THE LITERATURE REVIEW OF BENEFIT-COST ANALYSES

6.1 Introduction

There are a lot of decisions that we need to make in our life. Some of them are similar and others are very different even if their outcomes are the same. In fact, as a result of many different and complex options we are not easily able to decide which option is the best or more suitable to us among available alternatives. These issues of interests may be dams and highways or can be training programs and health care systems. Therefore, we need to know the benefits and costs for each project to make a rational decision. Benefit-cost analysis is simply rational decision-making. It is used every day by people. Our methods for assessing benefits and costs are sometimes inadequate, especially when the alternatives are complex or the data uncertain. When this occurs, formal techniques are required to keep our thinking systematic, clear, and rational. These techniques constitute a model for conducting a benefit-cost analysis.

They include a variety of methods:

- identifying alternatives;
- defining alternatives in a way that allows fair comparison;
- adjusting for occurrence of costs and benefits at different times;
- calculating dollar values for things that are not usually expressed in dollars;
- coping with uncertainty in the data; and

- summing up a complex pattern of costs and benefits to guide decision-making (Treasury Board of Canada Secretariat, July 1998)

6.2 A History and Theory of Benefit-cost Analysis

6.2.1 Early Beginnings

When Benjamin Franklin was confronted with difficult decisions, he often recorded the pros and cons on two separate columns and attempted to assign weights to them. While not mathematically precise, this "moral or prudential algebra," as he put it, allowed for careful consideration of each "cost" and "benefit" as well as the determination of a course of action that provided the greatest benefit (Gramlich, 1990). While Franklin was certainly a proponent of this technique, he was not the first. Western European governments, in particular, had been employing similar methods for the construction of waterway and shipyard improvements (Corbett et al, 2007). Ekelund and Hebert (1999) credited the French as pioneers in the development of benefit-cost analyses for government projects.

The first formal benefit-cost analysis in France occurred in 1708. Over the next century, French economists and engineers applied their analysis efforts to canals (Ekelund et al, 1999). During this time, the Ecole Polytechnique had established itself as France's premier educational institution, and in 1837 sought to create a new course in "social arithmetic" (Corbett et al, 2007). In the 1840s French engineer and economist Jules Dupuit (1844, tr. 1952) published an article "On Measurement of the Utility of Public Works," where he posited that benefits to society from public projects were not the revenues taken in by the government (Aruna, 1980). Rather, the benefits were the difference between the public's willingness to pay and the actual payments the public made (which he theorized would be smaller). This "relative utility" concept was what Alfred Marshall would later rename with the more familiar term, "consumer surplus" (Ekelund et al, 1999).

Vilfredo Pareto (1906) developed what became known as Pareto improvement and Pareto efficiency criteria. Simply put, a policy is a Pareto improvement if it provides a benefit to at least one person without making anyone else worse off (Boardman, 1996). A policy is Pareto efficient (optimal) if no one else can be made better off without making someone else worse off. British economists Kaldor and Hicks (Hicks, 1941; Kaldor, 1939) expanded on this idea, stating that a project should proceed if the losers could be compensated in some way. It is important to note that the Kaldor-Hicks criteria states it is sufficient if the winners could potentially compensate the project losers. It does not require that they be compensated (Zerbe, 1994).

Much of the early development of cost-benefit analysis in the United States is rooted in water related infrastructure projects. The US Flood Control Act of 1936 was the first instance of a systematic effort to incorporate benefit-cost analysis to public decision-making. The act stated that the federal government should engage in flood control activities if "the benefits to whomsoever they may accrue in excess of the estimated costs," but did not provide guidance on how to define benefits and costs (Aruna, 1980, Persky, 2001). Early Tennessee Valley Authority (TVA) projects also employed basic forms of benefit-cost analysis (US Army Corp of Engineers, 1988). Due to the lack of clarity in measuring benefits and costs, many of the various public agencies developed a wide variety of criteria. Not long after, attempts were made to set uniform standards (Corbett et al, 2007). The U.S. Army Corp of Engineers "Green Book" was created in 1950 to align practice with theory. Government economists used the Kaldor-Hicks criteria as their theoretical foundation for the restructuring of economic analysis. This report was amended and expanded in 1958 under the title of "The Proposed Practices for Economic Analysis of River Basin Projects" (Persky, 2001). The Bureau of the Budget adopted similar criteria with 1952's Circular A-47 - "Reports and Budget Estimates Relating to Federal Programs and Projects for Conservation, Development, or Use of Water and Related Land Resources" (Corbett et al, 2007).

During the 1960s and 1970s the more modern forms of benefit-cost analysis were developed. Most analyses required evaluation of:

1. The present value of the benefits and costs of the proposed project at the time they occurred

2. The present value of the benefits and costs of alternatives occurring at various points in time (opportunity costs)

3. Determination of risky outcomes (sensitivity analysis)

4. The value of benefits and costs to people with different incomes (distribution effects/equity issues) (Layard et al, 1994)

6.2.2 Recent Developments

Executive Order 12292, issued by President Reagan in 1981, required a regulatory impact analysis (RIA) for every major governmental regulatory initiative over $100 million. The RIA is basically a benefit-cost analysis that identifies how various groups are affected by the policy and attempts to address issues of equity (Boardman, 1996). According to Dorfman, (Dorfman, 1997) most modern-day benefit-cost analyses suffer from several deficiencies. The first is their attempt "to measure the social value of all the consequences of a governmental policy or undertaking by a sum of dollars and cents". Specifically, Dorfman mentions the inherent difficultly in assigning monetary values to human life, the worth of endangered species, clean air, and noise pollution. The second shortcoming is that many benefit-cost analyses exclude information most useful to decision makers: the distribution of benefits and costs among various segments of the population. Government officials require this sort of information and are often forced to rely on other sources that provide it, namely, self-seeking interest groups. Finally, benefit-cost reports are often written as though the estimates are precise, and the readers are not informed of the range and/or likelihood of error presents (Corbett et al, 2007).

6.2.3 Probable Benefit-Cost Analysis

In recent years, there has been a push for the integration of sensitivity analyses of possible outcomes of public investment projects with open discussions of the merits of assumptions used. This "risk analysis" process has been suggested by Lewis and Flyvbjerg in the spirit of encouraging more transparency and public involvement in decision-making (Gomez-Ibanez, et al.,1999; Lewis and Flyvbjerg, 2003). Their research attempts to incorporate their recommendations in the benefit-cost analysis of each of the relevant alternatives, because a sensitivity (or risk) analysis allows for a more accurate reflection of reality. The methodology adopted in their research resembles one prescribed by the Treasury Board of Canada, as it is one of the few recent and published guidelines put forth (Treasury Board of Canada Secretariat, July 1998).

The Treasury Board of Canada's Benefit-Cost Analysis Guide recognizes that implementation of a project has a probable range of benefits and costs. It posits that the "effective sensitivity" of an outcome to a particular variable is determined by four factors:

- The responsiveness of the Net Present Value (NPV) to changes in the variable;
- The magnitude of the variable's range of plausible values;
- The volatility of the value of the variable (that is, the probability that the value of the variable will move within that range of plausible values); and

- The degree to which the range or volatility of the values of the variable can be controlled (Corbett et al, 2007).

6.3 The benefit-cost analysis framework

The framework of benefit-cost analysis organizes the measurements of costs and benefits and reveals the clear data in full. It can be used wherever a decision is needed, and is not limited to any particular academic discipline, such as economics or engineering. It is a hybrid of several techniques from the management, financial and social sciences fields. In order to make a direct comparison, benefit-cost analysis puts both benefits and costs into standard units (usually monetary values). In many cases, putting the benefits into monetary values is not an easy task hence a cost-effectiveness analysis is used as an alternative to the benefit-cost analysis. Cost-effectiveness analysis is a cost-minimization technique, choosing among the options is based on the minimum cost (Treasury Board of Canada Secretariat, July 1998).

6.4 The steps in benefit-cost analysis

Benefit-cost analysis does not have the same steps for all different cases. It depends on the conditions of each situation. Each analysis requires a unique thought process, as each analysis is contingent per situation, yet having a standardized general arrangement of steps to follow is helpful. The following steps are the general standard for benefit-cost analysis and more details will be provided later.

1. Examine needs, consider constraints, and formulate objectives and targets. Assess benefits and costs based on the determined point of view.

2. Define options in a way that helps the analyst to compare them fairly.

3. Gather data about costs and benefits, and analyze the incremental effects, and subsequently arrange them over time in tables.

4. Express the cost and benefit data in a valid standard unit of measurement, such as converting nominal dollars to constant dollars, and use accurate, undistorted prices.

5. Run the deterministic model (using single-value costs and benefits as though the values were certain). Find the deterministic estimate of net present value (NPV) is.

6. Conduct a sensitivity analysis, to determine which variables appear to have the most influence on the model.

7. Analyze risk by using what is known about the ranges and probabilities of the costs and benefits values and by simulating expected outcomes of the investment.

8. All of the quantitative and qualitative analysis factors that cannot be expressed in dollars should be considered and explained with reasoned recommendation (Treasury Board of Canada Secretariat, July 1998).

6.5 The components of benefit-cost analysis

The main four components of benefit-cost analysis are following:

- a parameters table;

- an incremental-effects model;
- a table of costs and benefits over time; and
- a table of possible investment results and a statistical and graphical analysis of NPV and investment risk (Treasury Board of Canada Secretariat, July 1998)

The parameter table which is a list of variables used to calculate the costs and benefits is the first component of the model. The use of a parameter table also provides all kinds of 'what if' analyses, including sensitivity analysis and risk analysis. The analyst uses it to change the value of the parameter with ease, a key requirement of risk analysis. Instead of searching through the whole model for all the places where the factor which is changed was used, the analyst can change the value in the parameter table, and all its uses in the benefit-cost model will change automatically and simultaneously. The second component is the incremental-effects model. It provides the expected events and consequences over time. The nature of the events varies from one project to another. These events are often subject to uncertainty, so keeping them in the parameter table in the same way of keeping the table of costs and benefits is helpful. The next component of the model is the table of costs and benefits over time. A list of all the costs and benefits with the values for each are noted for every period that is set up. These values are best-expressed in nominal dollars so that adjustments normally calculated in nominal dollars can be made. Nominal dollars cannot be added or subtracted across periods, however, they must at some stage be converted to constant dollars, and then to present values, before they can be summed up. In order to do this, two ways should be followed: The first way is to calculate the full table of benefits and costs in nominal dollars, then in constant dollars, and then in present values. The second way is a little easier and more concise: All benefits and all costs within each period will be add to obtain a single nominal-dollar net for each period and then converts this nominal-dollar net cash flow to constant dollars and present values (by convention, the analyst is allowed to add and subtract nominal dollars within a single period, although this is an approximation of true value because the worth of a dollar might change if the period is lengthy) (Treasury Board of Canada Secretariat, July 1998). Nominal and constant dollars will be explained more later.

Finally, the last component of the model is the results table. Each time the benefit-cost model is run, it estimates an outcome of the model. If it is a deterministic model, in which all the inputs have fixed values, then the result of each run will always be the same outcome. If it is a risk-analysis model, in which the parameters' values vary within a stated range according to probabilities, the estimated outcome will also vary. The result of many runs of the model will be a list of possible outcomes, and this list itself will have to be analyzed statistically to determine the probable true outcome. This statistical analysis will show the maximum and minimum values of the outcome and the probabilities that the outcome is within various ranges. With this information, the analyst can apply decision rules to realize whether the project is a good one and whether it is the best alternative (Treasury Board of Canada Secretariat, July 1998).

6.6 Constructing tables of costs and benefits

Constructing the tables of costs and benefits takes the greatest amount of time in a benefit-cost analysis. The analyst should identify the full set of relevant costs and benefits, estimates their quantities for each period, and calculate their values by applying their prices to their quantities in each period. All these need to be done accurately to construct these tables.

6.7 Accounting conventions

Conventions are important for many aspects of the model, such as the investment horizon, time-of-occurrence assumptions, and the numeraire—a common unit of measurement (Treasury Board of Canada Secretariat, July 1998).

6.7.1 The investment horizon

The end of the period over which costs and benefits are compared assist in recognizing whether an investment is valid as defined by the investment horizon. The best investment horizon can be obtained by acquiring the full economic life of the investment. Costs and benefits could be identified for the entire economic life of the project making uncertainties low as a result. If not, there may be logical points in the economic life of the project at which to terminate the investment analysis (Treasury Board of Canada Secretariat, July 1998).

6.7.2 Time-of-occurrence assumptions

At different points within the standard period being used, costs and benefits analysis takes place. Therefore, there is a need for convention when establishing where all costs and benefits will be assumed to fall within the period. Usually, the one of three possibilities would be selected: either at the beginning of each period, in the middle, or at the end. Underlying this practice is the need to have a reasonably simple pattern of costs and benefits over time so that changing nominal dollars to constant dollars, and to present values, is not too difficult (Treasury Board of Canada Secretariat, July 1998).

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6.7.3 The numeraire-a common unit of value

All costs and benefits must be expressed in a common unit of value before they can be summed up. This involves three main things: expressing them all in a common numeraire (dollars of investment funds); adjusting for inflation where necessary (converting to constant dollars); and expressing all in present values (adjusting for differences in the time of occurrence of costs and benefits). The benefits and costs must be in a common monetary unit before they can be compared. Most investment analysis uses a dollar of investment as the unit of measurement. However, some public-sector models use a dollar of consumption or a dollar of foreign exchange as the numeraire. All are acceptable, but they should be clear and consistent. If price distortions are widespread in a particular economy, the benefit-cost analysis may use border prices or world prices as the numeraire, which is as the best measure of true value of benefits and costs (Treasury Board of Canada Secretariat, July 1998).

6.8 The report

In general, reports should contain at least the following:

- a description of the need, problem or opportunity;
- a description of the options with an explanation of why they were chosen and why it is fair to compare them;
- a statement of the point of view of the analysis;
- a statement of assumptions and scenarios;
- a deterministic analysis;
- a cost-benefit analysis and a risk analysis;
- a discussion of equity effects and other non-economic effects; and
- a ranking of the options (Treasury Board of Canada Secretariat, July 1998).

6.9 Defining fair options

6.9.1 Why are fair options difficult to define?

In order to achieve a fair comparison as well as to take all alternatives into account for a benefit-cost analysis, two requirements must be met. First, it must be ensured that all the relevant alternatives are considered. A comparison between the proposed investment and the best alternative uses of the resources should be conducted. It is not enough to assume that a proposed project has only to make a return equal to the discount rate to be acceptable. There may be alternative projects that would do even better. The second requirement is that each alternative must be fairly and consistently defined to be compared in the correct manner. Having two investment alternatives at different scales, occurring at different times, or involving different ownership can make a comparison even more difficult (Treasury Board of Canada Secretariat, July 1998).

