ALTERNATIVE SOLID FUELS FOR THE PRODUCTION

OF PORTLAND CEMENT

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ALTERNATIVE SOLID FUELS FOR THE PRODUCTION OF PORTLAND CEMENT

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ALTERNATIVE SOLID FUELS FOR THE PRODUCTION OF PORTLAND CEMENT

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Srikanth Akkapeddi , son of Sri. Lakshimpathy Akkapeddi and Smt. Venkata Lakshmi Akkapeddi *née* Thangirala, was born on August 1, 1983 in Hyderabad, India. He has one elder brother, Vijaykanth Akkapeddi. Srikanth graduated with a Bachelors of Technology (Honors) degree in Civil Engineering from Indian Institute of Technology, Kharagpur, India in June 2006. He immediately began his graduate studies at Auburn University.

THESIS ABSTRACT

ALTERNATIVE SOLID FUELS FOR THE PRODUCTION OF PORTLAND CEMENT

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Portland cement manufacturing involves the combustion of fuels with various raw materials at approximately 2,700 °F (1,500 °C) to produce clinker. Fuel costs and environmental concerns have encouraged the cement industry to explore alternatives to the use of exclusive conventional fossil fuels. The key objective of using alternative fuels is to continue to produce high-quality cement while decreasing the use of conventional fuels and minimizing the impact on the environment.

In this study, portland cement was produced at a full-scale cement plant during 3-day trial burns of various alternative fuels along with coal. The fuel combinations investigated were: 1) coal only, 2) coal and scrap tires, 3) coal, scrap tires, and waste plastics, 4) coal, scrap tires, and broiler litter, 5) coal, scrap tires, and woodchips, and 6) coal, scrap tires, and switchgrass.

During these trial burns, the cement plant was able to maintain its target production rates while utilizing substantial replacement of conventional fuel with alternative fuels. Samples of raw materials, fuels, cement kiln dust, clinker, cement, and emissions were systematically collected. Chemical compositions, physical characteristics, and mechanical properties were obtained for all the samples collected.

Scrap tires and waste plastics were found to have higher heat values than coal. Although broiler litter, woodchips and switchgrass have heat values lower than coal, they burned well with no feed problems, and are available in abundance. Chemical analyses showed that the primary chemical compounds of the clinker, cement kiln dust and cement (i.e. Al_2O_3, CaO, Fe_2O_3, and SiO_2) exhibited no changes of practical significance.

Various cement and concrete properties were determined for each trial burn. Tests of drying shrinkage, splitting tensile strength, and permeability of concrete showed no significant changes. The compressive strength of concrete from burns using alternative fuels showed an increase relative to the burn involving coal as the only fuel, though it is not possible to attribute this result exclusively to the use of these fuels. All the emission (NO_x, CO, SO_2 and Volatile organic compounds) levels were within the allowable limits set by Alabama Department of Environmental Management.

Overall, the cement plant was able to use alternative fuels to produce good quality cement with little impact on emissions levels. Therefore, it is concluded from the study described herein that scrap tires, waste plastics, broiler litter, woodchips and switchgrass are good potential alternative fuels for use during cement production. The final decision on the use of a specific alternative fuel will depend on the availability of the fuel, its cost, and its compatibility with the particular cement plant.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

The modern production of portland cement utilizes various materials, complex facilities, and involves closely monitored processes. All of these components are engineered to develop a product that satisfies the construction demands of the entire world. Portland cement is the key component of concrete, which is used to build roads, bridges, buildings, dams and just about any other type of structure used by mankind. However, the production of portland cement requires high temperatures sustained over long periods of time, which are supplied by the combustion of large quantities of fuels. The majority of these fuels have historically come from nonrenewable sources.

Portland cement is manufactured by blending raw materials, which are mined from the earth, and by chemically fusing them together in the presence of extremely high temperatures. The new product, known as clinker, is ground with sulfates to a specific particle size distribution, and this final product is known as portland cement.

The temperatures necessary to turn the raw materials into clinker are on the order of 1500 °C. These temperatures are maintained by burning large quantities of combustible fuels inside a rotary kiln, where the fusing of the materials takes place. In order to meet the demands of the construction industry, it is common for a portland cement production facility to operate 24 hours a day and seven days a week. With the quantities of fuels necessary to maintain that level of production, it is easy to see why the fuels used play a vital role in the production process.

It has been reported that the costs associated with fuels in a cement plant can be as high as 30 to 40 percent of the total production costs (Mokrzycki et al. 2003). These numbers are associated with traditional fuels such as coal, natural gas, and oil. Alternative fuels are typically a waste product from other industries. Since that is the case, it is often significantly cheaper for a cement plant to acquire waste that would otherwise be landfilled or incinerated. In fact, the cement plant may actually be paid to dispose of certain wastes. If a portland cement production facility is capable of acquiring an alternative fuel at significantly less, or even negative cost, it is worth exploring the fuel's entire potential.

Another reason why the utilization of alternative fuels in the cement production process is beneficial is the decrease in consumption of nonrenewable resources. In an efficient kiln system, where the production rates are high, it is possible for a single facility to consume as much as 1200 tons of coal a day (Manias 2004). All cement production facilities may not consume this quantity of material, but the quantities of fuels consumed in thousands of facilities worldwide are huge. If only a small portion of the nonrenewable resources used in this process are replaced in many of these facilities, a significant decrease in use of nonrenewable resources would result.

The emissions released by a cement production facility are an aspect of the production process that is closely monitored and controlled. The use of alternative fuels could influence the emissions. The combustion of the primary fuel currently used at any given cement plant may produce more emissions than the combustion of an alternative fuel that could possibly be utilized. Moreover, the incineration of wastes in a cement plant serves a dual purpose, in that the heat produced during the incineration process is used to manufacture a product. When wastes are incinerated otherwise, the heat developed is not used at all. The utilization, at a cement production facility, of alternative fuels that are derived from waste that would normally be incinerated, combines two emissions-producing processes into a single process (Greco et al. 2004). This consolidation directly reduces the amount of emissions released into the atmosphere.

Regardless of the fuel that is used to produce portland cement, the majority of the incombustible material is actually incorporated into the clinker that is being formed. Thus use of alternative fuels could alter the final chemical composition of the portland cement. In turn, this alteration of chemical composition may lead to changes in the properties of the ultimate product, concrete. For this reason, this study focused on measuring the chemical composition of all of the materials involved in the production process and the outputs from the production, with the goal of determining the effect on chemical composition, of the use of alternative fuels. In this study, the physical properties of the cement and concrete were tested to determine if there were any effects that can be directly associated with the implementation of the alternative fuels. In spite of all the positive aspects associated with the utilization of alternative fuels, if the final concrete product suffers from deficiencies in the properties that make concrete the versatile building material that it is, then the fuel in question may not be a viable alternative.

1.2 Statement of Objectives

The objectives of this project are numerous. However, due to the complex nature of the production process, and the research associated with it, some of the objectives have been given more attention than others. The primary objectives of this project are to determine the impact of using alternative fuels on the following:

1. the ability of the cement plant to maintain productive operations,
2. the chemical composition of clinker and portland cement produced,
3. the physical properties of the portland cement produced,
4. the properties of concrete made from this portland cement, and
5. the emissions released by the cement plant.

Researchers at Auburn University and a cement production facility, referred to as the cement plant, partnered to realize these objectives. The first objective was primarily studied by personnel at the cement plant itself. This objective was very important to the study. Obviously, if the utilization of a certain alternative fuel does not allow the plant to maintain production, that fuel cannot be used.

The second through fourth objectives listed above are closely related, and are the main focus of this study. Chemical compositions of all materials involved in the production process were determined, and an attempt was made to associate the utilization of alternative fuels with any chemical composition changes in the final product. Many physical properties of cement and concrete were measured, and the differences between the cement from each of the fuels were noted. Finally, an attempt was made to associate the differences in properties of cement and concrete to the chemical changes brought on by the utilization of alternative fuels.

The final objective is another one that the cement plant is very concerned with. Because the emissions released by a cement plant are closely monitored and controlled, any effects that the combustion of alternative fuels may have will be assessed.

1.3 Research Plan

Based on the objectives listed above, a complex yet thorough sampling and testing plan was developed. The research was conducted using a full-scale production plant that was operated under normal procedures typically used at this cement plant. The only change to the production process was to use the alternative fuels that are part of this study.

The research plan consisted of eight trial burns in which unique combinations of fuels were used. The first trial burn utilized pulverized coal as the only fuel. Coal is a common fuel source used by portland cement production facilities, and is the primary fuel used at the cement plant where this research was conducted. The second burn maintained coal as the primary fuel, but supplemented a portion of it with whole scrapped tires. Since this trial burn was completed, this has become the fuel combination that the cement plant currently uses in its everyday operations. Therefore, this fuel combination was considered the baseline to which each of the other fuel options was compared.

The third trial burn used a combination of pulverized coal, whole tires, and waste plastics. The waste plastics were considered to be the first alternative fuel used. Since significant time elapsed between the second burn and the third burn, and the sources of raw materials and coal were changed, it was decided to conduct another burn with the standard fuel combination of coal plus tires for comparison for the third burn. Hence the fourth trial burn used a combination of coal and scrap tires. The fifth trial burn used coal, scrap tires, and broiler litter. Broiler litter, which is a byproduct of the broiler farming industry, was considered to be the second alternative fuel. Since it was reported that the coal sources were again changed between the fourth and fifth trial burns, it became necessary to conduct another baseline burn with the standard fuel combination for comparison of results. Hence the sixth trial burn used coal and scrap tires. The seventh trial burn used coal, scrap tires, and woodchips as fuels, while the eight trial burn used coal, scrap tires, and switchgrass as fuels. Woodchips and switchgrass were the considered to be the third and fourth alternative fuels.

In order for the cement plant to burn the fuels implemented in this project, many modifications had to be made to the facilities at the cement plant. New equipment had to be installed that was capable of handling, transporting, measuring, and introducing the fuels into the production systems. This was the main reason for the delay between the trial burns.

Within each of these trial burns, a thorough sampling and testing procedure was used. Each of the materials used to produce the portland cement was sampled and tested for its chemical composition. Additionally, each of the outputs from the production process was collected and tested for its chemical composition. Each of the inputs and outputs was sampled and tested at different frequencies relative to its importance to the production process. The chemical analyses were conducted at the cement plant on each of these materials. Samples from each of these materials were also sent to an external laboratory for additional testing. This additional testing served to verify the results provided by the cement plant. Some specialty chemical analyses were conducted by a specialty laboratory that is a subsidiary of the company that owns the cement plant.

In addition to the chemical analyses, select physical properties of the cement, as well as many properties of concrete made from the cement, were evaluated. Many physical properties of the cement were evaluated at the cement plant. Most of the same properties were also determined by staff from Auburn University. Moreover, some of the concrete tests were conducted at both Auburn University and at the concrete laboratory of the cement plant. However, the testing conducted by Auburn was more extensive than that conducted at the cement plant. At Auburn University, there were two different concrete mixtures that were produced from the cement of each trial burn. Different mixtures were used to examine the interaction of the cement with various chemical admixtures.

The final aspect of the research plan was to collect and monitor the emissions during each of the trial burns. The emissions were monitored by the cement plant using a continuous emissions monitoring system. These results were then reported to Auburn University staff and an evaluation of these results is presented in this document.

1.4 Document Organization

This document is organized into five chapters, followed by a set of appendices. The current chapter introduces the reader to the possibilities and problems associated with alternative fuels and portland cement production. It is also where the objectives for this project are stated. Finally, Chapter One provides a brief description of the procedures that were implemented in satisfying the objectives.

The second chapter of this document is where background research on this study is presented. Literature from other studies pertaining to this research is examined and pertinent information is presented. Another important goal of Chapter Two is to provide a thorough explanation of the production process associated with portland cement. This discussion is based on the process in general, and is not specific to the cement plant used in this study. After that, an introduction to each of the materials involved in the production process, and how each may be affected by the use of alternative fuels is given. Chapter Two concludes with a thorough explanation of how many elemental compounds, that may be introduced into the portland cement by the alternative fuels, can potentially affect the properties of cement and concrete. All of the information in Chapter Two originates from a review of outside literature, and is not the original work of the author.

A thorough explanation of the methods used to research the problem at hand is presented in Chapter Three. Each of the input and output materials relating to the production of portland cement was sampled and tested in various manners. Chapter Three expands on this sampling and testing procedure.

The results of this study are presented, analyzed, and discussed in Chapter Four. Due to the large quantity of data associated with some of the results, the primary method of data presentation used in this chapter is the utilization of summary statistics. Once the statistics have been presented, they are analyzed and discussed. Where the results allow for conclusions to be drawn, they are discussed, and in some cases, compared to the relevant historical data obtained from prior studies that were presented in Chapter Two.

The final chapter of this document contains summaries, conclusions, and recommendations related to this study. A summary of the reasons why this study is important is provided, along with the way this study was conducted. The objectives stated in Chapter One are restated, and conclusions pertaining to each one are provided. In some cases definitive conclusions could not be reached, but in such cases, reasons for this are given. Chapter Five concludes with recommendations on a number of aspects of this study. Suggestions for future work, possible ways to improve the research and aspects that may have been overlooked in the current study are provided.

Following Chapter Five, there is a set of appendices. Appendix A presents the sampling and testing plan in tabular form. Chapter Three discusses the plan in more detail, and the same are shown in Appendix A in a simplified table.

The final section of this document is Appendix B. This appendix has eight parts. Each part serves to present in a tabular form all of the raw data associated with each trial burn. For instance, Appendix B.1 presents all of the data for the coal only burn.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Concrete is a material used in building construction, consisting of hard, chemically inert particulate substances, known as aggregates (usually made from different types of sand and gravel), that are bonded together by cement and water. Various types of cementing material are available today; however, the most common one used is portland cement.

The invention of portland cement is generally credited to Joseph Aspdin, an English mason (Kosmatka et al. 2002). Aspdin experimented with calcareous cement formulations, and in 1824 he took out a patent. His patented cement was lightly calcined lime with little, if any, lime-silica reaction. It was his son, William Aspdin, who made the first in-depth CaO-SiO_2 reaction by accident when the so-called over-burnt clinker, which had been previously rejected, was incorporated into his product (Blezard 1998).

Cement production has advanced dramatically from the days of the Aspdins. High temperatures on the order of 1500 °C were introduced, enabling the raw materials to blend well enough to form a relatively uniform product. These high temperatures render the process extremely fuel-intensive (Jackson 1998). The typical costs associated with fuels may be as much as 30 to 40% of the total production costs (Mokrzycki et al. 2003).

In order to reduce this cost, many cement producers are looking into the utilization of alternative fuels (Mound and Colbert 2004).

Alternative fuels (also known as waste-derived fuels) are materials that are rich in energy, such as used tires, waste wood, used oil, and spent solvent, which can be used to replace coal or gas as source of thermal energy in the cement manufacturing process (PCA 2004).

The utilization of alternative fuels can be not only economically profitable but also ecologically beneficial. The most significant benefits are preservation of fossil fuel resources, reduction in the volume of wastes that must be disposed of by other means, and a decrease in the global greenhouse effect (Greco et al. 2004). However, it is important that an alternative fuel does not produce adverse side effects, such as changes to product chemistry and performance, or increased emissions (Mokrzycki and Uliasz-Bocheńczyk 2003). Therefore, it is imperative that a thorough study establishes the possible effects of the utilization of alternative fuels in cement production before its implementation.

This chapter provides a review of literature regarding the parameters that have significant bearing on the feasibility of introducing alternative fuels to the portland cement industry.

2.2 Portland Cement Production

In cement manufacturing, appropriate proportions of raw materials containing calcium, silica, alumina, and iron are fused together at approximately 1500 °C to form a product known as clinker. Such clinker is cooled and ground with an appropriate quantity of sulfate to a predetermined fineness to form portland cement (Taylor 1997). Due to the high level of complexity of the production process, and in order to be as economical as possible, the exact process varies from one facility to another (Jackson 1998). Some facilities adopt a wet process where the raw materials are suspended in water during the processing. However, most modern facilities adopt the more energy-efficient dry process, in which grinding and blending are completed on dry raw material (Kosmatka et al. 2002).