6.9.2 An optimized base Case

Identifying the set of most promising options is important. On what will or will not work here takes the focus, the question of financial attractiveness puts aside for the moment. No option should be eliminated at this stage of the benefit-cost analysis on the grounds of politics or equity before its net economic values are known (Treasury Board of Canada Secretariat, July 1998).

6.9.3 How to construct fair options

Standardizing options whose present values for time, for scale, and for already-owned components is the only way to ensure that alternatives are fairly being compared (Treasury Board of Canada Secretariat, July 1998).

6.9.4 Standardize the options for timing

The longer time frame for two investment alternatives must be taken to standardize with different time frames. If one project starts earlier and the other finishes later, then the earlier start and the later finish normally define the standardized time frame. All resources need to be accounted for, in all alternative time frame projects, for the full timeframe (Treasury Board of Canada Secretariat, July 1998).

6.9.5 Standardize the options for scale

Similarly, as standardizing the options for time, if there are two investment alternatives involving different levels of investment, then there must specifically account for the resources left over after making the smaller investment rather than just assuming they generate a zero net present value (NPV) (Treasury Board of Canada Secretariat, July 1998).

6.9.6 Standardize the options for already-owned components

"If one investment option uses a resource that is already owned by the government, then the analyst must also show what would happen to this resource for each of the alternative investment options" (Treasury Board of Canada Secretariat, July 1998).

6.9.7 Non-essential components of options

"Options must be self-standing, as well as fair. That is, they must be complete and spare. Spare means there should not be anything in the option that is not essential to it" (Treasury Board of Canada Secretariat, July 1998).

6.9.8 Incremental effects analysis

There is a need of clear understanding of the incremental events and consequences to be expected before undertaking a financial or economic analysis of a proposed project or program.

In benefit-cost analysis, then, two ‘subject matter’ skills will always be needed:

• Expertise in estimating the expected frequency of events; and

• Expertise in assessing the potential consequences of events.

The benefit-cost analyst brings two additional skills to bear on the information provided by the subject-matter experts:

• Expertise in valuing outcomes in dollars

•Expertise in making fair comparisons between benefits and costs (Treasury Board of Canada Secretariat, July 1998).

6.10 Measuring and valuing costs and benefits

6.10.1 Some Important Concepts

In benefit-cost analysis transfers, incrementally, opportunity cost, sunk cost and residual value are important concepts that need to be watching carefully during the counting in standard units. Only incremental benefits and costs caused by the project should be compared, not those that are just associated with the project in some way. An in-depth understanding of the proposed investment and a consistent of view are important to be able to identify a coherent set of costs and benefits without double counting (Treasury Board of Canada Secretariat, July 1998).

6.10.2 Transfers compared with true benefits and costs

In benefit-cost analysis, only resources that are created or used up should be counted. Resources that are simply transferred from one pocket to another are not counted as costs or benefits (Treasury Board of Canada Secretariat, July 1998).

6.10.3 Opportunity cost and sunk cost

"In calculating the benefits of public projects, the proper valuation to use is the price consumers are willing to pay for the output, that is, producer's price plus taxes minus subsidies. In evaluating costs, the correct approach is less clear-cut" (Treasury Board of Canada Secretariat, July 1998).

6.10.4 Externalities

All of the locative effects in evaluations of the efficiency of government expenditures should be trying to take into account. Some of which may be less obvious than others, such implicit effects may be internal (to direct actors in the project) or external (to persons not directly acting in the project but included in the group whose point of view is being taken in the analysis) (Treasury Board of Canada Secretariat, July 1998).

6.10.5 Residual value

"A residual value is the value of an asset at the end of the investment horizon" (Treasury Board of Canada Secretariat, July 1998).

6.10.6 General administrative and overhead costs

Analyzing many possible investments over time may lead to a particular problem, which is deciding how to treat general costs that are not specific to a project. Such costs are sometimes called overhead costs or general and administrative costs. These are more or less fixed costs. The standard practice in benefit-cost analysis is to take the marginal or incremental approach to counting benefits and costs, but this approach ignores most of the program and overhead costs (Treasury Board of Canada Secretariat, July 1998).

6.10.7 Valuing costs and benefits by market prices

In benefit-cost analysis, market prices normally are considered as being good measures of the benefits and costs of an investment (Treasury Board of Canada Secretariat, July 1998).

6.10.8 Consumer surplus and producer surplus as components of value

The concepts of consumer surplus and producer surplus are basic to modern benefit-cost analysis. In 1844, Jules Dupuit, a French engineer, pointed out that the market price is the minimum social benefit produced by the output of a project. In fact, some consumers would be willing to pay more for the outputs than they actually have to pay (Treasury Board of Canada Secretariat, July 1998).

6.10.9 Consumer surplus when a public investment changes the price of a good

The price of the output in water, power, and telecommunications may be lowered by public investments. As a result, valuing the benefits of the project at the new lower price understates the project's contribution to society's welfare, because this may not consider the fact that the product with a lower price is accessible to more consumers (Treasury Board of Canada Secretariat, July 1998).

6.10.10 Consumer surplus and loss of financial viability

The analyst must clarify the amount of the financial shortfall and the source of funds of financing it when a public investment depends on estimates of consumer surplus for its viability, and is not viable on a strictly commercial basis (Treasury Board of Canada Secretariat, July 1998).

6.10.11 Valuing costs and benefits without good market prices

In cases of distorted market prices, what prices would be in the absence of the distortions should be estimated; these adjusted market prices (sometimes called social prices or true prices) should be used. In cases of no market prices -

distorted or undistorted, the analyst has to start from the first principles of using the concepts of consumer surplus and producer surplus to estimate the values for costs and benefits (Treasury Board of Canada Secretariat, July 1998).

6.10.12 Estimating value when market prices are distorted

Actually, the point of view of the benefit-cost analysis plays the main role of how important distortions in prices. In this case, the benefit-cost analysis is conducted for the government, and the country as a whole is the most important point of view for the analyst. This requires the analyst to use social prices (sometimes called shadow prices) rather than market prices if the market prices are distorted (Treasury Board of Canada Secretariat, July 1998).

Such social prices may be substantially different from market prices in some situations, including the following:

- When the currency is miss valued because of foreign-exchange controls;
- When wage rates are kept artificially high by union rules or legislation, despite unemployment;
- When anti-competitive conditions, monopolies (only one buyer) exist;
- When taxes or tariffs are applied directly to the good or service, as in value-added taxes; and
- When the government regulates, otherwise controls, or subsidizes prices (Treasury Board of Canada Secretariat, July 1998).

6.10.13 Estimating value when no market prices exist

When there are no market prices at all or the market mechanisms are indirect and difficult to observe, it is difficult to achieve the true values of resources used or generated by an investment, such as following cases:

- The value of travel-time savings;
- The value of health and safety;
- The value of the environment;
- The value of jobs created;
- The value of foreign exchange;
- The residual value of special-use facilities; and
- Heritage values (Treasury Board of Canada Secretariat, July 1998).

6.10.14 Some cases of difficult-to-estimate values

6.10.14.1 The value of health and safety

The "value of a life" can be defined in the form of the question: How much is it worth to avoid death? This question offers the point of view about the benefits and costs of health and safety that was being considered. It gradually became clear that this was not a sensible formulation of the question. In terms of considering small increments of risk about health and safety, this is a better way of thinking. The result of government investment in health and safety measures tends to be a small lessening of the risks encountered by broad segments of the population. It is this lessening of risk that can be valued in benefit-cost analysis.

Researchers use three methods to estimate the value of reductions in risk to health and safety (Treasury Board of Canada Secretariat, July 1998).

Method (1) is to observe people's actual behavior in paying to avoid risks or in accepting compensation to assume additional risk (Treasury Board of Canada Secretariat, July 1998).

Method (2) is to ask people to declare how much they value changes in the risks to which they are exposed. Both of these methods are based on the willingness-to-pay principle, and both of them assume that people have the information and skills needed to assess risk and to report their risk-and-reward preferences accurately; unfortunately, these assumptions almost certainly false. As well, it has not been demonstrated that people have stable risk preferences, even when they do have clear information on the costs and risks and have the skills to assess that information (Treasury Board of Canada Secretariat, July 1998).

Method (3) uses historical data to assess statistically the number and type of injuries expected. Then, the treatment costs and wage-loss costs should be counted and extrapolated to determine the whole affected population. This is a rational approach because it ignores people's preferences (which are subjective and may or may not be well informed and rational) in favor of a rigorous estimate of the treatment costs and wage-loss costs that would be avoided by the proposed investment. The methodological difficulties of methods (1) and (2) can be avoided by using this method, but at a cost. It tends to underestimate the true benefit of an investment that reduces risks. When people avoid injury, their benefit is almost certainly greater than avoiding medical treatment costs and wage losses: they also avoid pain and suffering, as well as perhaps the additional costs of becoming disabled. Therefore, method (3) gives a minimum estimate of values, but by how much it underestimates the true value we do not know (Treasury Board of Canada Secretariat, July 1998).

6.10.14.2 The value of the environment

Health, aesthetics, recreation, and respect for nature are considered environmental benefits and costs. Respect for nature is close to an absolute value and extremely difficult to quantify, let alone value in dollars. The aesthetic aspects are also difficult to deal with in benefit-cost analysis: first, it is difficult to quantify the aesthetics of a situation at all; and, second, even if quantified, there is no market for aesthetic environmental benefits, or at least no direct market. Although valuation of environmental goods presents problems, economists have developed some ingenious techniques to estimate the value that people place on such things as water quality and environmental protection. A general technique, which relies on the willingness-to-pay principle, does exist (contingent valuation), but its use in the environmental area is controversial because the results it produces may not be as reliable as those produced by other techniques. Using a combination of techniques to measure all environmental consequences is more adequate (Treasury Board of Canada Secretariat, July 1998).

6.11 Misuse of benefit multipliers

When new resources are generated in a community, the total effect may be larger than the initial transaction would indicate. "Some analysts have applied multipliers to the benefit of a project without any consideration of the equivalent multipliers that should be applied to the costs. This is legitimate only if the analysis is being undertaken from a local point of view and some outside agency such as the federal government is paying all the costs. Except in this special case, multipliers must be applied even-handedly to both costs and benefits" (Treasury Board of Canada Secretariat, July 1998).

6.12 Time values

6.12.1 Why time matters

Actually, there two are reasons why benefits and costs are spread over time. First, many people prefer to make payments later and receive benefits sooner. There is a loss of earning power if income is postponed until a future date or costs are paid early on. The second reason, the value of the unit of measurement itself changes over time because of inflation leading to loss of the purchasing power of the currency. These two factors, inflation and time preference, are independent. There is still preference of benefits earlier and costs later even if there was no change in the purchasing power of a dollar. Therefore, two separate adjustments to cash flow figures across time should be converted to standard units of value that can be added or subtracted. The first adjustment is for changes in the purchasing power of the dollar, and the second adjustment involves discounting to reflect time preference (Treasury Board of Canada Secretariat, July 1998).

6.12.2 Inflation, nominal dollars and constant dollars

There are three reasons why benefits and costs across all periods should be tabulated initially in nominal dollars. First, this is the form in which financial data are usually available. Second, adjustments, such as tax adjustments, are accurately and easily made in nominal dollars. Finally, the analyst who uses nominal dollars can construct a realistic picture over time, taking into account changes in relative prices. The mechanics of adjusting future values to present values, and vice versa, are simple. These values are linked by compound interest. Interest is compounded when the interest earned on an initial principal becomes part of the principal at the beginning of the second compounding period (Treasury Board of Canada Secretariat, July 1998).

The relationship between constant dollars and nominal dollars is the same. If we start with a constant-dollar amount at t_0 and want to calculate the equivalent nominal-dollar amount at t_n, then we use the formula:

$$N = C\,(1 + i)^{n}$$

Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

Where *N* is the amount in nominal dollars ($); *C* is the same amount in constant dollars ($); *i* is the annual rate of inflation (%); and *n* is the number of periods between t_0 and the actual occurrence of the cost or benefit at t_n. In benefit-cost analysis, however, we often find ourselves working in the other direction - that is, we know the nominal dollar amount for some cost or benefit that will occur at some time in the future, so we need to calculate the equivalent constant-dollar amount for an earlier point in time, such as t_0. In that case, we use this formula:

$$C = N/ (1+i)^{n}$$

Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

6.12.3 Changes in relative prices

A consistent treatment of inflation and relative price changes is as follows:

1. Estimate the future relative price changes for each input and output for each period during the life of the project.

2. Estimate the shadow price of foreign exchange if imports and exports are involved.

3. Obtain estimates of the expected annual changes in the general price level (commonly called inflation).

4. Using these two estimates, calculate the nominal price for each input and output for each year of the project.

5. Using the prices estimated above; construct the first complete table of costs and benefits in nominal dollars.

6. Make any adjustments to the cash flows that need to be calculated in nominal dollars (such as adjustments for taxes or loan payments and

adjustments in the stock of cash, sometimes called working capital). This gives the pro forma cash-flow table.

7. Deflate all items in the pro forma cash-flow statement for each year by the price index. This gives the constant dollar table of costs and benefits that is the basis for all further analysis (Treasury Board of Canada Secretariat, July 1998).

6.12.4 Future and present values

Even when the table of costs and benefits is in constant dollars, the figures are not yet in a standard unit. Constant dollars have standard purchasing power, but it makes a difference whether this is current purchasing power or future purchasing power. To make costs and benefits fully comparable, you must convert their values at various times to values at a single point in time. Present values are dollar values that are not only standardized for constant purchasing power, but are also standardized for the time of occurrence (Treasury Board of Canada Secretariat, July 1998). To make the conversion to present values, there is a need of a discount rate that reflects the time preference of the reference group. How much is it worth to receive a benefit now rather than at some future time? In federal government benefit cost analysis, the choice of discount rate has been contentious. Advocates of a project have tended to argue against high discount rates because they make projects look bad (benefits tend to occur later than costs; therefore, high discount rates tend to decrease the benefits more than the costs) (Treasury Board of Canada Secretariat, July 1998).

Once the discount rate is selected, calculating present values from future values and vice versa is straightforward. The formula of present value is following:

$$PV = FV/ (1 + k)^{n}$$

Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

Where PV is the present value at t_0 ($); FV is the future value at t_n ($); k is the discount rate (%); and n is the number of periods between t_0 and t_n.

6.12.5 Discount rates

The appropriate discount rate depends on the point of view taken in the analysis.

6.12.5.1 The social discount rate

"The social discount rate is roughly equal to the opportunity cost of capital, weighted according to the source of investment capital" (Treasury Board of Canada Secretariat, July 1998).