Figure 2.1 shows a schematic diagram of the typical dry process. Appropriate proportions of raw materials are ground to powder in a grinding mill, mixed thoroughly in the blending mill, and sent to the storage silo. Throughout the process, dust is removed and collected at various locations. The raw material blend is then fed to the preheater, where it is calcinated before entering the kiln. Once in the kiln, the raw material feed is fused together into clinker which is then cooled and stored in silos. The stored clinker is then mixed with gypsum and ground into cement in the grinding mills. The final product, cement, is then stored, packaged, or shipped to the consumer.

2.2.1 Raw Materials

The selection and processing of raw materials are important components of the portland cement manufacturing process. The raw materials used in the manufacture of portland cement generally constitute calcareous (high $CaCO_3$ content) and argillaceous (high silica and alumina content) material (Kosmatka et al. 2002). Some of the most common sources of raw materials are listed in Table 2.1.

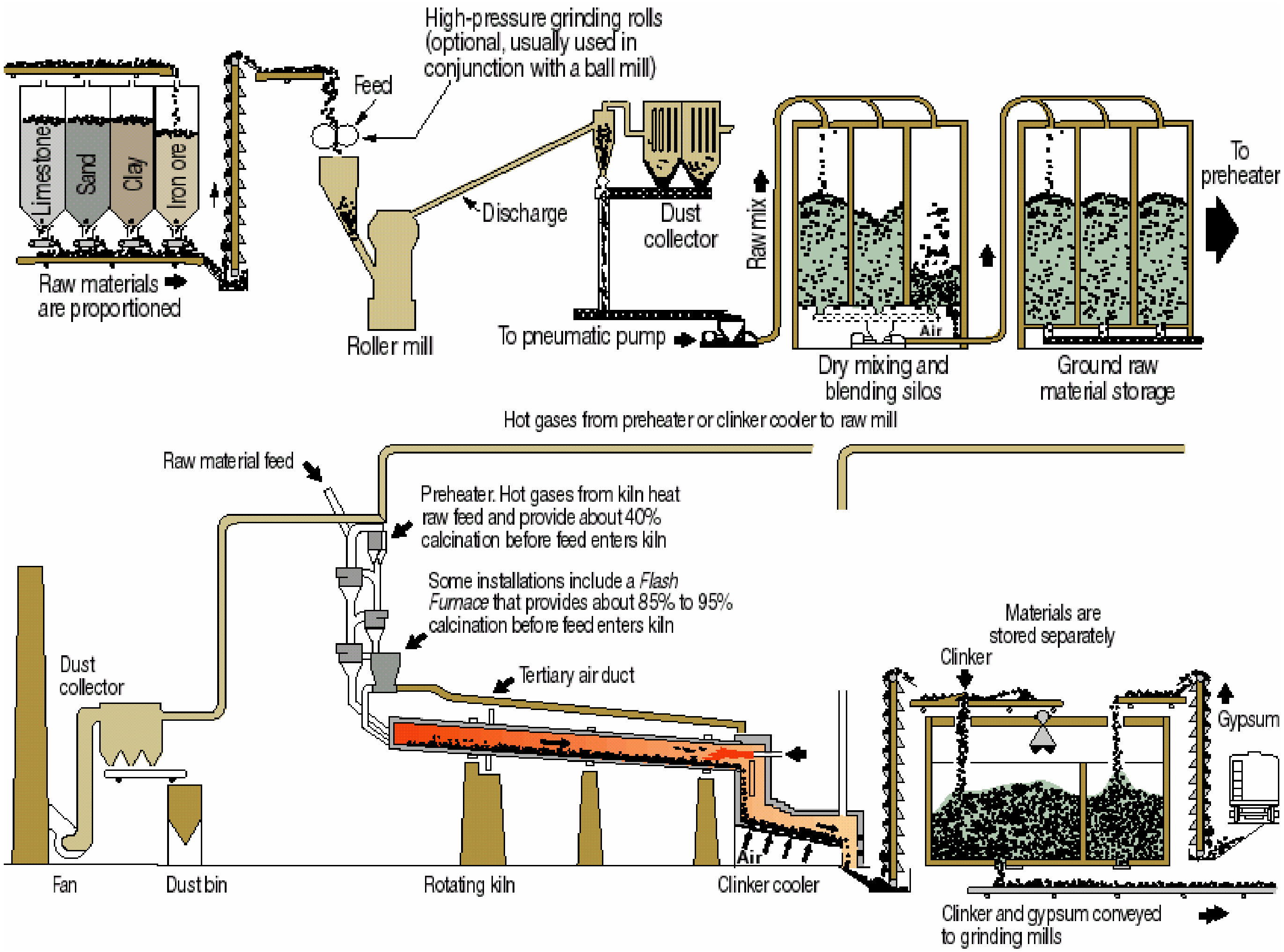


Figure 2.1: Layout of a Typical Dry-Process Portland Cement Production Facility (Kosmatka et al. 2002)

The raw materials must be crushed and proportioned so that the appropriate chemical composition of the raw material feed is reached (Kosmatka et al. 2002). The goal of the crushing process is to achieve the desired particle size distribution, average particle size, and specific surface area with the least amount of energy consumption and other operating costs (Chatterjee 2004). Just like the chemical composition, the size distribution of the raw materials is crucial to both the quality of the product and the operation of the process. Appropriate fineness of the feed enables the kiln to run at lower temperatures and hence, with lower fuel consumption, than that involving a coarser material (Jackson 1998). Once the appropriate fineness has been reached, the raw materials are mixed together to form a homogenous mixture with the predetermined chemical composition (Chatterjee 2004).

Table 2.1: Typical Sources of Raw Materials (from Kosmatka et al. 2002)

Calcium	Iron	Silica	Alumina	Sulfate
Alkali waste	Blast-furnace flue dust	Calcium silicate	Aluminum-ore refuse*	Anhydrite
Aragonite*	Clay*	Cement rock	Bauxite	Calcium sulfate
Calcite*	Iron ore*	Clay*	Cement rock	Gypsum*
Cement-kiln dust	Mill scale*	Fly ash	Clay*	
Cement rock	Ore washings	Fuller's earth	Copper slag	
Chalk	Pyrite cinders	Limestone	Fly ash*	
Clay	Shale	Loess	Fuller's earth	
Fuller's earth		Marl*	Granodiorite	
Limestone*		Ore washings	Limestone	
Marble		Quartzite	Loess	
Marl*		Rice-hull ash	Ore washings	
Seashells		Sand*	Shale*	
Shale		Sandstone	Slag	
Slag		Shale*	Staurolite	
		Slag		
		Traprock		

Note: * Most common source

2.2.2 Pyro-processing

Pyro-processing is the process in which materials are subjected to high temperatures in order to bring about a chemical or a physical change. Once the raw materials have been proportioned and mixed, they are ready to be fused together on a chemical level. The raw mixture is sent through preheater and precalciner to heat it to approximately 850 °C before it is fed into the kiln. In the process, some of the carbon is removed as CO_2, leaving a material with a higher CaO content (Jackson 1998). This makes the process much more fuel and cost efficient.

The raw material passes through the kiln at a rate determined by the slope and rotational speed of the kiln (Kosmatka et al. 2002). The kiln systems perform the following on the raw mixture, starting from the feed end (Manias 2004):

1. Evaporating free water, at temperatures up to 100 °C
2. Removal of adsorbed water in clay materials, 100 °C – 300 °C
3. Removal of chemically bound water, 450 °C – 900 °C
4. Calcination of carbonate materials in the preheater, 700 °C – 850 °C
5. Formation of belites, aluminates and ferrites, 800 °C – 1250 °C
6. Formation of liquid phase melt, >1250 °C
7. Formation of C_3S, 1330 °C– 1450 °C
8. Cooling of clinker to solidify liquid phase, 1300 °C – 1240 °C
9. Final clinker microstructure frozen in clinker, <1200 °C
10. Clinker cooled in cooler, 1250 °C – 100 °C

In this process, the C_3S (alite), C_2S (belite), C_3A (aluminate), and C_4AF (ferrite), known as Bogue Compounds, are the major clinker phases. When portland cement is mixed with water, these four compounds react with the water to form the majority of the hydrated cement products that give cement its cementitious properties (Taylor 1997).

Figure 2.2 shows the gas temperature (solid line), and the material temperature (broken line) as they progress through the various parts of the kiln system. Additionally, the retention times in each area of the system are shown at the bottom.

2.2.3 Clinker Cooling

Clinker cooling is essential since it locks in desirable product qualities by freezing mineralogy and makes it possible to use conventional conveying equipment (EPA 1995). Cement exhibits its best strength-giving properties when the clinker is cooled rapidly from the temperature at the burning zone to about 1200°C, which inhibits the further reaction of clinker phases (Jackson 1998).

The cooling of clinker takes place in two locations: 1) in the kiln after the burning zone region, and 2) in a specially designed clinker cooler (Manias 2004). The most common types of clinker coolers are 1) reciprocating grate, 2) planetary and, 3) rotary. In these coolers, clinker is cooled from about 1100 °C to 93 °C by ambient air that passes through the clinker and into the kiln for use as combustion air. This way about 30 percent of the heat input to the kiln may be recovered (EPA 1995).

2.2.4 Grinding and Finishing

The final step in portland cement manufacturing is grinding the blend of clinker and gypsum. Up to 5 percent (by weight) of gypsum, or other sulfate source, is added to the clinker after it is cooled (EPA 1995). The amount of gypsum is adjusted to regulate cement properties such as setting time and shrinkage and strength development (Kosmatka et al. 2002).

Typically, the grinding process is accomplished using a ball mill, roller mill, roll press, or a combination of these (Strohman 2004). However, in most modern facilities, finish milling is done almost exclusively by ball mills (EPA 1995). A ball mill consists of a horizontal tube rotating about its axis, filled with steel balls ranging in size from 13 *mm* to 100 *mm*. As the mill rotates, the balls frequently collide with the clinker, causing it to fracture into progressively smaller pieces (Jackson 1998). In general, the finished product will be ground so that almost every particle will pass through a 45 micrometer sieve (Kosmatka et al. 2002). Once grinding is completed, the finished product is the portland cement, which is packaged, stored in silos or shipped to consumers.

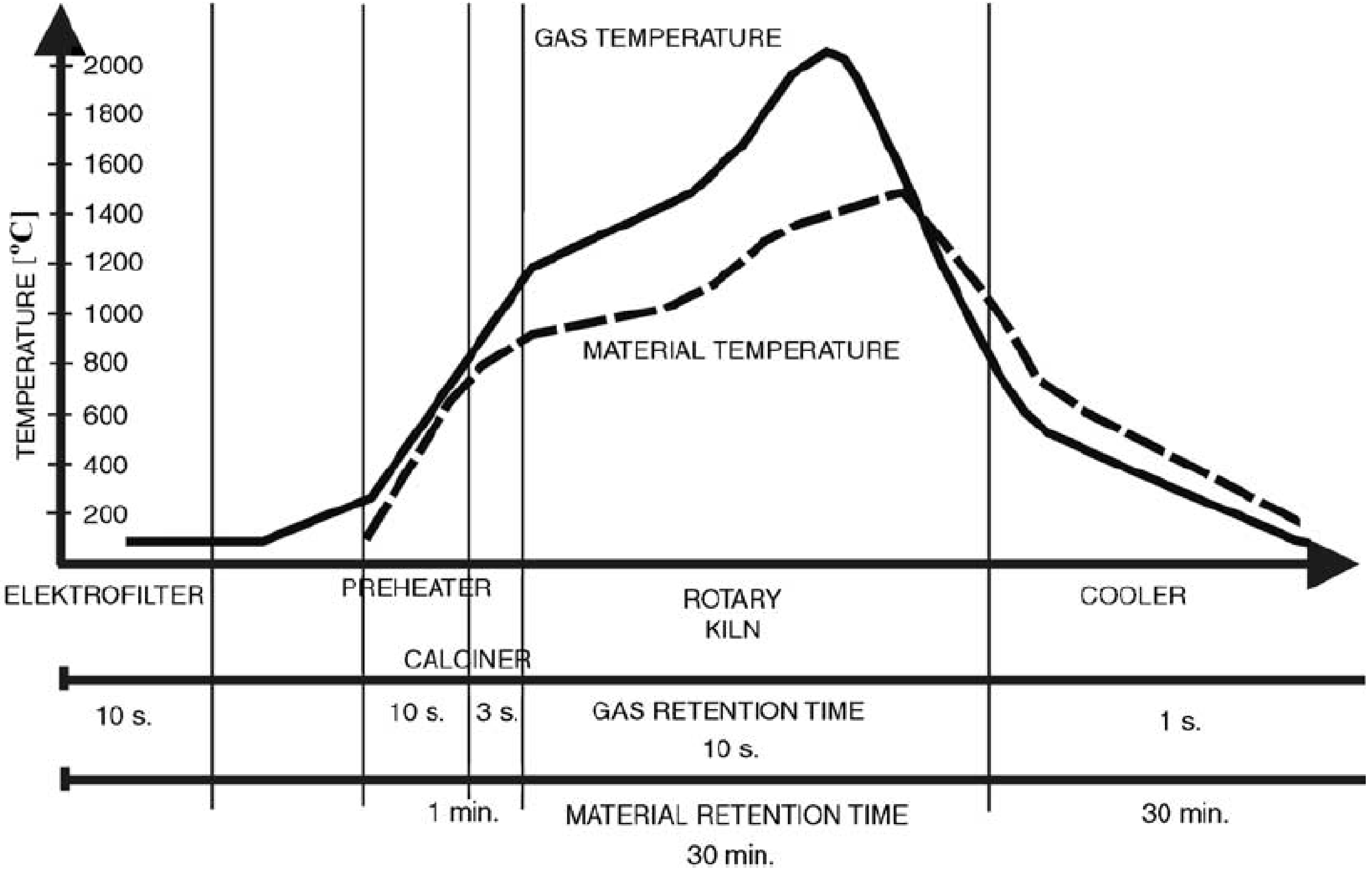


Figure 2.2: Gas and Material Temperature inside a typical cement kiln (Mokrzycki and Uliasz-Bocheńczyk 2003)

2.3 Alternative Fuels and Portland Cement Production

According to Greco et al. (2004), fuels are “substances that in the presence of an oxidant (usually, but not exclusively, atmospheric air) and provided there is an “initial energetic impulse,” give rise to a chemical reaction of oxidation that is exothermic, self-sustainable, and very rapid.”

The production of portland cement requires a high degree of thermal energy. Based on the endothermal reactions of decarbonation of limestone and dehydration of the kaolinite ($Al_2Si_2O_5(OH)_4$) and exothermal reaction of phase forming, 1 kg of clinker requires about 175 MJ of thermal energy in basic calculation (Wurst and Prey 2002).

Figure 2.3 shows both traditional and alternative fuels. In many cases, the terms alternative fuels and waste (or waste-derived) fuels are used interchangeably. For the purpose of this document, the term “alternative fuels” will refer to anything used as a substitute for traditional fuels.

2.3.1 Alternative Fuels in Cement Kilns

Cement kilns have technical conditions very favorable for use of alternative fuels. Some of these important dry process kiln characteristics favorable to alternative fuel use are as follows (Greco et al. 2004):

- The temperatures in the kiln, upwards of 1500°C, are considerably higher than the threshold ignition temperature, as established by environmental regulations,
- Long retention time of products under high temperature combustion,
- The high alkalinity atmosphere readily absorbs most acidic gases released by the oxidation of sulphur and chlorides,

- Most of the non-fuel compounds, such as metallic oxides, do not harm the production of clinker, and
- Most of the noncombustible products, particularly metals, are either incorporated into the clinker itself, or are trapped by and recycled with the cement kiln dust.