6.12.5.2 The rate-of-time preference for consumption

Using different numeraires (the units of value) causes considerable confusion. In a matter of more clarity, using a 'dollar of investment' as the numeraire and 10% per annum as the real social discount rate should be considered. This common approach to investment and rates of return is familiar to economists and non-economists alike (Treasury Board of Canada Secretariat, July 1998).

6.12.5.3 Strategic effects of high and low discount rates

The choice of a discount rate has a strong influence on the direction of an organization, so it is very important.

6.12.5.4 The discount rate as a risk variable

"Most projects look good at a 5% discount rate and poor at a 15% discount rate. A credible and more useful range for the social discount rate is normally about 8-12% real per annum (for risk analysis), with a most likely value of 10% real per annum" (Treasury Board of Canada Secretariat, July 1998). Risk analysis using simulation deals with some uncertainty about the correct value of the discount rate. This makes it less important to fix on a precise value of the discount rate and places more emphasis on identifying the likely range of values of the discount rate and on interpreting the results of the financial simulation (Treasury Board of Canada Secretariat, July 1998).

6.13 Decision rules

To know whether an investment is worthwhile and whether one investment is better than another is a valid reason regarding decision rules.

6.13.1 Net present value

"NPV is the present value of all benefits, discounted at the appropriate discount rate, minus the present value of all costs discounted at the same rate. An NPV is always specific to a particular point in time, generally t_a, the time of the analysis, or t_0 the start of the project" (Treasury Board of Canada Secretariat, July 1998).

The formula which is adopted from (Treasury Board of Canada Secretariat, July 1998) for the calculation of net present value is as follows:

NPV = initial investment costs + the sum of the present values of costs and benefits for each period within the investment horizon

There are several different ways to calculate the NPV. The NPV can be calculated separately for benefits and costs and then subtract them. Subtracting costs from benefits in each period, giving a single line of net cash flow, and then discounting the net cash flow to give the NPV are the steps of procedure that most analysts follow.

6.13.2 Net present value and break even

"An NPV of zero does not mean 'break even' in the normal sense of costs equaling benefits. NPV is more like excess profit than it is like profit. If a project has an NPV of zero, the project earns the normal rate of return (which is, of course, equal to the discount rate)" (Treasury Board of Canada Secretariat, July 1998).

6.13.3 Two essential decision rules

There is a need of decision rules for a proper guiding, especially when projects have complex patterns of costs and benefits over time. Two rules are consistently accurate and reliable. These are given below.

Decision rule 1: not undertaking projects whose NPV is less than zero, unless there is a willing to 'lose money' to achieve a non-economic objective.

Decision rule 2: Given a choice among alternative projects, maximize the total NPV (Treasury Board of Canada Secretariat, July 1998).

6.13.4 Unreliable decision rules

6.13.4.1 The internal rate of return

The Internal Rate of Return (IRR) is the discount rate that makes the NPV of the project zero. An IRR higher than the standard discount rate indicates that you should go ahead with the project (Treasury Board of Canada Secretariat, July 1998).

The limitations of using IRR

Limitation 1: Simple comparisons between IRRs may be misleading if the projects are not the same size. A project with an IRR of 7 percent is not necessarily a better choice than one with an IRR of 6 percent. The size of each project and the discount rate can influence which project is best (Treasury Board of Canada Secretariat, July 1998).

Limitation 2: In many cases, more than one value of the IRR will solve the equation, and it may not be apparent to the analyst that other equally good values exists because the computer typically stops when it finds any acceptable value of the IRR (Treasury Board of Canada Secretariat, July 1998).

6.13.4.2 The benefit-cost ratio, payback period, and present value of costs

The three most common involve benefit-cost ratios, payback period and the present value of costs.

6.13.4.3 Benefit-cost ratios

A benefit-cost ratio is the ratio of the present value of benefits to the present value of costs. The decision rule here is that any project with a benefit-cost ratio of less than 1 should be rejected, and ranking projects in order of their benefit-cost ratios. The first part of this rule works. The second part, however, may not. This is because it is possible to change the benefit-cost ratio substantially by artificial changes in the accounting for benefits and costs (Treasury Board of Canada Secretariat, July 1998).

6.13.4.4 Payback period

The payback period is the time it takes for the cumulative present value of benefits to become equal to the cumulative present value of costs. In general, shorter payback periods are better. However, this can be a misleading decision rule because it ignores everything that happens after the payback point (Treasury Board of Canada Secretariat, July 1998).

6.13.4.5 Present value of costs

When the benefits of two alternatives are exactly the same, analyst may choose between them on the basis of the lowest present value of costs. This is not a reliable decision rule, however, because analyst cannot tell from the present value of costs whether the project should be done at all. Additionally, the premise that benefits are constant is a general simplification and may not be valid (Treasury Board of Canada Secretariat, July 1998).

6.14 Sensitivity analysis

6.14.1 What is sensitivity?

The outcomes are typically influenced by several uncertain factors in benefit-cost analysis, it is important to know how 'sensitive' the outcome is to changes in those uncertain factors. Sensitivity analysis helps to determine whether it is worthwhile spending money to obtain more precise data and whether we can act to limit uncertainty. In addition, sensitivity analysis helps to communicate to decision makers the extent of the uncertainty and risk in the program. Nevertheless, sensitivity analysis is a limited tool as it treats variables individually while holding other parameters constant. Simultaneous actions and interactions among variables in the real world are ignored. It can be a mistake to take the results too seriously because a variable that appears to be key when considered in isolation might or might not be key when considered along with other variables that strengthen or weaken its effect on the outcome of the project. Only a risk analysis (Hertz and Thomas 1983, 1984) can accurately identify the influence of each variable. However, sensitivity analysis is a helpful (although limited) step in exploring the deterministic model. (Treasury Board of Canada Secretariat, July 1998).

It is the second of three phases in the general analysis:

1. Build a deterministic model using single 'best' values (base values) for the input variables.

2. Explore the outcome's sensitivity to each input variable and then take action to reduce the risk of uncertainty where possible.

3. Make a full risk analysis using probabilities for many variables simultaneously.

6.14.2 Gross sensitivity

Gross sensitivity analysis is recommended to understand how one variable influenced the outcomes of the model.

6.14.3 What determines sensitivity?

The 'effective sensitivity' of the outcome to a particular variable is determined by four factors:

- The responsiveness of the NPV to changes in the variable;
- The magnitude of the variable's range of plausible values;
- The volatility of the value of the variable (that is, the probability that the value of the variable will move within that range of plausible values); and
- The degree to which the range or volatility of the values of the variable can be controlled (Treasury Board of Canada Secretariat, July 1998).

The responsiveness of the NPV to changes in the variable has two components. The first component is the direct influence of the variable on the NPV. The second component is the indirect influence of the variable through its relationships with other variables that correspond to the NPV. Positive correlations with other influential variables will augment the ultimate influence of both, and negative correlations will weaken their influence. A capable simulation model, which deals with individual interactions of many variables at the same time enables to fully identified these influences. (Treasury Board of Canada Secretariat, July 1998).

6.14.4 Sensitivity and decision-making

In fact, the sensitivities that might change a positive decision on the project to a negative decision and vice versa catch the attention of decision makers. Four calculations help us estimate the likelihood of such a switch:

1. What is the range of influence? That is, how much does the NPV change when the variable changes from its lowest plausible value to its highest plausible value?

2. Does this range of influence contain an NPV of zero? If it does, then the variable has a switching value - that is, a value at which our appraisal of the project switches from positive to negative.

3. What is the switching ratio for the variable? That is, by what percentage does the variable have to change to hit a switching value?

4. What is the switching probability? That is, how likely is the variable to reach the switching value? (Treasury Board of Canada Secretariat, July 1998).

6.14.5 Graphic analysis of sensitivity

The variable x outcome interaction is visible over a reasonable range of values, there is a need to use graphs. Sensitivity analysis is exploratory, not definitive, so making the patterns in the data visible is the first priority (Treasury Board of Canada Secretariat, July 1998).

6.14.5.1 Sensitivity curves

The graph features changes in NPVs against changes in the risk variable, which when read, one is able to understand why sensitivity analysis is simple and useful. One may easily read the shifting values to observe how sensitive the outcome is to changes in the variable. If the changes in the variable are presented on the graph in percentages, and thereby standardized, it becomes possible to put the curves for two or more variables (calculated one at a time) on the same graph. This is useful, as the slopes of the curves indicate the relative sensitivity of each variable to NPV changes. The more the NPV changes in relation to a given change in a variable, the more sensitive it is said to be to that variable, with volatility being equal (Treasury Board of Canada Secretariat, July 1998).

6.14.5.2 Tornado charts

Tornado charts presents a clear picture of relative sensitivity. Each bar in the tornado chart shows the range of the NPV when each variable is allowed to change (one at a time) from its highest to its lowest value (Treasury Board of Canada Secretariat, July 1998).

6.14.6 Action on sensitivities

Once the key sensitivities among the risk variables are identified among the risk variables, managing risk becomes available. Points that should be considered about managing risk are summarized as following:

- Are there input variables in the model that are correlated and therefore dampen or enhance the influence each might have in isolation?
- Can diversification help? Are there other investments that could be made at the same time where the same variable works in the opposite direction?
- Could you identify the value of the key variable with more certainty by gathering more information, and if so, is the information worth the cost to gather?

Once these questions have answered, an action plan to minimize uncertainty and thereby limit risk can be done (Treasury Board of Canada Secretariat, July 1998).

6.15 General approaches to uncertainty and risk

6.15.1 Approaches to quantifying uncertainty-related risk

There are three approaches to dealing with financial and economic risk in benefit-cost analysis:

- Expected values (certainty equivalents) of scenarios;
- Risk-adjusted discount rates; and
- Risk analysis through simulation.

The first two approaches have limited applicability. Only the third method, simulation, offers a practical technology for analyzing the overall risk of a project.

6.15.2 Expected values of scenarios

Benefit-cost analysts do not often use this scenario approach because in most cases there are so many possible outcomes that it is not easy to think clearly about the probability of each separately. However, sometimes scenarios can help identify risks.

6.15.3 Risk-adjusted discount rates

Risk-adjusted discount rates are another approach that purports to deal analytically with risk. The basic idea is that all investments earn the same rate of return - given a perfect market. Otherwise, capital would flow to the high-return areas, resulting in a decrease of average returns until the rates equalize. Therefore, visibly different rates of return must incorporate the same basic rate plus a premium for risk so that, in the long run, only the basic return is gathered by the investor. In this case, the appropriate discount rate (cost of capital) is the basic rate plus a premium for risk. This combination is called the risk-adjusted discount rate.

6.15.4 Risk analysis through simulation

Simulation is considered a feasible method to conduct a risk analysis. It predicts the possible outcomes of the benefit-cost model.

6.16 Risk analysis

6.16.1 Introduction

Knowing how much risk guides us to accept or reject any project, there is a need of using a technique that provides analysis of risk. This technique is financial and economic risk analysis. In addition, this technique can be used to compare the likely outcomes of two or more alternative projects and obtaining results of the likely outcomes by using data that are uncertain.

6.16.2 The steps of risk analysis

Benefit-cost analysis is best approached as a risk analysis because there is always some uncertainty in the data. The steps in risk analysis are the following:

1. Set up the basic model that will calculate NPV. This model is sometimes called the deterministic model because it uses a single deterministic value for each variable.

2. Link the uncertain variables in the model to information about their maximum and minimum values (range) and about the probabilities of various values within those ranges.

3. Run the model many times to obtain a large number of NPVs (to see what all the possibilities are) - that is, construct an investment results table.

4. Determine the frequency with which various NPVs occur in the results, and, on this basis, predict the likely range of the NPV and the probabilities of various NPVs within that range.

5. Using the decision rules, interpret this information to identify the best alternative investment or, if there is only one, to decide whether it is likely to be a good investment (Treasury Board of Canada Secretariat, July 1998).

6.16.3 The mechanics of risk analysis

Careful and detailed tables of costs, benefits and parameters are relevant keys in a benefit-cost model and risk analysis relies on these aspects. Risk-analysis software builds on the underlying benefit-cost model. Once the deterministic model is working adequately, there are two additional steps for using the software:

- Selecting sets of values for the uncertain variables, according to specified probabilities, for each run of the benefit-cost model;
- Using these sets of values to calculate the possible outcomes and analyze the results (Treasury Board of Canada Secretariat, July 1998).

Selecting sets of values for the uncertain variables is based on sampling. Most risk-analysis programs use the Monte Carlo method, which is simple random sampling according to a specified probability distribution. A second method used is the Latin Hypercube method of stratified sampling; some use both methods. These methods employ iteration to run the model. Generally, the Latin Hypercube can accurately re-create the specified probability distributions in less iterations than Monte Carlo can, and is therefore the best choice if software can use either one. Each run of the program completely samples for all risk variables and recalculates the worksheet (Treasury Board of Canada Secretariat, July 1998). The whole procedure of iteration measurement is conducted within a simulation. The program simulates the range and probabilities of the investment outcomes in the real world.

6.16.4 Adjusting for the covariance of related risk variables

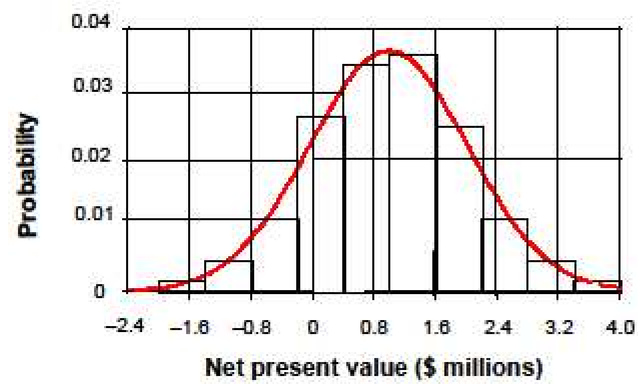
Some risk variables might be correlated. If the outcome of analysis is to be realistic, then these correlations must be taken into account. Large errors in judging can happen if the covariance has not been taken into account.

6.16.5 How many times does the model need to run?

An NPV is generated each time the benefit-cost model is run; eventually, a full picture of the likely outcome of the model will become apparent given the number of resulting outcomes. How wide the ranges of the variables in the model and how predictable the values are within those ranges affect the number of runs needed (Treasury Board of Canada Secretariat, July 1998).