Since most of the noncombustible products are incorporated into the final product, it is necessary to establish that the performance of the cement is not adversely affected by the altered chemical composition. A thorough discussion of the elements and their possible effects on the product can be found in Section 2.6. Similarly, a discussion of the cement kiln dust and the impact of altered compositions can be found in Section 2.5.

2.3.2 Advantages of Alternative Fuels

One major environmental advantage of substituting alternative fuels in the cement industry is the reduction of waste disposal sites. As the consumption of goods increases to satisfy our consumer-driven life-styles, the manufacturing wastes also build up considerably (Barger 1994). As industries produce wastes such as oils, plastics, tires, etc., the environmental impact of landfilling or incinerating these wastes becomes a serious problem (PCA 2004). Landfills require large areas of land that may become unsightly and ecologically detrimental. The waste incinerators too are hazardous to the environment. Incinerators burn garbage, but do not use the heat generated; however a cement plant does the same thing while using the heat generated to manufacture portland cement. Therefore a cement facility serves in both ways (Mokrzycki and Uliasz-Bocheńczyk 2003).

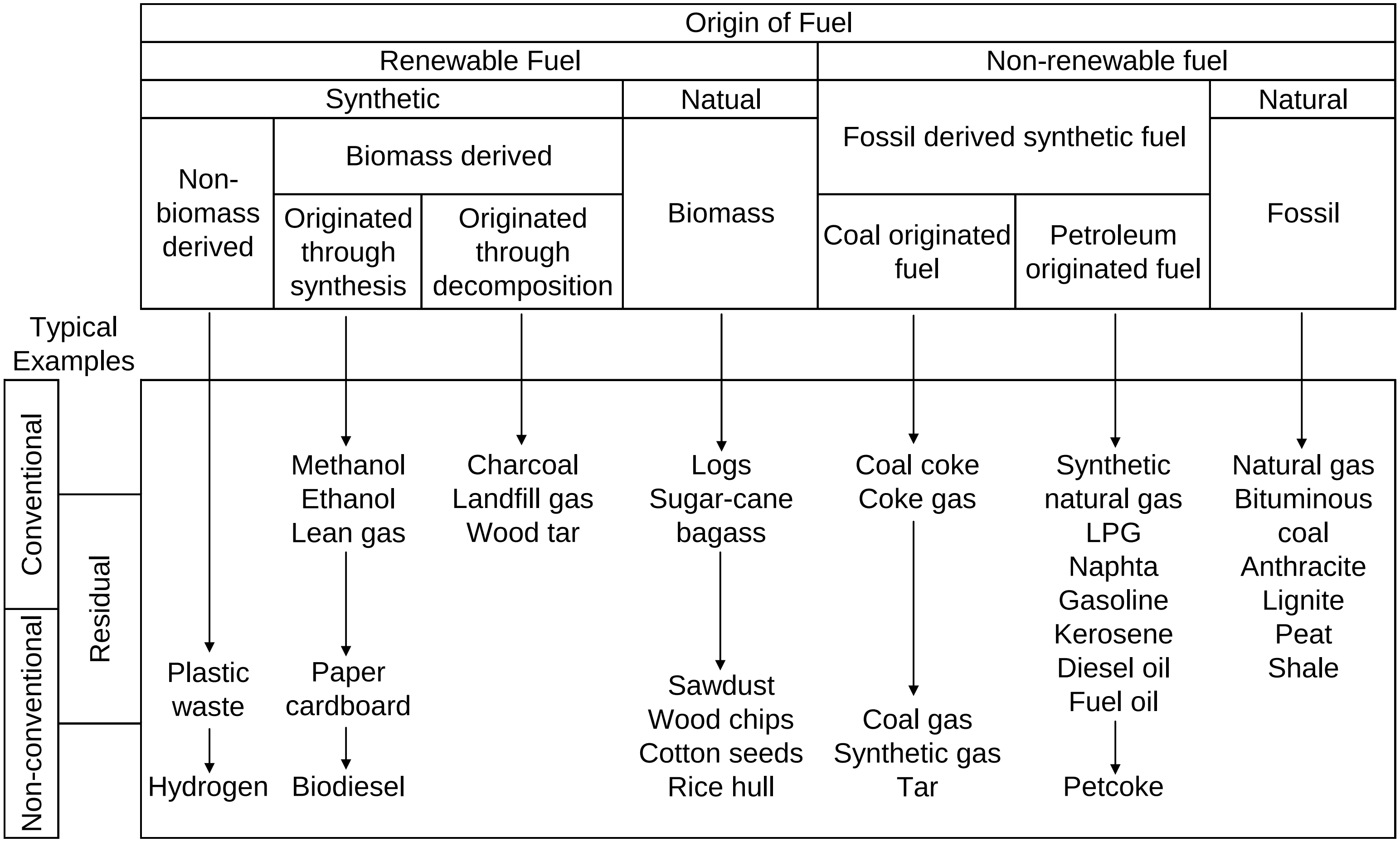


Figure 2.3: Various fuels and their origin (Adapted from Greco et al. 2004)

Another significant environmental advantage of alternative fuel substitution is the preservation of nonrenewable energy sources (Trezza and Scian 2000). For instance, the process of mining coal takes its toll on the environment (Mokrzycki et al. 2003). Although coal is used for many applications other than firing cement kilns, even a small reduction in coal consumption will make a beneficial difference. In general, a decreased use of nonrenewable resources in cement plants can make a significant difference in the total volume of consumption around the world (Wurst and Prey 2002). It was reported that the utilization of alternative fuels in the Australian cement industry accounted for a reduction of 57,000 tons of coal consumption in 1999 (PCA 2004).

Alternative fuels can also supplement the raw material requirement in cement production. For instance, due to the high silica content (78 to 90 percent) in the ash of rice husks, the amount of silica required in the raw feed may be significantly reduced (Jackson 1998). Additionally, the steel belts in tires may be used to replace a portion of the iron required in the raw materials (Kääntee et al. 2002).

2.3.3 Disadvantages of Alternative Fuels

In order to make educated decisions concerning the use of alternative fuels in cement production, the disadvantages must be addressed and, if possible, overcome. Fundamentally, the co-firing of alternative fuels must be carried out under conditions guaranteeing total efficiency of combustion. Otherwise, problems associated with the quality of the product and/or environmental protection may occur (Greco 2004). Additionally, in order for alternative fuels to be implemented, many logistical problems such as fuel preparation and conditioning, storing, dosing, feeding, and burning must be overcome (Wurst and Prey 2002).

Many studies have previously been conducted to investigate the effect of burning various alternative fuels on the environment. Specifically, a number of these studies have been concerned with changes in emission characteristics. One such study was conducted in California where a cement plant had petitioned to use tires as a fuel supplement. In this study, it was found by the air quality management district of Cupertino, California, that tire burning substantially increases emissions of potentially toxic chemicals such as benzene, nitrogen oxides, furans and lead, as well as others (Martinez 1996). A detailed discussion of emissions can be found in Section 2.4. If results such as these were found to be true of any alternative fuel, it would be very difficult to make use of this type of fuel substitution.

One potential constraint on the implementation of alternative fuels is the final clinker composition (Mound and Colbert 2004). Because the combustion byproducts are incorporated into clinker, any undesirable compounds/elements present in the fuels may be deposited into the cement itself. If even one of these compounds/elements affects the quality of the cement, the very benefits derived may be negated.

The replacement of traditional fuels by alternative fuels inherently requires investment costs associated with adjustment or replacement of a burner, implementation of alternative fuel delivery systems, new fuel storage facilities, and fuel distribution systems (Greco et al. 2004).

The production of clinker requires an even combustion of fuels in order to consistently heat the raw materials (Peray 1986). Considering this, the fuels must be processed and conditioned to have the following characteristics (Wurst and Prey 2002):

- even particle size distribution
- as high and uniform calorific value as possible
- free of detrimental contents like some metals, glass, and minerals, and
- low moisture content.

In most situations, modifications to facilities will have to be made in order to process and condition alternative fuels to meet these criteria.

Each of the other logistical hurdles listed above must be overcome within economical constraints.

2.3.4 Alternative Fuel Options

In addition to the ability of a substance to release large amounts of energy when consumed, there are a number of other characteristics that a substance must possess in order to be considered for implementation. For instance, composition and heat value are of significant importance to the operation of a kiln (Peray 1986). It would make little sense to replace coal with a fuel that has a heating value too small to allow for its utilization with reasonable quantities.

The specific criteria that a material must meet in order to be considered as a fuel are typically specific to either the facility or the corporation that owns the facility. In general, each company that may be considering alternative fuel substitution usually develops its own set of standards. As an example of some of these standards, the following criteria must be met in order for the Lafarge Cement Polska group to use a substance as an alternative fuel (Mokrzycki et al. 2003):

- Energy value – over 14 MJ/kg (6019 BTUs/lb)
- Chlorine content – less than 0.2 percent
- Sulphur content – less than 2.5 percent
- Polychlorinated Biphenyls (PCBs) content – less than 50 parts per million (ppm), and
- Heavy metals content – less than 2500 ppm.

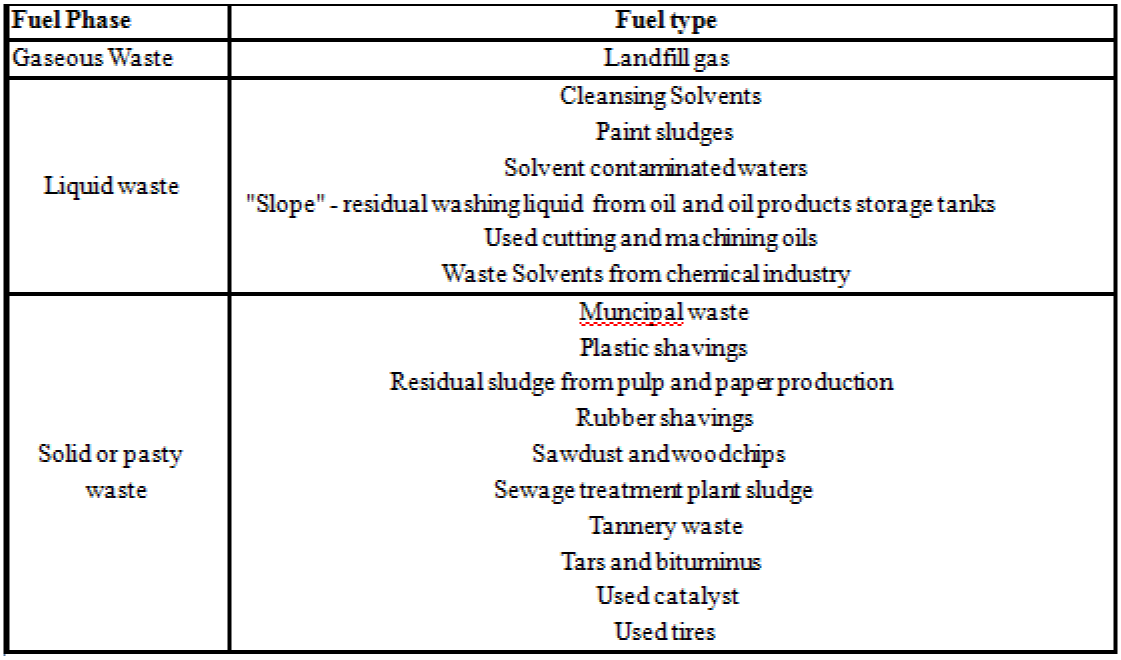
It can be seen that a wide range of materials can be considered as viable alternative fuels. Alternative fuels are categorized by the phase in which they exist, those phases being solid, liquid, and gas (Peray 1986). A variety of fuels fall into each of the classifications, all of which present their own unique advantages as well as problems. Table 2.2 shows a number of alternative fuels from each classification that have been successfully burned in cement kilns. In this study, only the solid fuels have been considered, and hence, liquid or gas fuels will not be discussed here onwards.

Solid fuels are the most commonly used, and particularly, pulverized coal is the predominant fuel used for cement production worldwide (Greco et al. 2004). Therefore, coal is quite obviously not an alternative fuel, and due to widespread literature on its use, it will not be addressed any further. The alternative fuels investigated in this study are: scrap tires, waste plastics, broiler litter, woodchips, and switchgrass.

2.3.4.1 Scrap Tires as Fuel

Scrap tires were recognized as a serious waste threat in the mid 1980s, when an estimated 2 to 3 billion scrap tires had accumulated in both legal and illegal dump sites in the United States (Schmidthals 2003). As reported in 1993, 234 million scrap tires were produced annually in the U.S., 82 percent of which were landfilled, stockpiled or illegally dumped. A mere nine percent were consumed by energy recovery projects (Barlaz et al. 1993). This trend is not unique to the U.S.; it is present around the world. Corti and Lombardi (2004) reported that during the year of 1999, Italy produced 330,000 tons of waste tires. These staggering quantities of scrap tires represent considerable environmental and public health hazards to which the cement kiln could be a tremendous solution (Greco et al. 2004). For instance, if all Italian cement plants were able to use tires as fuel at a replacement rate of fifteen percent, 646,000 tons of tires could be disposed of per year, almost 100 percent more than is actually produced in that country (Corti and Lombardi 2004).

Table 2.2: Classifications of Many Alternative Fuels (Greco et al. 2004)



Fuel Phase	Fuel type
Gaseous Waste	Landfill gas
Liquid waste	Cleansing Solvents Paint sludges Solvent contaminated waters "Slope" - residual washing liquid from oil and oil products storage tanks Used cutting and machining oils Waste Solvents from chemical industry
Solid or pasty waste	Muncipal waste Plastic shavings Residual sludge from pulp and paper production Rubber shavings Sawdust and woodchips Sewage treatment plant sludge Tannery waste Tars and bituminus Used catalyst Used tires

Fifteen percent replacement is not unreasonable, but it is approximately the upper limit for whole tire substitution through conventional means. Whole tire replacement rates are typically limited to 10 to 15 percent, because the excess energy supply may result in localized overheating and reducing conditions. This promotes the volatilization of sulphur, which leads to material melting and build-ups in the kiln and preheater (Schmidthals 2003). There is no known upper limit for shredded tires due to the fact that they are typically fed through the primary burner.

Some typical characteristics of tires used as fuel in the kiln system are: ash content of 12.5 to 18.6 percent (by weight), 1.3 to 2.2 percent sulphur, one to two percent zinc, and an energy value of 26,987 to 33,472 kJ/kg (11,602 to 14,390 BTUs/lb) (Jackson 1998). Wurst and Prey (2002) report average energy values of tires to be 25,104 to 29,288 kJ/kg (10,793 to 12,592 BTUs/lb), with zinc and sulphur as the primary elements of concern. Table 2.3 shows the energy value of tire-derived fuel (TDF) relative to two sources of coal. Sulphur, nitrogen, and chlorine are also shown in terms of content in the tires, as well as production. Finally, this report also gives zinc concentrations of 1.4 percent and 1.53 percent in chipped tires with and without the steel belts present, respectively.

Waste tires not only act as fuel, they supplement some of the raw materials needed for cement production (Kääntee et al. 2002). When the iron belts in tires are not removed before introduction to the kiln, a portion of the raw feed iron is replaced, thus decreasing the quantities of iron that must be otherwise acquired (Corti and Lombardi 2004).