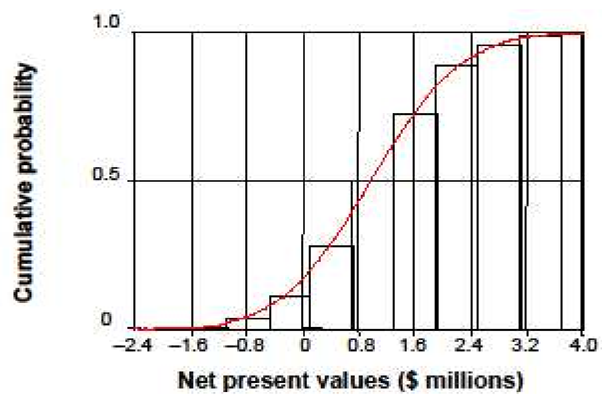
6.16.6 Interpreting the results of the risk analysis

A list of NPVs is produced by a risk analysis, one for each run of the benefit-cost model. Statistically and graphically analysis can be done for the outcomes of the benefit-cost model to see what the probabilities of various outcomes are. There are two types of graphs that show the probability distribution of the NPV. The first type is a probability-density graph, which shows the individual probability of each NPV (Figure 6.1). The second type is a cumulative-distribution graph, which shows how probable it is that the NPV will be lower than a particular value (Figure 6.2). Both types of graphs are useful for communicating with the decision-maker. Additionally, constructing the graphs to show the distribution of results. Most simulation software calculates some useful numbers, including the likely range of the NPV (minimum to maximum), the key probabilities (such as the probability that the NPV will be greater than zero), and the expected value of the investment. Together, these factors guide the investment decision towards a certain direction (Treasury Board of Canada Secretariat, July 1998).



Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

Figure 6.1: Probability-density distribution of net present values approximated by a normal curve



Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

Figure 6.2: Cumulative-probability distribution of net present values approximated by a curve

6.16.7 Decision rules adapted to uncertainty

After recognizing uncertainty in the data, making decisions becomes less clear-cut, although the principles are the same. The general rule is to choose the project with the highest benefit. At the same time, it is important to make risk transparent to the decision-maker. In case the benefits are the same, there is no immediate reason to choose one project over the other. On the other hand, if one is holding a portfolio of investments, then any project might have advantages in terms of improving the portfolio as a whole. Therefore, the best strategy in choosing among projects is rational risk neutrality, which is simply choosing the best outcome over a large portfolio (Treasury Board of Canada Secretariat, July 1998).

6.16.8 Assessing overall risk

The expected-loss ratio and the risk-exposure coefficient are useful summaries of the overall level of risk.

6.16.9 The expected-loss ratio

The expected-loss ratio is the absolute value of expected loss (all possible losses weighted by their probabilities) as a proportion of total expected value of all possible outcomes (Treasury Board of Canada Secretariat, July 1998).

6.16.10 The risk-exposure coefficient

In general, the expected-loss ratio may be an adequate indicator of risk. However, it does not capture all aspects of risk. Two projects can have the same expected-loss ratio but different levels of risk because one's outcomes are more spread out than the other project, or because more of the spread is in the negative-NPV area (Treasury Board of Canada Secretariat, July 1998).

There is a need to look at two additional aspects of risk:

- How spread out (dispersed) are the possible outcomes (measured by standard deviation)?

- What proportion of the possible outcomes is on the loss side of the outcome distribution (that is, to the left of the NPV = 0) (Treasury Board of Canada Secretariat, July 1998).

When considering these two factors along with the expected-loss ratio, a risk-exposure coefficient (REC) will be obtained, a more complete measure of risk:

$$REC = L_E \,(SD)\, (D_L/D)$$

Source: (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998)

Where L_E is the expected loss ratio; SD is standard deviation of the outcome distribution; D_L is the distance on the NPV axis from the minimum value to zero; D is the distance on the NPV axis from the minimum to the maximum value. We may find the risk-exposure coefficient too mathematically complex to be intuitively appealing if we are dealing with a relatively simple 'go' or 'no go' decision on a single project. In that case, we might find the expected-loss ratio more useful. If we are comparing two or more alternatives and if those alternatives involve the investment of large resources, however, it is worth going the extra step to calculate the risk-exposure coefficient so that we can rank the projects according to risk (Treasury Board of Canada Secretariat, July 1998).

6.16.11 The advantages and limitations of risk analysis

Some advantages of risk analysis are the following:

- It can rescue a deterministic benefit-cost analysis that has run into difficulties because of unresolved uncertainties in important variables.

- It can help bridge the communications gap between the analyst and the decision-maker. A range of possible outcomes, with probabilities attached, is inherently more plausible to a decision-maker than a single deterministic NPV. Risk analysis provides more and better information to guide the decision.
- It identifies where action to decrease risk might have the most effect.
- It aids the reformulation of projects to better suit the preferences of the investor, including preferences for risk.
- It induces careful thought about the risk variables and uses information that is available on ranges and probabilities to enrich the benefit-cost data. It facilitates the thorough use of experts (Treasury Board of Canada Secretariat, July 1998).

The limitations of the risk analysis include the following:

- The problem of correlated variables, if not properly contained, can result in misleading conclusions.
- The use of ranges and probabilities in the input variables makes the uncertainty visible, thereby making some managers uncomfortable.
- If the deterministic benefit-cost model is not sound, a risk analysis might obscure this by adding a layer of probabilistic calculations, thereby creating a spurious impression of accuracy (Treasury Board of Canada Secretariat, July 1998).

6.17 Probability data

There have been discussed earlier some difficult-to-measure inputs to benefit-cost analysis. In this part, that early discussion has been extended and some general aspects of collecting data have been considered as well.

6.17.1 Types of variables

Three types of risk variables are used in benefit-cost analysis:

- Full-horizon variables - Some variables are the same for each period of the analysis: once a value is selected, it is used throughout the benefit-cost model. For each run of the model, the risk-analysis computer program will select a different value within the plausible range, but only one value is used in each run. The social discount rate is an example. We know that it is stable over time.
- Single period variables - Some variables have values that change over time within a known range, and the true value in each period is independent of the value in any other period. In this case, it is simplest to have a separate variable for each period of the analysis (Treasury Board of Canada Secretariat, Benefit-Cost Analysis Guide, July 1998).
- Path variables - Some variables change over time in a regular pattern. The value in one period is related in a systematic way to the value in the previous period. For example, the inflation rate in one year is likely to be within a certain range (up or down) from the rate in the previous year, and

a trend, once established, tends to continue for some time. We know the starting rate of inflation - the rate in the current year. We would have inflation rates in our benefit-cost model, but we would also have to program the model so that each time it runs it selects a different path of inflation rates for the investment period. The path selected must be in accordance with the rules of behavior for this variable (Treasury Board of Canada Secretariat, July 1998).

6.17.2 Using historical data

To do a risk analysis, knowing the range of values is a necessity. Each variable can take the probability distribution of values inside of, as well as, minimum to maximum. Resulting is the computer obtaining all the necessary information to sample values to use in iterations of the benefit-cost model. If historical data are available, the minimum and maximum values that occurred in the past may be usable as an appropriate range for the current values of the variable (Treasury Board of Canada Secretariat, July 1998).

6.17.3 Expert judgment

If historical data is not enough to support an estimate of the range and probabilities of a particular variable, then we have to rely on expert judgment.

6.17.4 Common probability distributions

The probability distributions for the input variables to the benefit-cost model have different levels of affectation. Usually, a fairly simple, straightforward approach is adequate. This means selecting probability-distribution shape in one of two ways:

- Specifying a standard statistical shape, such as a flat, normal, triangular, or Poisson distribution; or
- Specifying a step distribution, which notes the probabilities for each segment of the variable's range (Treasury Board of Canada Secretariat, July 1998)?

6.18 Comparing options of different types against different criteria

6.18.1 Issues of fairness

The issues of fairness have the most difficulty in benefit-cost analysis. The general assumption in benefit-cost analysis is that everyone in the reference group takes the same point of view. However, that would not be an easy issue.

6.18.1.1 Equity approach 1: Ignore distributional issues

The idea is to make efficient investments to create the largest benefit, which can then be divided as society wishes through instruments that do not involve high transaction costs or economic inefficiencies (Treasury Board of Canada Secretariat, July 1998).

6.18.1.2 Equity approach 2: Use distributional weights

In the 1960s and 1970s, the use of distributional weights was popular among many benefit-cost analysts. However, decision-makers could not trust the analyses because they did not know how its outcome had been affected by the inclusion of subjective weights to change the values of costs and benefits (Treasury Board of Canada Secretariat, July 1998).

6.19 Summary

In this study, as implemented in the next chapter (chapter 7), benefit-cost analysis model of using fly ash-based green cement in masonry components has been established on the following steps. First, examining needs, considering constraints and formulating objectives and targets. Second, defining options in a way that enables the analyst to compare them fairly. Next, analyzing incremental effects and gathering data about costs and benefits. Subsequently, expressing the cost and benefit data in a valid standard unit of measurement (for example, calculating dollar values for things such as environmental impacts that are not usually expressed in dollars). Next, conducting a sensitivity analysis to determine which variables appear to have the most influence on the model. Then, analyzing risk by using what is known about the ranges and probabilities of the costs and benefits values and by simulating expected outcomes of the model. Last, summing up a pattern of costs and benefits to guide decision-making.

CHAPTER 7 BENEFIT-COST ANALYSIS MODEL OF USING CLASS F FLY ASH-BASED GREEN CEMENT IN MASONRY UNITS (BCM)

7.1 Introduction

The environmental benefits of using Fly Ash-Based Green cement in masonry components were estimated using a benefit-cost model. The reductions in energy use, water consumption, and GHG emissions are primarily obtained by offsetting the production of conventional materials (e.g., the use of fly ash in concrete precludes the need to produce Portland cement). Economic benefits were calculated based on the monetary value of the environmental benefits. Unit benefits (e.g., environmental benefits per ton of fly ash-based green cement used in the given application per year) were obtained from predictions made with replacing Portland cement with green cement making masonry walls. The model contains environmental data for using Portland cement and green cement making masonry walls.

The Benefit-Cost Analysis Model (BCM) environmental performance data serves as quantitative estimation of the energy and resource flows into a product as well as releases to the environment from the product. Total output is summed across stages of producing a unit product (e.g., one ton of cement). Manufacturer-specific unit environmental impact data for the production of a product are obtained primarily using a unit process and facility-specific approach. Output from BCM includes energy use, raw materials, atmospheric emissions (e.g., carbon dioxide (CO_2), Methane (CH_4), Carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulates), social costs of CO_2, tax costs, and nonhazardous waste. Several different sources of information and analysis methods are used in this model to characterize the environmental impact of green cement and Portland cement. The economic model quantifies energy, material, and emissions. BCM uses average US producer prices ($/ton) to calculate emissions per mass of material used.

7.2 Methodology for Determining Benefits

The benefit-cost analysis in this study investigated three different mixes. Mix 1 (Portland cement, Sand, Aggregate, and Limestone #9), Mix 2 green cement (Fly ash, Meta, Silica Fume, and Sand) with sodium hydroxide (NaOH) as an activator, and Mix 3 green Cement (Fly ash, OPC clinker, and Sand) with sodium sulfate (Na_2SO_4) as an activator. The environmental and economic benefits of green cement and Portland cement use were quantified by computing differences in energy expenditure and global warming potential between products that were produced with green cement and Portland cement. Fly ash, which is the main component in green cement, is a byproduct of energy generation and is not produced specifically, as is the construction material it replaces. Consequently, the resources embodied in their production are accounted for in electricity production and are expended regardless of whether fly ash is used beneficially. The major application was considered: Masonry walls using Fly Ash-Based Green cement. In the nearly 7 billion square feet of masonry walls produced yearly in North America (American Institute of Architects, 2008), cement represents a portion of each unit (8.5% to 12% by weight), limestone, sand, and aggregate or only about 3 lbs per block (each block weighs from 25 to 35 pounds each).

Under normal circumstances the volatile organic compound (VOC) content of the exhaust gas from cement kilns ranges between 1 and 60mg/Nm^3, whereas the "N" in Nm^3 means "normal" which means the gas volume, which depends on temperature and pressure, is measured at 101.325 kpa and 0 °C. (BREF 2010). Also, cement production is a minor source of hydrogen chloride (HC) and hydrogen fluoride (HF), so their impacts were considered negligible (EPA, 2007b). Emissions of airborne pollution in the form of dust, gases, noise and vibration when operating machinery and during blasting in quarries often occur during cement production; however, this difference could not be adequately quantified and therefore was ignored.

The primary unit of measure that has been used for this assembly is the square footage of the wall; other estimators may use the unit of measure "number of blocks." Both measures are equally effective. The reason to look at the cost of a masonry wall per square foot rather than the cost per block is because the unit cost per square foot is more interchangeable or comparable to other framing systems unit of measure. Concrete masonry units (CMUs) are made in a variety of sizes but for the purpose of this study, the standard CMUs are normally 8" thick (front to back) and have a nominal face dimension of 16" long and 8" high. Figures 7.1 and 7.2 show a sample of a typical masonry wall and the masonry units that are considered in this study

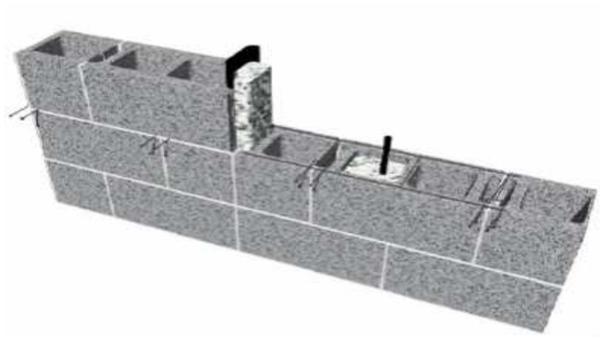


Figure 7.1: Typical masonry walls that are considered in this study

Figure 7.2: Typical masonry unit that is considered in this study

The parameters that have been considered in this model are as follows:

1-The impacts of emissions of Carbon Dioxide (CO_2)

2-The impacts of emissions of Nitrogen Oxides (NOx)

3- The impacts of emissions of Sulfur Dioxide (SO_2)

4- Energy Savings

5- Damaging the natural resources, reducing consumption raw material for cement manufacture such as limestone, clay, and sand

6- Benefits due to avoided land filling of fly ash

Fly ash is a waste byproduct. Therefore, fly ash is considered zero CO_2 emission. Total annual benefits were obtained as the product of unit benefits for energy, and GHG emissions and the most recent annual beneficial use quantity (in tons) provided by (ACAA 2012). All financial quantities were adjusted to 2014 US dollars.

7.3 Assumptions

Based on the available data some assumptions have been made:

1- Only raw materials are considered, and all other factors in masonry manufacturing using green cement or Portland cement are assumed the same and therefore cancel out in a comparative benefits analysis.