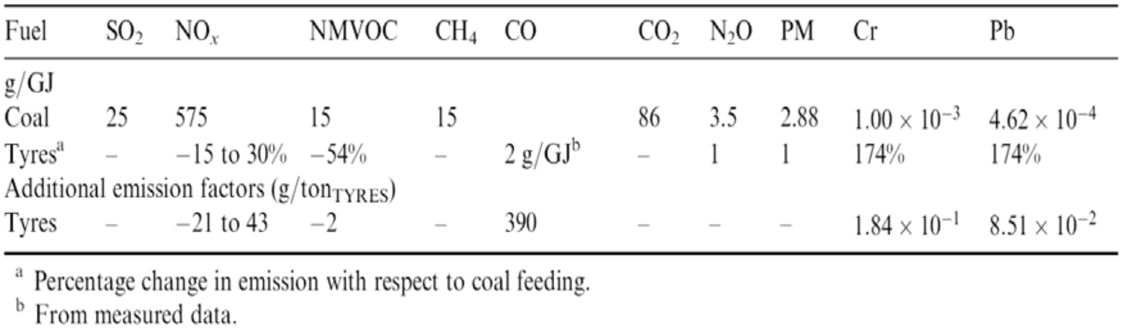
Table 2.3: Various Properties of Tire-Derived Fuel Relative to Two Coal Sources (Barlaz et al. 1993)

	Energy Source		
	TDF	Coal (Eastern U.S.)	Coal (Western U.S.)
Energy Value (kJ/kg)	34,000	27,000	27,000
Sulfur (%)	1.2	2.0	0.8
Sulfur Production (kg x $10^6/kJ$)	0.35	0.74	0.30
Nitrogen (%)	0.24	1.76	1.76
Nitrogen Production (kg x $10^6/kJ$)	0.07	0.65	0.65
Chlorine (%)	0.15	0.08	0.08
Chlorine Production (kg x $10^6/kJ$)	0.04	0.03	0.03

One cement plant in Redding, California, which replaces 25 percent of its energy requirements with shredded tires, has reported a decrease in iron ore costs of 50 percent (Kearny 1990). Obviously, tire substitution can make a significant contribution to decreased raw materials cost.

Corti and Lombardi (2004) reported on a study in which tires were substituted for coal at a replacement rate of 15 percent. Table 2.4 shows the change in emission characteristics between a kiln fired with coal alone, and the same kiln fired with coal and tires. The two abbreviated compounds presented are non-metallic volatile organic compounds (NMVOC) and particulate matter (PM). Table 2.5 shows the change in input characteristics required for the substitution of the tires. The latter shows a decrease in the amount of coal and iron required, while at the same time, an increase in the amount of electricity required to run the tire-specific feed system. Additionally, the diesel fuel required for transportation of the tires a distance of 35 *km* is shown. The final result of this study, by life-cycle assessment, was that the substitution of tires for coal in the cement production process was a better source of waste tire disposal than as mechanically or cryogenically pulverized filler, or conventional waste-to-energy processes.

Table 2.4: Emissions of Coal Relative to Coal and Tires (Corti and Lombardi 2004)

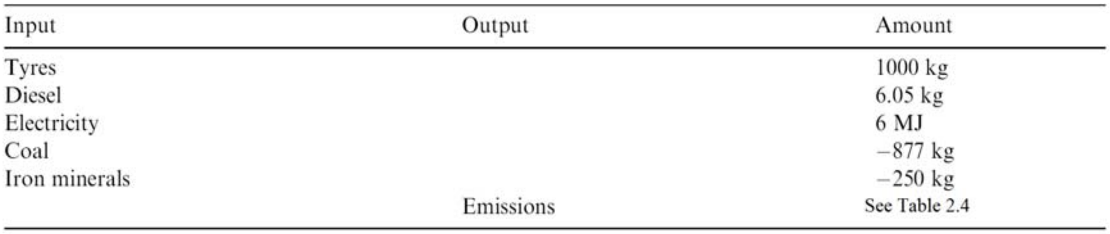


Fuel	SO_2	NO_x	NMVOC	CH_4	CO	CO_2	N_2O	PM	Cr	Pb
g/GJ										
Coal	25	575	15	15		86	3.5	2.88	1.00×10^{-3}	4.62×10^{-4}
Tyres[a]	–	−15 to 30%	−54%	–	2 g/GJ[b]	–	1	1	174%	174%
Additional emission factors (g/$\text{ton}_{\text{TYRES}}$)										
Tyres	–	−21 to 43	−2	–	390	–	–	–	1.84×10^{-1}	8.51×10^{-2}

[a] Percentage change in emission with respect to coal feeding.

[b] From measured data.

Table 2.5: Effect on Input and Output Quantities for Tires Used as Fuel (Corti and Lombardi 2004)



Input	Output	Amount
Tyres		1000 kg
Diesel		6.05 kg
Electricity		6 MJ
Coal		−877 kg
Iron minerals		−250 kg
	Emissions	See Table 2.4

The results of the studies shown above reveal the tremendous possibilities for tire-derived fuel usage in cement plants. Figure 2.4 shows the rate of increase in facilities using tires in the United States (PCA 2005). This trend is certainly a step in the right direction as far as scrap tire disposal and cement production is concerned.

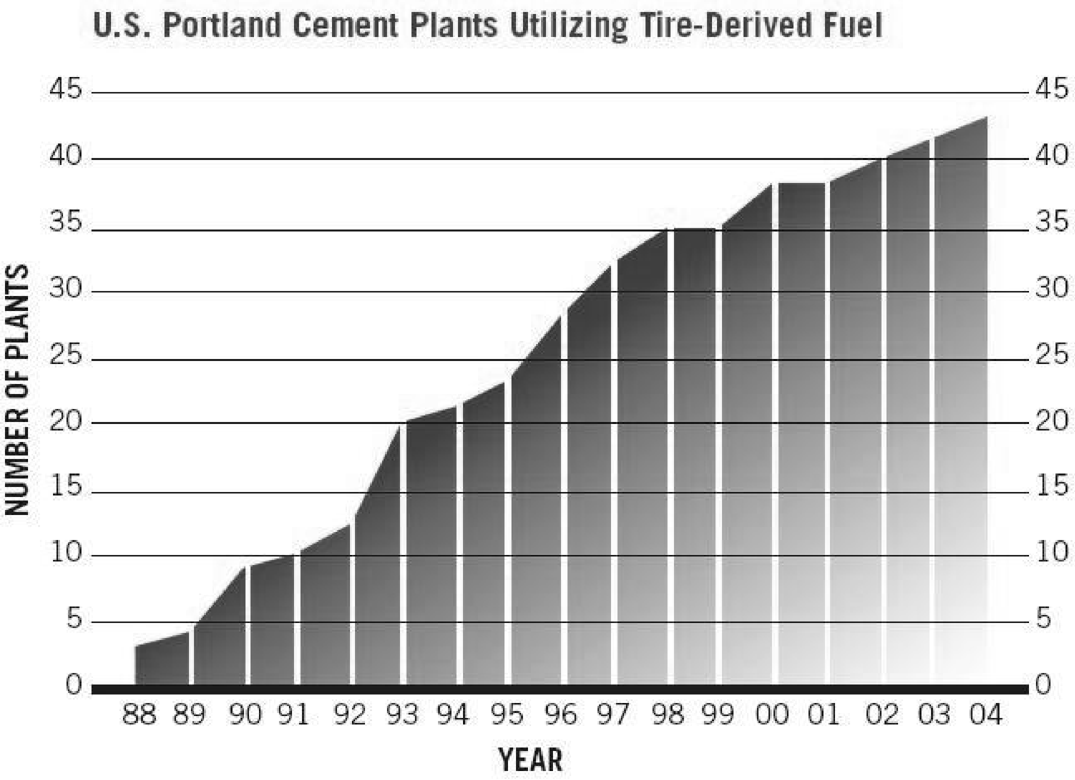


Figure 2.4: Trend of Tire Use as Fuel in Cement Plants in the U.S. (PCA 2005)

2.3.4.2 Waste plastics as Fuel

Currently, very little literature exists on the use of plastic wastes as an alternative fuel in the cement industry. However, it is certainly a viable option that is continuously gaining consideration for such applications.

Wurst and Prey (2002) have reported a limited amount of data on plastic waste fuels. Based on their research, plastics typically have an energy value on the order of 28,870 kJ/kg (12,412 BTUs/lb). Additionally, the elements that are deemed the most worthy of concern in cement production applications are cadmium, lead, and zinc. The final result which is reported is that the optimum particle size for implementation is 10 mm (0.4 inch). This is to avoid conglomeration of particles upon introduction to the kiln, which may result in noncombusted plastic fractions.