2- The other sources of CO_2 emissions stemming from cement manufacturing operations include transportation equipment used in the mining and transport of raw and finished materials and the fuels required for operating the process were not considered in this study.

7.4 Cost Analysis

Concrete Masonry Units (CMUs) have been produced on a large scale during each year. The price of the final products, CMUs, on the market includes manufacturing costs, raw material costs, profits, and others. For Green cement masonry units, however, it is impossible to get the market price of the final commercial products because no one has started manufacturing them commercially yet. Since the manufacturing process of concrete masonry units and green cement units are almost same, it makes sense to compare the cost of raw materials only, especially Portland cement versus green cement.

The cost of the green cement mixture is estimated by researching the material price of fly ash, metakaolin, silica fume, and two activators (sodium hydroxide, sodium sulfate), which are listed in Table 7.1. Based on this information, the cost of one square foot of green cement masonry was calculated.

Table 7.1- The breakdown of material price for components that are used in green cement mixture

Material	Price ($/ton)
FA	50 - 80
Meta	380 - 600
SF	380 - 600
Sand	38 - 40
NaOH	280 - 490
Na_2SO_4	80 - 150
Portland cement	95-106

This range of prices is adopted from different providers

Table 7.2 shows the breakdown of material prices for concrete masonry units made with Portland cement (National Block Company). The amount of material in Table 7.2 yields 138 units of 8x8x16 blocks. Therefore, the cost of one block is $56.28/138 = $ 0.4078 per block, since one square foot is equivalent to 1.126 block, then the direct cost, cost of raw materials only, of one square foot of masonry units made with Portland cement is 1.126*$0.4078 = $0.46 per square foot. Similarly, Mix (2) which is for green cement with NaOH has direct cost, cost of raw materials only, on average $2.28 and Mix (3) which is for green cement with Na_2SO_4 has direct cost, cost of raw materials only, on average $0.943.

Table 7.2- The breakdown of material prices for masonry units that are made with Portland cement (National Block Company)

Material	Price ($/ton)	Price ($/lb)	Usage (lbs)	Total
Sand	$9.85	0.00492	2480 lbs	$12.20
Aggregate	$24.60	0.0123	1360 lbs	$16.72
Cement III	$95.74	0.0478	500 lbs	$23.90
Limestone #9	$11.55	0.00577	600 lbs	$3.46
				$56.28

7.5 Results and Discussions

7.5.1 Fly Ash Use in Masonry

The unit benefits of using fly ash as a cement substitute in Masonry were obtained from different references as numbered in the tables. The analysis considered green cement (Fly ash, Meta, Silica Fume, and Sand) which has 28.8% of fly ash required to produce one square foot of masonry for Mix 2 (green cement with NaOH as an activator), and green cement which has 21.4% of fly ash for Mix 3 green cement (Fly ash, OPC clinker, and Sand) with Na_2SO_4 as an activator. On the other hand, around 10% of Portland cement required producing one square of masonry for Mix 1 (Portland cement, Sand, Aggregate, and Limestone #9). Tables 7.3 and 7.4 show the impacts of using Portland cement and Fly Ash-Based Green cement in masonry industry in terms of GHG emissions, energy consumption, damage to natural resources, avoiding land filling of fly ash, and their corresponding financial savings.

7.5.2 Benefits of Avoided Fly Ash Disposal

Using fly ash in sustainable construction activities results in additional environmental and economic benefits through avoiding landfill disposal of fly ash. These additional savings were calculated using life cycle analysis data. The major components are landfill construction, landfill operation, landfill closure, landfill post-closure care, and leachate treatment (assumed for 100 years). (Electric Power Research Institute, Quantifying the Benefits of Using Coal Combustion Products in Sustainable Construction, 2010). The impact benefits of avoiding the landfill disposal of fly ash are summarized in Table 7.4.

7.5.3 Cumulative Benefits

The total benefits of using green cement in construction applications (Masonry walls) are reported in Tables 7.4 in terms of reduced energy, lower global warming potential, and avoided land filling of fly ash. Financial impacts of using Portland cement are shown in Table 7.5. In addition, the environmental and financial quantities in Tables 7.3 through 7.5 are also reported in terms of equivalent tangible quantities such as annual household, emissions from cars and the cement industry, and solid waste produced by an average American. Conversions to these tangible quantities were based on the average American household energy use of 96.4 billion Btu per 1000 households (EIA, 2009). The greatest environmental benefits in sustainable construction are currently being accrued through the use of coal combustion products (CCPs) (mainly fly ash) in concrete production. Use of fly ash as a cement substitute annually saves more than 55 trillion Btu of energy annually (≈ equivalent to 600,000 households) and reduces GHG emissions by 9.6 million tons CO_2 (≈ equivalent to 1.7 million passengers cars) (Electric Power Research Institute, quantifying the Benefits of Using Coal Combustion Products in Sustainable Construction, 2009). In 2008 United States Environmental Protection Agency (EPA) found that every used one ton of fly ash avoids 0.7 ton of greenhouse gas emissions and saves 4 million Btu of energy. Therefore, using green cement in masonry wall manufacturing results in even more energy savings as one square foot of fly ash block saves 0.024 million Btu of energy and reduces 4.20 kg of green house gases.

Though annual emissions of pollutant particulate matter (PM), pollutant CO, pollutant organic hazardous air pollutant (HAP), and mercury (Hg) from cement were quantified as small as 37,000 tons/yr, 150,000 tons/yr, 3,700 tons/yr, and 7 tons/yr respectively (EPA, 2007b); we should realize that they still have negative impacts on our environment. Replacing one-ton cement with fly ash would reduce carbon dioxide emissions equal to two months use of an automobile (ACAA, 2010). If all the fly ash generated each year were used in producing concrete, the reduction of carbon dioxide released because of decreased cement production would be equivalent to eliminating 25 percent of the world's vehicles (ACAA, 2010). The use of one square foot of wall (5985.03 g of fly ash) would reduce carbon dioxide emissions equal to 0.36 day or 8.5 hours of automobile use.

Table 7.3 displays the summary impacts of using Portland cement by category that were used in BCM. It shows for carbon emissions from cement manufacture are 820 kg CO_2/t cement (Matthew Stanley Cullinen, Cement, March 2011). However, the other sources of CO_2 emissions stemming from cement manufacturing operations include transportation equipment used in the mining and transport of raw and finished materials and the fuels required for operating the process were not considered in this study. The cement industry is responsible for about 1.5% of all nitrogen oxides emissions (US Environmental Protection Agency-EPA, 1995). The U.S. Department of Energy estimated the national monetized benefits of NOx reductions associated with this rulemaking, based on environmental damage estimates from the literature. Available estimates suggest a very wide range of monetary values for the reduction of NOx emissions, ranging from $370 to $3,800 per metric ton of NOx in 2001 (Burtraw et al, July 2001). Regarding the damage to natural resources, one ton of cement requires 1.67 tons of raw materials such as limestone, shale, clay, iron ore and sand (United States Geological Survey, 2005). Approximately 70% of crushed stone production in the United States is limestone, one of the basic raw materials required for cement production (USGS 2003). Table 7.4 displays the summary impacts of using green cement by category that were considered in BCM.

Table 7.3- Impacts of using Portland cement

Impact		Quantity
GHG Emission	CO_2 (Annual Emissions from cement)	66 to 81.4 Million (tons/yr) (1)
	Tax cost of CO_2 (beginning in 2012 to 2025)	\$22/ton to \$53/ton (1)
	The Social cost of CO_2	\$ 12 to \$ 61 / ton (2)
	CO_2	820 kg CO_2 /t cement(3)
	NO_x (Annual Emissions from cement)	219,000 tons/yr (4)
	Average of NOx emissions from wet kilns	9.7 lb NOx/tone of clinker(5)
	Average of NOx emissions from dry kilns	3.8 lb NOx/tone of clinker(5)
	Benefits from reduced NOx emissions	\$432 to \$4,441 ton reduced (6)
SO_2	SO_2 (Annual Emissions from cement)	159,000 (tons/yr) (4)
	The sulfur dioxide (SO_2).Without trading, damages average (from 2000 to 2007)	\$1,580 per ton (4)
	The sulfur dioxide (SO2).With trading, damages average (from 2000 to 2007)	\$1,670 per ton (4)
Energy	The average amount of electricity used at a cement plant	111 kWh/t cement (7)
	The main firing of a cement kiln requires at least	18-20 GJ/ton cement (8)
	Each tone of cement produced requires	60 to 130 kg of fuel oil or its equivalent (9)
Damage to natural resources	To produce 1 ton of cement requires	1.67 tons of raw materials (9)
	Price of Raw Materials (\$/metric ton)	(\$4.76 to \$13.34) (10)

1- Overview of GHG Data Reported in 2012 (EPA).
2- EPA, Fact Sheet: Social Cost of Carbon, Nov.2013.
3- Matthew Stanley Cullinen, Cement, March 2011.
4-David D. et al, The Social Cost of Trading: Measuring the Increased Damages from Sulfur Dioxide Trading in the United States, 2011.
5-U.S. EPA, 2007a
6- Cost-Effective Reduction of NO_X Emissions from Electricity Generation, Dallas Burtraw, Karen Palmer, Ranjit Bharvirkar, and Anthony Paul, July 2001
7- WBCSD 2009
8-The European Cement Association
9-United States Geological Survey, 2005
10-U.S. Environmental Protection Agency, Regulatory Impact Analysis: National Emission Standards for Hazardous Air Pollutants from the Portland cement Manufacturing Industry, April 2009

Table 7.4- Impacts of using one ton of Fly Ash-Based Green cement

Impact		Quantity
GHG Emission	Avoiding of greenhouse gas emissions	0.7 ton [1]
	Financial Savings (US$/ton fly ash)	$3.29 /ton to $43.00/ton [1]
Energy	Saving enough electricity to power the average American home for	24 days [2]
	Financial Savings for energy	($123.50/ton fly ash)[1]
Avoiding land filling of Fly ash	Conserving landfill space of solid waste produced by an average American for	455 days [2]

1- USEPA, 2008
2- ACAA, 2010

Table 7.5 has financial data that was derived from Table 7.3 and was calculated for one square foot of masonry wall by using Portland cement. The Social Cost of CO_2 (SCC) is an estimate of the monetized damages associated with an incremental increase in carbon emissions in a given year. In February of 2010, an interagency committee of the U.S. government published its first estimates of the "social cost of carbon" (SCC), a monetized value of the marginal benefit of reducing one ton of CO_2. This committee, established in 2009 under the direction of the Obama Administration (Laurie T. Johnson & Chris Hope, The social cost of carbon in U.S. regulatory impact analyses: an introduction and critique, 2012).

One ton of CO_2 is the basic unit of emissions for climate policy, but it may be hard to visualize–especially since it is a colorless, odorless gas that mixes into the air around us. In the United States, one ton of CO_2 is emitted, on average, by a family car every two and half months, and a household's use of heating and cooking fuel every four months (if energy use were spread equally throughout the year). In addition, a household's use of electricity every six weeks and the typical use of a microwave oven every seven years or of a refrigerator every 15 months also leads to the emission of one ton of CO_2 (Frank et al, 2010).

U.S. residents emitted 21 tons of CO_2 per person in 2005: 33 percent from transportation, 15 percent from residential electricity, 6 percent from home heating and cooking, and the remaining 46 percent from industry, retail stores, and government (Frank et al, 2010). Each person's annual production of 21 tons of CO_2 add to the stockpile of greenhouse gases in the atmosphere. The more CO_2, the hotter the average global temperature (the "greenhouse effect"), the faster sea levels rise (warmer waters expand to take up more room, while glaciers and polar ice caps melt), and the more our weather patterns diverge from historical trends (changes to rainfall, more intense storms) (Frank et al, 2010).

A carbon tax is an "upstream" tax on the carbon content and it is the most efficient means to instill crucial price signals that spur carbon-reducing investment. Figure 7.3 displays U.S. CO_2 emissions with and without a carbon tax. As shown in the figure 7.3, carbon tax has a significant impact to reduce emissions of CO_2.

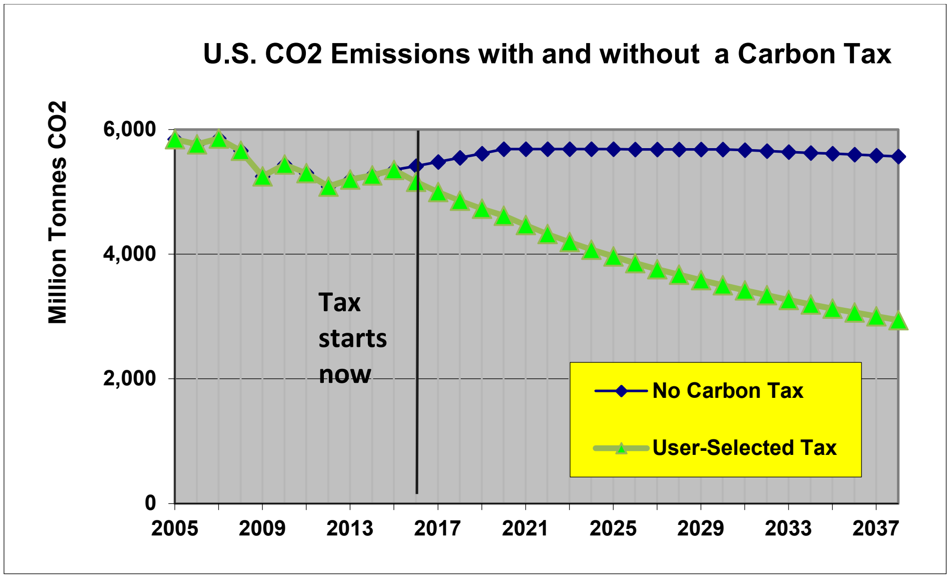


Figure 7.3: U.S. CO_2 emissions with and without a carbon tax
Source: Carbon Tax Center (CTC), 2015

Table 7.5 - Economic Influences due to Making Masonry Walls by using Portland cement per Square Foot

Impact		Quantity
Direct Cost	1 SF of wall of Portland cement costs	$ 0.459
GHG Emission	with Tax Cost costs	$ 0.0407 to $ 0.098
	with Social Cost of CO_2 costs	$ 0.022 to $ 0.113
	with reducing the emissions of NO_x costs	$0.010
SO_2	with reducing the emissions of SO_2 costs	$0.0053 to $0.0056

This schedule was estimated on nearly 8 billion block produced annually in North America, cement represents a small portion of each unit (8.5% to 12% by weight), or only about 3 lbs per block (each block weighs from 25 to 35 pounds each). In terms of square feet, 6,000,000,000 SF per year to 8,000,000,000 SF per year = 8,656,125 ton cement/year to 11,541,500 ton cement/year.

7.5.4 Outputs of the simulation of Benefit-Cost Analysis Model

7.5.4.1 Introduction

Simulation with risk analysis has been conducted for three models (Mix 1, Mix 2, and Mix 3) to combine all the uncertainties that have identified in modeling situation. There is no longer the need to reduce what is known about a variable to a single number. Instead, it has been included in all what has been known about the variable, including its full range of possible values and some measures of the likelihood of occurrence for each possible value. The techniques of risk analysis have long been recognized as powerful tools to help decision-makers successfully manage situations subject to uncertainty.

7.5.4.2 Why Risk Analysis is useful

Traditionally, analyses combine single point estimates of a model's variables to predict a single result. This is the standard excel model. Estimates of model variables must be used because the values that will actually occur are not known with certainty. In reality, however, many things just do not turn out the way that they have been planned. Maybe there were too conservative considerations with some estimates and too optimistic with others. The combined errors in each estimate often lead to a real-life result that is significantly different from the estimated result. The decision that is being made is based on expected results might be the wrong decision, and a decision we never would have made if we had a more complete picture of all possible outcomes. Business decisions, technical decisions, and scientific decisions all use estimates and assumptions.

With risk analysis, one can explicitly include the uncertainty present in our estimates to generate results that show all possible outcomes.

Figure 7.4 shows the probability of cost of one SF of wall using Portland cement (Mix 1). As shown, the probability of getting costs from $0.55 to $0.65 is 90%. There is only a 5% chance of having a cost of one SF of wall using Portland cement greater than this. Figure 7.5 represents the same probability in a cumulative ascending chart.

@RISK Output Report for Total Cost of one square foot of Wall (Portland Cement) Mix 1

Performed By: Khaled

Date: Tuesday, January 27, 2015 11:37:10 AM

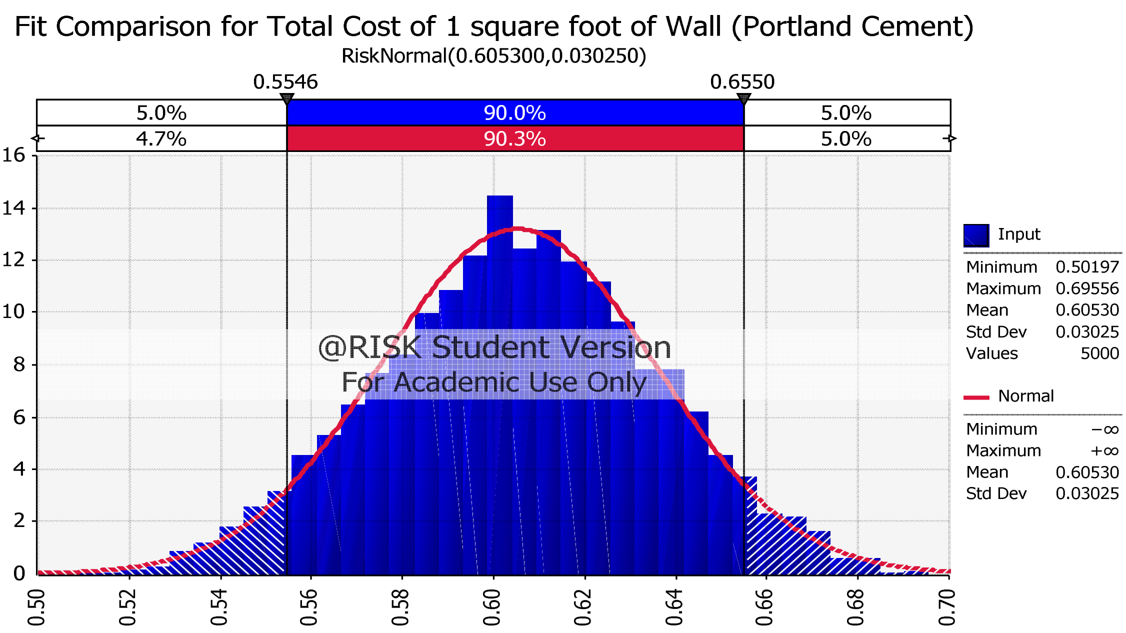


Figure 7.4: Cost of one SF of Wall Portland cement (Mix 1)

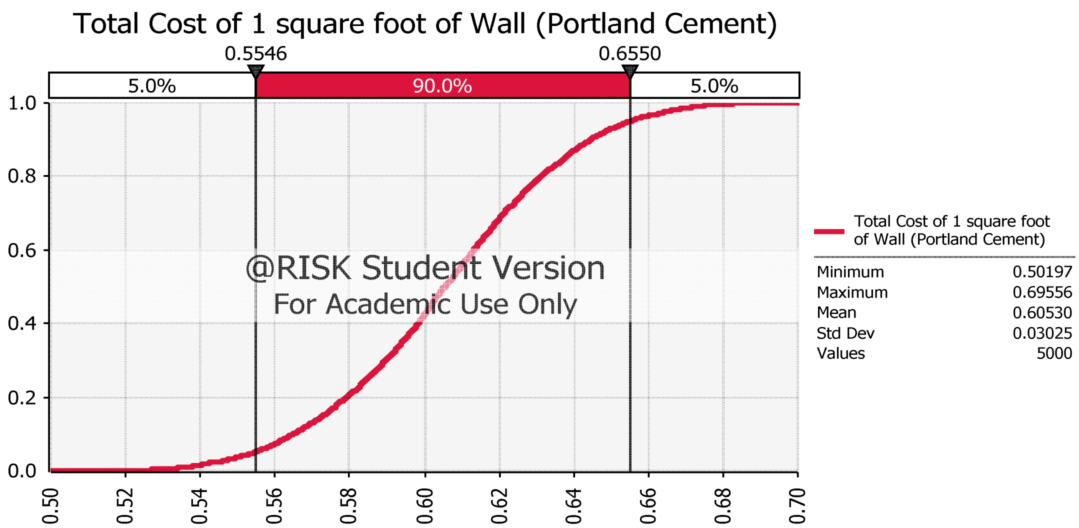


Figure 7.5: A cumulative ascending chart cost of one SF of wall Portland cement (Mix 1)

Table 7.6 represents summary for the cost of one SF of wall Portland cement (Mix 1). It shows the minimum ($0.50) and the maximum ($0.69) expected cost of one square foot of wall of Portland cement. The mean for this distribution was $0.60 and standard deviation was $0.03. There are many other statistical details presented in Table 7.6.

Table 7.6 - Summary Statistics for cost of one square foot of wall Portland cement (Mix1)

Statistics		Percentile	
Minimum	0.501974909	5%	0.554638713
Maximum	0.695558814	10%	0.565144267
Mean	0.605300001	15%	0.573048706
Std. Dev	0.030249821	20%	0.579442006
Variance	0.000915052	25%	0.584731739
Skewness	-0.052278173	30%	0.589812303
Kurtosis	2.729760457	35%	0.594089611
Median	0.605498145	40%	0.598244717
Mode	0.600891354	45%	0.60184055
Left X	0.554638713	50%	0.605498145
Left P	5%	55%	0.609427261
Right X	0.65504422	60%	0.613252629
Right P	95%	65%	0.617257203
Diff X	0.100405507	70%	0.621333278
Diff P	90%	75%	0.626007453
#Errors	0	80%	0.631237638
Filter Min	Off	85%	0.637678193
Filter Max	Off	90%	0.644426878
#Filtered	0	95%	0.65504422

Figure 7.6 shows the probability of cost of one SF of wall using green cement with NaOH as an activator (Mix 2). As shown in the figure below, the probability of getting costs ranging from $1.13 to $1.33 is close to 90%. There is only about 5% chance of having a cost of one SF of wall using green cement (Mix 2) greater than this. Figure 7.7 represents the same probability in a cumulative ascending chart.

@RISK Output Report for Total Cost of one square foot of Green Wall (NaOH) Mix 2

Performed By: Khaled

Date: Tuesday, January 27, 2015 11:37:11 AM

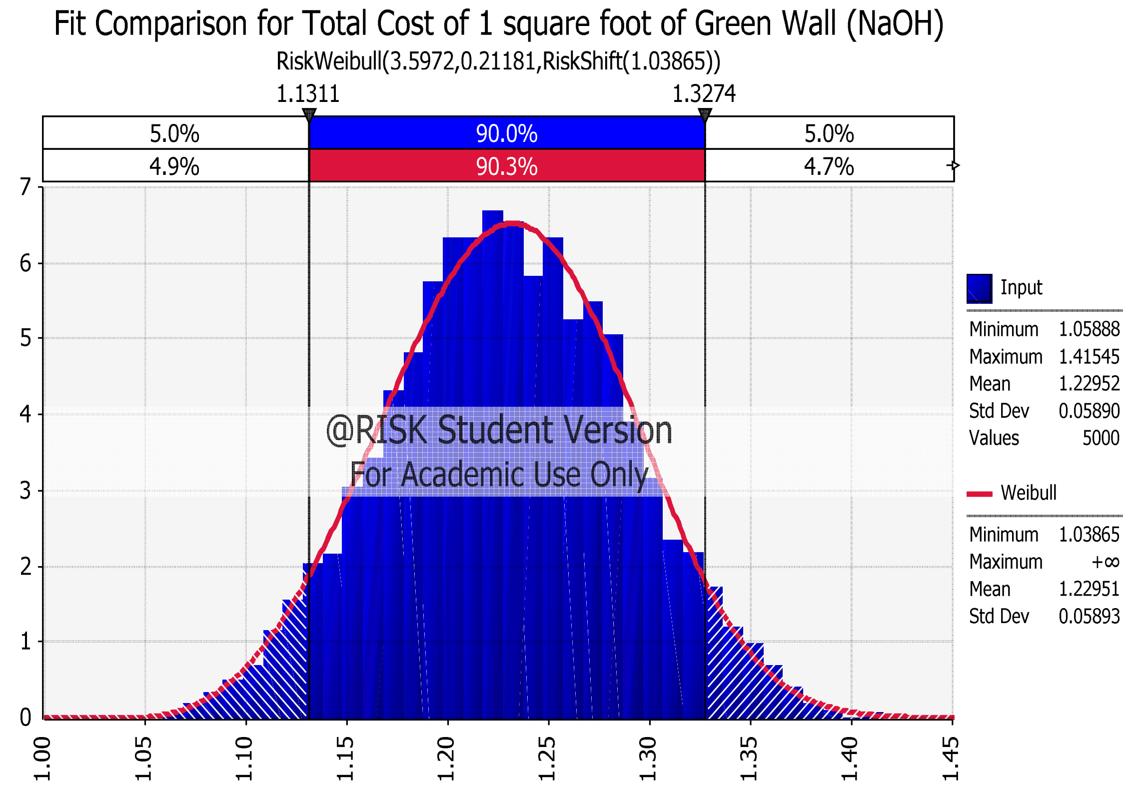


Figure 7.6: Cost of one SF of Wall Green cement (NaOH) (Mix 2)

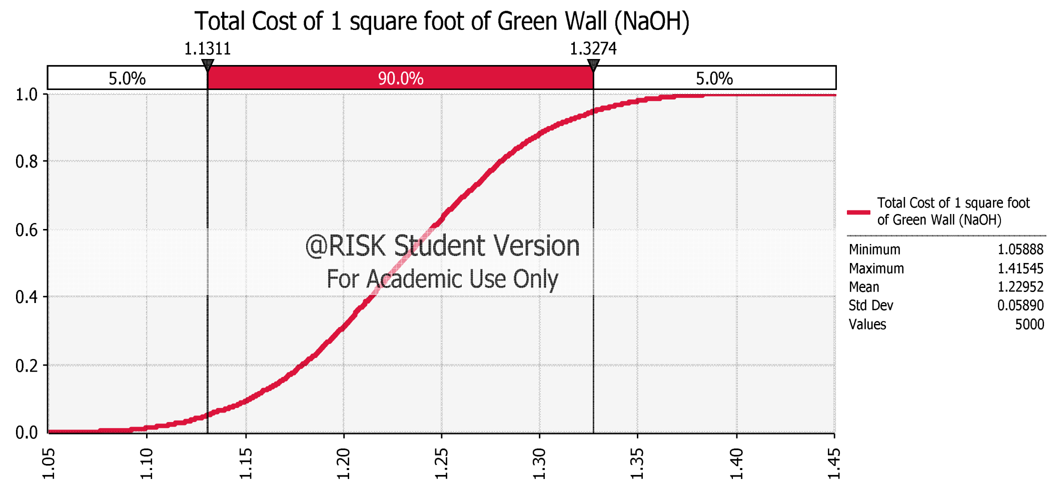


Figure 7.7: A cumulative ascending chart cost of one SF of wall Green cement (NaOH) (Mix 2)

Table 7.7 represents summary statistics for costs of one SF wall of Green cement with (NaOH) as an activator (Mix 2). It shows the minimum ($1.04) and the maximum ($1.43) expected cost of one square foot of wall of Green cement (Mix 2). The mean for this distribution was $1.22 and standard deviation was $0.059. There are many other statistical details presented in Table 7.7.

Table 7.7 - Summary Statistics for cost of one SF of wall green cement (NaOH) (Mix 2)

Statistics		Percentile	
Minimum	1.047485447	5%	1.13108936
Maximum	1.430409556	10%	1.15088765
Mean	1.229517012	15%	1.164801264
Std Dev	0.059788144	20%	1.176886655
Variance	0.003574622	25%	1.187380881
Skewness	0.020976728	30%	1.196887088
Kurtosis	2.667816606	35%	1.205567897
Median	1.229393171	40%	1.213961726
Mode	1.228892026	45%	1.222163237
Left X	1.13108936	50%	1.229393171
Left P	5%	55%	1.237563227
Right X	1.329315964	60%	1.24485035
Right P	95%	65%	1.252644508
Diff X	0.198226603	70%	1.26170761
Diff P	90%	75%	1.271105609
#Errors	0	80%	1.280377584
Filter Min	Off	85%	1.293052976
Filter Max	Off	90%	1.307823698
#Filtered	0	95%	1.329315964

Figure 7.8 shows the probability of cost of one SF of wall using green cement with Na_2SO_4 as an activator (Mix 3). As shown in the below figure, the probability of getting a cost ranging from \$-0.19 to \$-0.024 is about 90%. The sign (-) here indicates that there is a saving as a result of the benefits of impact using green cement with Na_2SO_4. In other words, the monetary value of benefits using one SF of wall green cement is greater than its cost. There is only about 5% chance of having a cost of one SF of wall using green cement (Mix 3) greater than this. Figure 7.9 represents the same probability in a cumulative ascending chart.

@RISK Output Report for Total Cost of one square foot of Green Wall (Na_2SO_4) Mix 3
Performed By: Khaled
Date: Tuesday, January 27, 2015 11:37:12 AM

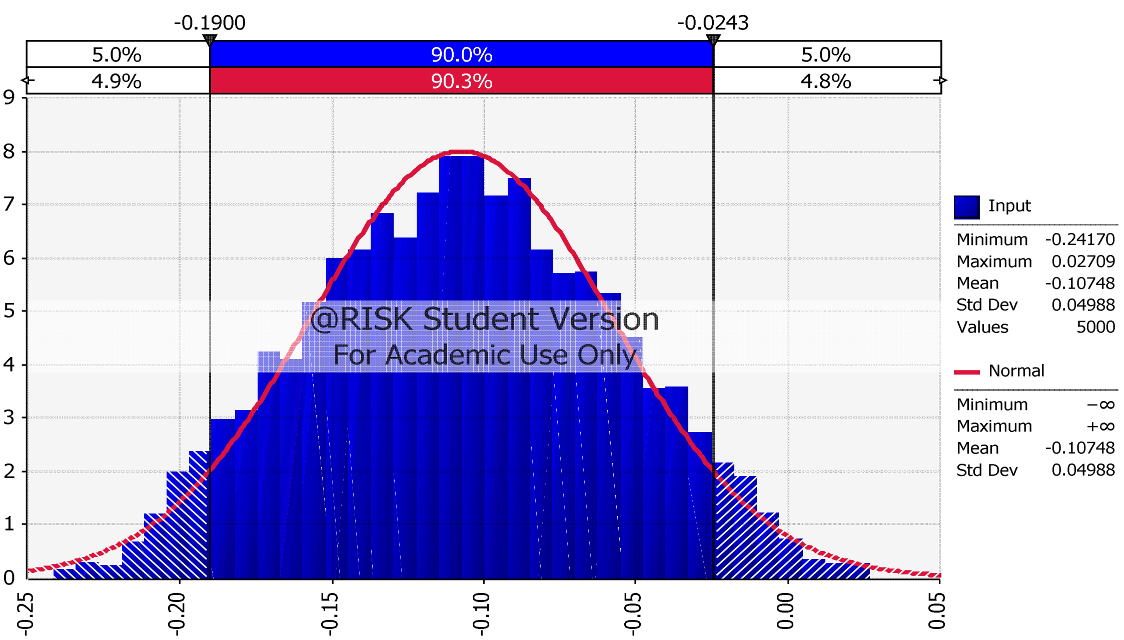


Figure 7.8: Cost of one SF of wall green cement (Na_2SO_4) Mix 3

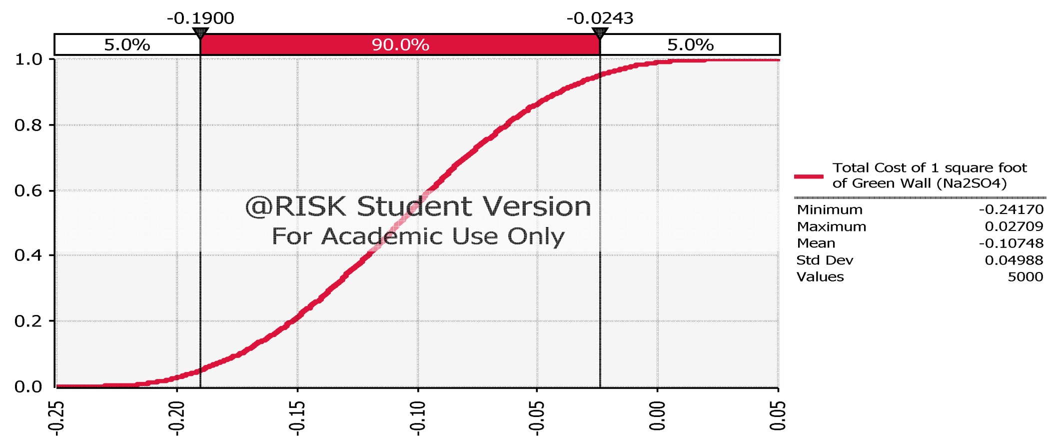


Figure 7.9: A cumulative ascending chart cost of one SF of wall green cement (Na_2SO_4) Mix 3

Table 7.8 represents summary statistics for the cost of one SF wall of green cement with (Na_2SO_4) as an activator (Mix 3). It shows the minimum ($-0.23) and the maximum ($0.02) expected cost of one square foot of wall of green cement (Mix 3). The mean for this distribution was $-0.10 and standard deviation was $0.049. There are many other statistical details presented in Table 7.8.

Table 7.8- Summary Statistics for cost of one SF of wall green cement (Na_2SO_4) (Mix 3)

Statistics		Percentile	
Minimum	-0.236756664	5%	-0.190582
Maximum	0.020530727	10%	-0.174577
Mean	-0.107483103	15%	-0.161809
Std Dev	0.049839673	20%	-0.151794
Variance	0.002483993	25%	-0.14294
Skewness	-0.003104298	30%	-0.134917
Kurtosis	2.425210871	35%	-0.128205
Median	-0.10736042	40%	-0.121322
Mode	-0.104115447	45%	-0.114391
Left X	-0.190582262	50%	-0.10736
Left P	5%	55%	-0.10122
Right X	-0.024763351	60%	-0.093782
Right P	95%	65%	-0.086905
Diff X	0.165818911	70%	-0.080001
Diff P	90%	75%	-0.071573
#Errors	0	80%	-0.062446
Filter Min	Off	85%	-0.052324
Filter Max	Off	90%	-0.040642
#Filtered	0	95%	-0.024763

7.5.4.3 Why Sensitivity Analysis is conducted

The sensitivity analysis gives a better understanding of the model. As this understanding develops, one can take action when appropriate. The more one can minimize the sensitivities, the more precise the estimate of the outcome will be. Sensitivity analysis has been conducted in order to determine which of the inputs has the greatest effect on cost of one SF of Portland cement wall (Mix 1) and green cement wall (Mix 2, Mix 3). Therefore, sensitivity analysis was done to all involved parameters (direct cost, social cost of CO_2, and so on) in each model, and it displayed the effect of each parameter on the entire model.

Figure 7.10 shows the tornado chart for the change in the output mean option of one SF of Portland cement wall (Mix 1). Each bar indicates how much the mean cost of one SF of Wall (Portland cement) changes as a particular input varies over its range. Clearly, the direct cost and the social cost of CO_2 have by far the greatest effect. As it varies over its range and the other inputs remain at their static values, the range of direct cost parameter of one SF of Portland cement wall (Mix 1) varies from about \$0.56 to about \$0.64, and social cost of CO_2 has the second highest range which is from \$0.57 to about \$0.64. The parameters of SO_2's emissions have the lowest impact with a range from \$0.603 to \$0.607. Table 7.9 represents the range of change in output statistics of all involved parameters from lower to upper values for cost of one SF of Portland cement wall (Mix 1).

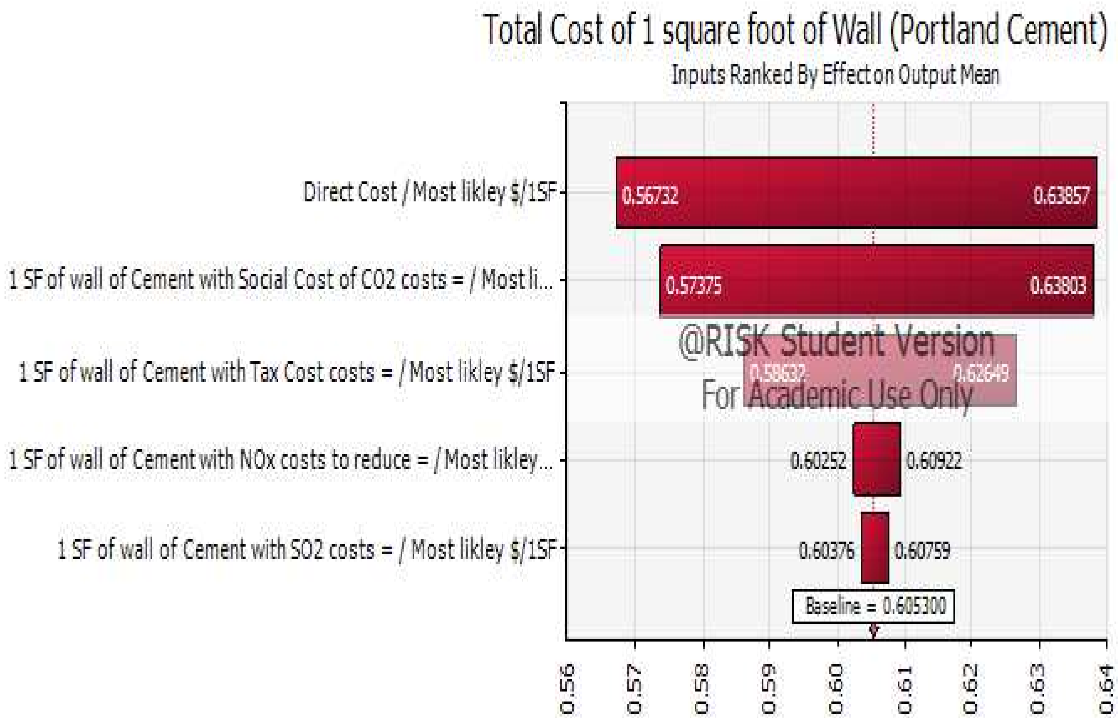


Figure 7.10: Sensitivity analysis (Tornado chart) for cost of one SF of wall (Portland cement) Mix 1

Table 7.9- Change in output statistics for cost of one SF of wall (Portland cement) (Mix 1)

Rank	Name	Lower	Upper
1	Direct Cost	0.5673174	0.63857160
2	1 SF of wall of Cement with Social Cost of CO_2 costs	0.573754	0.63802642
3	1 SF of wall of Cement with Tax Cost costs	0.5863187	0.62648652
4	1 SF of wall of Cement to reduce NOx	0.6025166	0.60921728
5	1 SF of wall of Cement with SO_2 costs	0.6037572	0.60759176

Figure 7.11 shows the tornado chart for the change in the output mean option of one SF of Green cement wall (Mix 2). Each bar indicates how much the mean cost of one SF of green cement wall (Mix 2) changes as a particular input varies over its range. Clearly, the savings on CO_2 emissions impact have by far the greatest effect. The range of savings on reducing emissions of CO_2 impact varies from about \$1.14 to about \$1.31. Next, the direct cost has a range from \$1.17 to \$1.28. The two parameters, savings on NO_x emissions, and savings on avoiding land filling have the lowest impact with a range from \$1.22 to \$1.23. Table 7.10 represents the range of change in output statistics of all involved parameters from lower to upper values for cost of one SF of green cement wall (Mix 2).

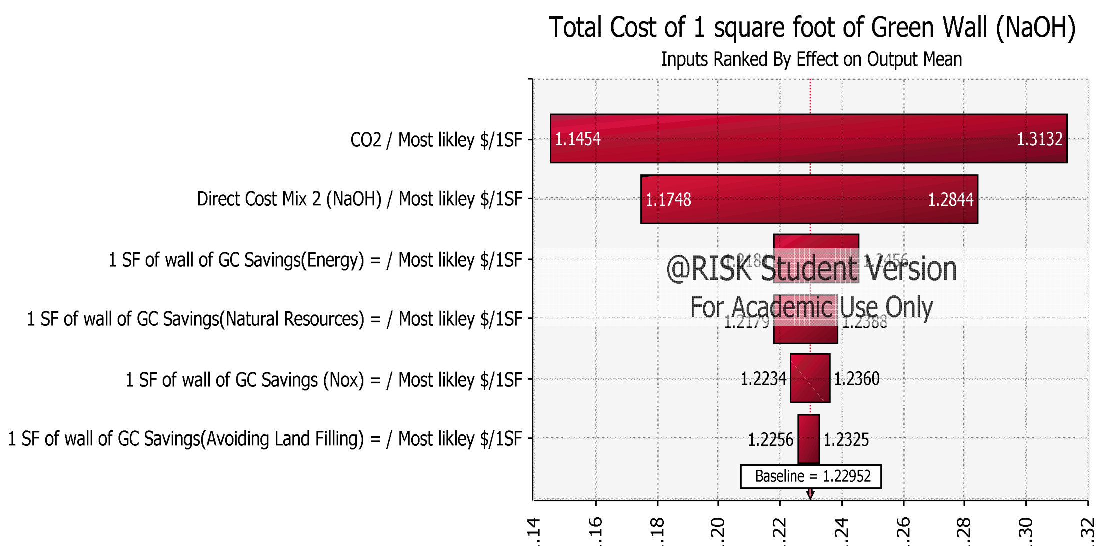


Figure 7.11: Sensitivity analysis (Tornado chart) for cost of one SF of wall green cement (NaOH) Mix 2

Table 7.10 - Change in output statistics for cost of one SF of wall green cement (NaOH) (Mix 2)

Rank	Name	Lower	Upper
1	1 SF of wall of GC Savings on reducing emissions of CO_2	1.145217	1.313044
2	Direct Cost of Mix 2 (NaOH)	1.1733878	1.287525
3	1 SF of wall of GC Savings (Energy)	1.2181632	1.2453089
4	1 SF of wall of GC Savings (Natural Resources)	1.2179908	1.2435422
5	1 SF of wall of GC Savings on reducing (No_x)	1.2193383	1.23771
6	1 SF of wall of GC Savings (Avoiding Land Filling)	1.2251964	1.2337806

Figure 7.12 shows the tornado chart for the change in the output mean option of one SF of green cement wall (Mix 3). Each bar indicates how much the mean cost of one SF of green cement wall (Mix 3) changes as a particular input varies over its range. Clearly, the savings on CO_2 emissions impact have by far the greatest effect. The range of savings on reducing emissions of CO_2 impact varies from about \$-0.19 to about \$-0.023. Next, savings on energy have a range from \$-0.12 to \$-0.09. The parameter of savings on avoiding land filling has the lowest impact with a range from \$-0.109 to \$-0.103. Table 7.11 represents the range of change in output statistics of all involved parameters from lower to upper values for cost of one SF of green cement wall (Mix 3).

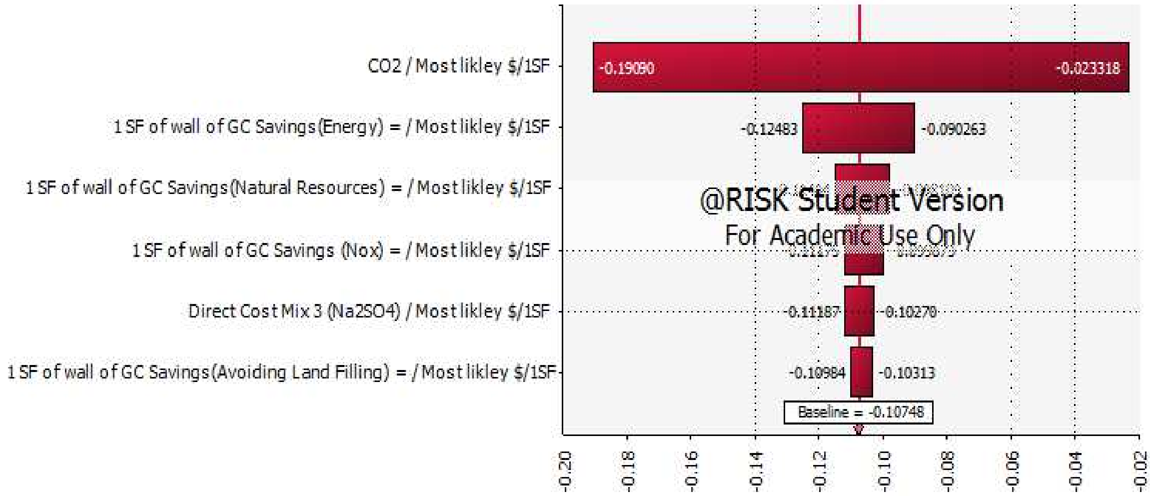


Figure 7.12: Sensitivity analysis (Tornado chart) for cost of one SF of wall green cement (Na_2SO_4) Mix 3

Table 7.11 - Change in output statistics for cost of one SF of wall green cement (Na_2SO_4) (Mix 3)

Rank	Name	Lower	Upper
1	1 SF of wall of GC Savings on reducing emissions of CO_2	-0.190901	-0.023318
2	1 SF of wall of GC Savings (Energy)	-0.124827	-0.090263
3	1 SF of wall of GC Savings (Natural Resources)	-0.114841	-0.098109
4	1 SF of wall of GC Savings on reducing (Nox)	-0.11175	-0.099873
5	Direct Cost of Mix 3 (Na_2SO_4)	-0.111868	-0.102695
6	1 SF of wall of GC Savings (Avoiding Land Filling)	-0.109837	-0.103128

7.6 Summary and Conclusions

This study has quantified the environmental and economic benefits of the use of fly ash-based green cement in masonry components. Savings associated with reductions in energy and lower green house gas (GHG) emissions are primarily accrued by offsetting the need for material production. In regards to finance, this study has found that Mix (1) which is for Portland cement has direct cost, cost of raw materials only, on average $0.460, and indirect cost (the monetary value of benefit-cost analysis model, as a result of negative impacts) on average $0.152. Therefore, the total cost (direct cost + indirect cost) is $0.612. Mix (2) which is for green cement with NaOH has direct cost, cost of raw materials only, on average $2.28, and savings (the monetary value of benefit-cost analysis model, as a result of positive impacts) on average $-1.057. Therefore, the actual cost (direct cost - savings) is on average $1.222. Mix (3) which is for green cement with Na_2SO_4 has direct cost, cost of raw materials only, on average $0.943 and savings (the monetary value of benefit-cost analysis model, as a result of positive impacts) on average $-1.057. Therefore, the actual cost (direct cost - savings) is on average $-0.114, which means that we save $0.114 in each one square foot of masonry wall with Mix 3.

The total environmental benefits obtained by replacing Portland cement with green cement are remarkable. Based on nearly 7 billion square feet of masonry walls produced yearly in North America (American Institute of Architects, 2008), if we were to replace concrete masonry with green cement masonry, approximately 168 million Btu of energy would be saved, 29.4 million tons of GHG emissions would be avoided, 16.86 million tons of raw material for cement manufacture such as limestone would be reduced in its consumption. In addition, 1.7 million tons of extra CO_2 emissions would be avoided due to the fact that we can prevent the land filling of fly ash. In case of average 7 billion square feet of masonry walls using green cement is produced yearly, this model shows that the financial savings are large and that $5 to 10 billion yearly is made available for other uses by using green cement in sustainable construction. The total value of savings of $5 to $10 billion yearly is included in the monetary value of benefits (energy saving, reducing emissions of GHG, reducing consumption of raw materials, and avoiding CO_2 emissions due to avoid land filling of fly ash) by producing an average of 7 billion square feet of masonry walls using green cement per year. These quantities indicate that fly ash-based green cement use in construction contributes significantly to sustainability in the US, and should be nurtured and enhanced.

CHAPTER 8 CONCLUSION AND FUTURE WORK

8.1 Overview of Research

This study displays results of research on the benefit-cost analysis of using fly ash-based green cement in masonry components. The study may be grouped into four main components. The first component is to present a literature review of the cement industry, fly ash, and their environmental impacts. The second component of the study is to experimentally evaluate the compressive strength of fly ash-based green cement specimens to meet the strength requirements of ASTM C90 and C129 for masonry walls. At the same time, it is to evaluate the durability performance of fly ash-based green cement mortar. The third component is to offer a theoretical understanding of the benefit-cost analysis model, and to investigate the reasons why sensitivity and risk analysis are applied to the benefit-cost analysis model. The final component of this research investigation is to conduct a benefit-cost analysis model for masonry walls as an application of using fly ash-based green cement.

To explain in further detail, in the second component, fly ash-based green cement specimens have been tested for compressive strength at different ages (1-day, 3-day, 7-day, 28-day, and 90-day). Typically, the 1-day, 3-day, 7-day, 28-day, and 90-day average compressive strengths are 25 MPa, 34 MPa, 49 MPa, 63 MPa, and 77 MPa respectively that met the strength requirements of ASTM C90 and C129 for masonry walls. In addition, fly ash-based green cement specimens have been tested to evaluate their performance of durability using freeze-thaw performance. The freeze-thaw test was done according to ASTM C666 at different cycles (50-cycle, 100-cycle, 200-cycle, and 300-cycle). The results showed that fly ash-based green cement specimens have good performance of durability.

The last component demonstrates the benefit-cost analysis of using fly ash-based green cement in masonry components. The potential application of fly ash-based green cement materials is investigated based on the market needs and their advantages over Portland cement. It has been established that fly ash-based green cement may be a good candidate to replace Portland cement in the making of masonry units. Then, the material cost of fly ash-based green cement is analyzed in comparison to Portland cement. The price of typical fly ash-based green cement materials is estimated based on the present market price of each component. This study has found that Mix (1) has total cost (direct cost + indirect cost) = $0.612, Mix (2) has total cost (direct cost - savings)= $1.22, and Mix(3) has total cost (direct cost - savings)= $-0.114 which means that we save $0.114 in each one square foot of masonry wall with Mix 3.

In summary, the objectives defined at the beginning of this study are met. Fly ash can be recycled into value-added building products by using fly ash-based green cement. Compressive strength and durability properties are evaluated. For monetary value of various environmental impacts, costs were estimated by collecting information from different resources such as USEPA and USGS on the costs associated with specific control measures required by US

Environmental Protection Agency regulations, using estimates of the average cost per ton of pollutant emission reduced, and damaging the natural resources. Then, monetary valuation has been applied to assign monetary value to the various environmental impacts due to substitute of Portland cement by fly ash.

Finally, a benefit-cost analysis model of using fly ash-based green cement in masonry units is conducted. The research outcomes may lay the foundation for industrial scale production of fly ash-based green cement building products.

8.2 Conclusions

The study results included to the following points:

1-There are major drawbacks associated with Portland cement, such as the emission of greenhouse gasses and high-energy consumption from cement production. Therefore, Portland cement concrete has many disadvantages that can only be overcome by being replaced with new materials such as fly ash-based green cement.

2-Recycling fly ash and using it as a replacement for Portland cement has very positive impacts on our environment, such as conserving landfill spaces, reducing CO_2 emissions, and saving energy.

3- Fly ash can be recycled into value-added building products by using fly ash-based green cement.

4- The compressive strength of fly ash-based green cement mortar specimens met the strength requirements of ASTM C90 and C129 for masonry walls.

5-The freeze-thaw test results showed that fly ash-based green cement mortar has a very good freezing-thawing performance with high strength retention.

6-Mix (1) which is for Portland cement has a direct cost (the cost of raw materials) on average of only $0.460, and an indirect cost (the monetary value of benefit-cost analysis model, as a result of negative environmental impacts), resulting in an average cost $0.152. Therefore, the total cost (direct cost + indirect cost) is $0.612.

7- Mix (2) which is for green cement with NaOH has the direct cost (the cost of raw materials only) on average of $2.280, and savings (the monetary value of benefit-cost analysis model, as a result of positive environmental impacts) resulting in an average savings $-1.057. Therefore, the actual cost (direct cost - savings) is on average $1.222.

8- Mix (3) which is for green cement with Na_2SO_4 has a direct cost (the cost of raw materials only) on average of $0.943 and savings, the result of benefit-cost analysis, on average $-1.057. Therefore, the actual cost is on average $-0.114, which means that we save $0.114 in each square foot of masonry wall with Mix (3).

9- Based on nearly 7 billion square feet of masonry walls produced yearly in North America, if we were to replace concrete masonry with green cement masonry, approximately 168 million Btu of energy would be saved, 29.4 million tons of green house gases (GHG) emissions would be avoided, and 16.86 million tons of raw material for cement manufacture such as limestone would be reduced in its consumption. In addition, 1.7 million tons of extra CO_2 emissions would be avoided due to the fact that we can prevent the land filling of fly ash.

10- By producing an average of 7 billion square feet of masonry walls using fly ash-based green cement per year, this model shows that the financial savings for total market value of masonry walls are large and that \$5 to \$10 billion is included in the monetary value of benefits (energy saving, reducing emissions of GHG, reducing consumption of raw materials, and avoiding CO_2 emissions due to avoid land filling of fly ash).

11- Getting better understanding of the model will lead to take action when appropriate. Therefore, Sensitivity analysis has been conducted in order to determine which of the inputs has the greatest effect on cost of one SF of Portland cement wall (Mix 1) and green cement wall (Mix 2, Mix 3). Therefore, sensitivity analysis was done to all involved parameters (direct cost, social cost of CO_2, and so on) in each model, and it displayed the effect of each parameter on the entire model. For one SF of Portland cement wall (Mix 1), the direct cost and the social cost of CO_2 have by far the greatest effect. The range of direct cost parameter of one SF of Portland cement wall (Mix 1) varies from about \$0.56 to about \$0.64, and social cost of CO_2 has the second highest range which is from \$0.57 to about \$0.64. The parameters of SO_2's emissions have the lowest impact with a range from \$0.603 to \$0.607. For Mix (2), The range of savings on reducing emissions of CO_2 impact varies from about \$1.14 to about \$1.31. Next, the direct cost has a range from \$1.17 to \$1.28. For Mix (3), The range of savings on reducing emissions of CO_2 impact varies from about \$-0.19 to about \$-0.023. Next, savings on energy have a range from \$-0.12 to \$-0.09. The parameter of savings on avoiding land filling has the lowest impact with a range from \$-0.109 to \$-0.103.

12- With risk analysis, one can explicitly include the uncertainty present in our estimates to generate results that show all possible outcomes. Therefore, risk analysis was conducted to this model. For Mix (1), the probability of getting costs from \$0.55 to \$0.65 is 90%. There is only a 5% chance of having a cost of one SF of wall using Portland cement greater than this. For Mix (2), the probability of getting costs ranging from \$1.13 to \$1.33 is close to 90%. There is only about 5% chance of having a cost of one SF of wall using green cement (Mix 2) greater than this. For Mix (3), the probability of getting a cost ranging from \$-0.19 to \$-0.024 is about 90%. The sign (-) here indicates that there is a saving as a result of the benefits of impact using green cement with Na2SO4. In other words, the monetary value of benefits using one SF of wall green cement is greater than its cost. There is only about 5% chance of having a cost of one SF of wall using green cement (Mix 3) greater than this.

13- Based on market needs, the benefit-cost analysis model, the physical properties of fly ash-based green cement materials, and the advantages of fly ash-based green cement over Portland cement, concrete masonry units are found to be a good application for fly ash-based green cement. More and more applications are expected for fly ash-based green cement materials with the acceptance by industries and with a new legislation regarding environmental protection based on sustainable development concepts. This study can set a solid foundation for conducting comprehensive benefit-cost analyses for many other environmentally sustainable materials and their engineering applications.

8.3 Recommendation for Future Study

Fly ash-based green cement is found to be a good material for masonry wall components application due to its superior mechanical property, durability performance, and environmental protection. Some suggestions should be considered in the future:

1- Since there is no need for high strength in the masonry industry as the present fly ash-based green cement mortar possesses, optimizing mix compositions and/or porosity contents in terms of reduced strength and unit weight can be considered to lessen costs.

2-Activators, such as sodium sulfate (Na_2SO_4) and sodium hydroxide (NaOH), which have the highest price of the fly ash-based green cement materials, may limit the widespread acceptance use of fly ash-based green cement. Therefore, studying alternate activators is highly recommended in future studies.

3- Raw material costs and environmental costs were considered in this study. Furthermore, lifetime maintenance costs should be evaluated in future studies to consider more economic advantages of fly ash-based green cement products over the conventional Portland cement concrete products. Such cost models may help to promote the widespread use of fly ash-based green cement materials.

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ABSTRACT

BENEFIT-COST ANALYSIS OF USING CLASS F FLY ASH-BASED GREEN CEMENT IN MASONRY UNITS

by

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The Portland cement concrete is the most popularly used building material around the world. However, there are major drawbacks associated with Portland cement, such as the emission of greenhouse gasses and high-energy consumption from cement production. Therefore, Portland cement concrete has many disadvantages that can only be overcome by being replaced with new materials such as fly ash-based green cement. Recycling fly ash and using it to replace cement has positive impacts on our environment, such as conserving landfill spaces, reducing CO_2 emissions, and saving energy. Fly ash can be further recycled into value-added building products by using fly ash-based green cement. Two experimental works were undertaken to evaluate the durability performance of fly ash-based green cement mortar for freezing-thawing resistance and the other for compressive strength.

Finally, a benefit-cost model analysis of using fly ash-based green cement in masonry units is conducted. The potential application of fly ash-based green cement materials is investigated based on the market needs and their advantages over Portland cement. It has been established that fly ash-based green cement can be a good candidate to replace Portland cement in making of masonry units. It is observed that more and more applications could be found for fly ash-based green cement materials with acceptance by industries and new legislation regarding environmental protection and global sustainability concepts. The research outcomes may lay the foundation for industrial scale production of fly ash-based green cement construction products.

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