The results of a study done by Miller et al. (2002) are presented in Tables 2.6 and 2.7. Table 2.6 shows typical concentration ranges of various elements present in plastic used as fuel, relative to the same elements and their concentrations in coal. Table 2.7 shows relative percentages of the same elements that were retained in the ash after each of the fuels was combusted at a temperature of 800 to 900 °C in a suspension firing reactor. Therefore, the elements with the lowest retention quantities are the elements that were the most volatilized, and would have the greatest tendency to end up in stack emissions. Also, the elements with the highest retention quantities would be most likely to be incorporated into the clinker if these fuels were burned in a cement kiln. The results of this study, as they relate to plastics, are that Cd, Cu, Hg, Pb, and Tl have the greatest potential to end up in emissions, while Be, Co, Mo, and Ni are the most likely to be incorporated into the clinker. A discussion of these elements and their effects on cement properties is presented in Section 2.6.

Table 2.6: Concentrations of Elements in Coal and Plastic Fuels (Miller et al. 2002)

Fuel	less than 1 ppm	1 to 10 ppm	10-100 ppm	greater than 100 ppm
Colombian coal	Be, Cd, Hg, Sb, Tl	As, Co, Cu, Ni, Mo, Pb, Se	Ba, Cr, Mn, Sr, V, Zn	
Polish coal	Cd, Hg, Mo, Tl	As, Be, Co, Sb, Se	Cr, Cu, Ni, Pb, Sr, V, Zn	Ba, Mn
plastic waste	As, Be, Hg, Se, Tl	Cd, Co, Ni, Mo, Sb, V	Cr, Cu, Mn, Pb, Sr	Ba, Zn

Table 2.7: Concentrations in Ash From Coal and Plastic Fuels (Miller et al. 2002)

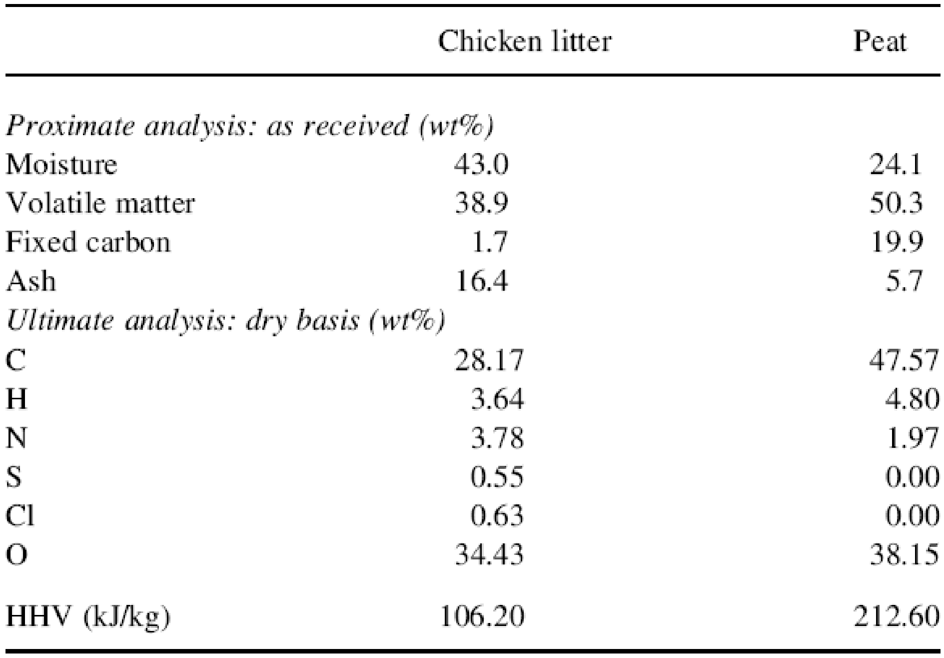
	percentage of trace elements retained in ash				
Fuel	0-20%	21-40%	41-60%	61-80%	81-100%
Colombian coal	Hg, Se	As, Cd		Cr, Mn, Mo, Sb, Sr, Tl	Ba, Be, Pb, Co, Cu, Ni, V, Zn
Polish coal	Hg, Se	Tl	As, Cd, Pb, Sb	Ba, Cr, Cu, Mo, Sr	Be, Co, Mn, Ni, V, Zn
plastic waste	Hg	Cd, Cu, Pb, Tl,	V	Cr, Ba, Mn, Sr	Be, Co, Mo, Ni

2.3.4.3 Broiler Litter as Fuel

Broiler litter is the material removed from the floors of poultry houses. The two main components are chicken litter and some sort of bedding material, such as sawdust. Other components that are generally present are feathers, dirt, etc. The UK produces 1.5 million tons of poultry litter per year, which is typically land-applied as fertilizer. However, some environmental problems have manifested themselves, such as phosphorus-rich water runoff (Dávalos et al. 2002). Broiler litter is oftentimes also referred to as poultry litter, and for the purpose of this document, these terms will be used interchangeably. Due to the lack of research conducted utilizing broiler litter in cement kilns, a basic discussion of its composition and combustion characteristics will be presented.

In a study reported by Abelha et al. (2003), poultry litter alone, and mixed with 50 percent (by weight) peat, was burned in a fluidized bed combustor, under various combustion conditions. The results of a proximate and an ultimate analysis on the litter and peat are shown in Table 2.8, along with an ash analysis of the litter in Table 2.9.

Table 2.8: Proximate and Ultimate Analysis of Chicken Litter and Peat (Abelha et at. 2003)

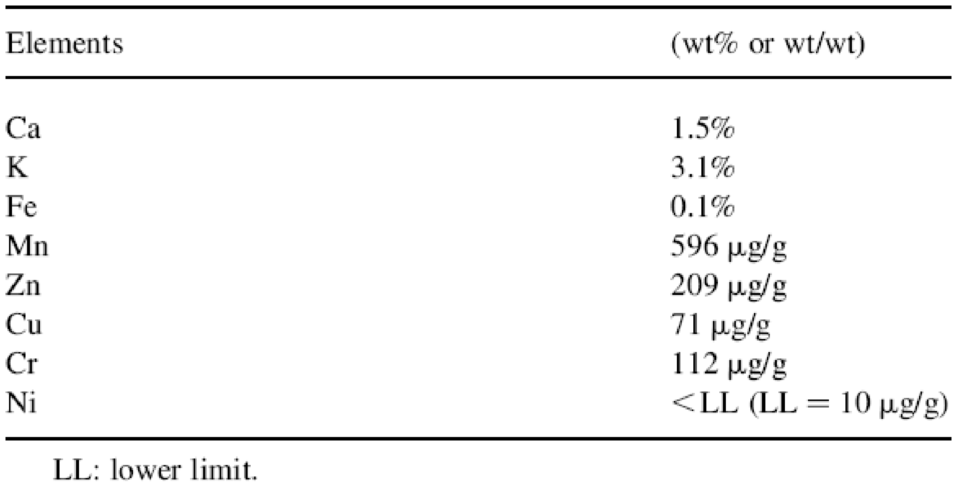


	Chicken litter	Peat
Proximate analysis: as received (wt%)		
Moisture	43.0	24.1
Volatile matter	38.9	50.3
Fixed carbon	1.7	19.9
Ash	16.4	5.7
Ultimate analysis: dry basis (wt%)		
C	28.17	47.57
H	3.64	4.80
N	3.78	1.97
S	0.55	0.00
Cl	0.63	0.00
O	34.43	38.15
HHV (kJ/kg)	106.20	212.60

HHV- Higher heating value

Table 2.10 shows the ranges in CO and Volatile Organic Content (VOC) emissions concentration. In the case of CO with no secondary air, the concentrations are excessively high, which indicates incomplete mixing of air with the fuel, and possibly incomplete combustion of the fuel. In all other cases, CO levels were at or below the regulated levels. VOC concentrations followed the same trends as CO. Although these tests were not conducted in a cement kiln, this study provides results that may be typical of broiler litter combustion.

Table 2.9: Ash Analysis of Chicken Litter (Abelha et al 2003)



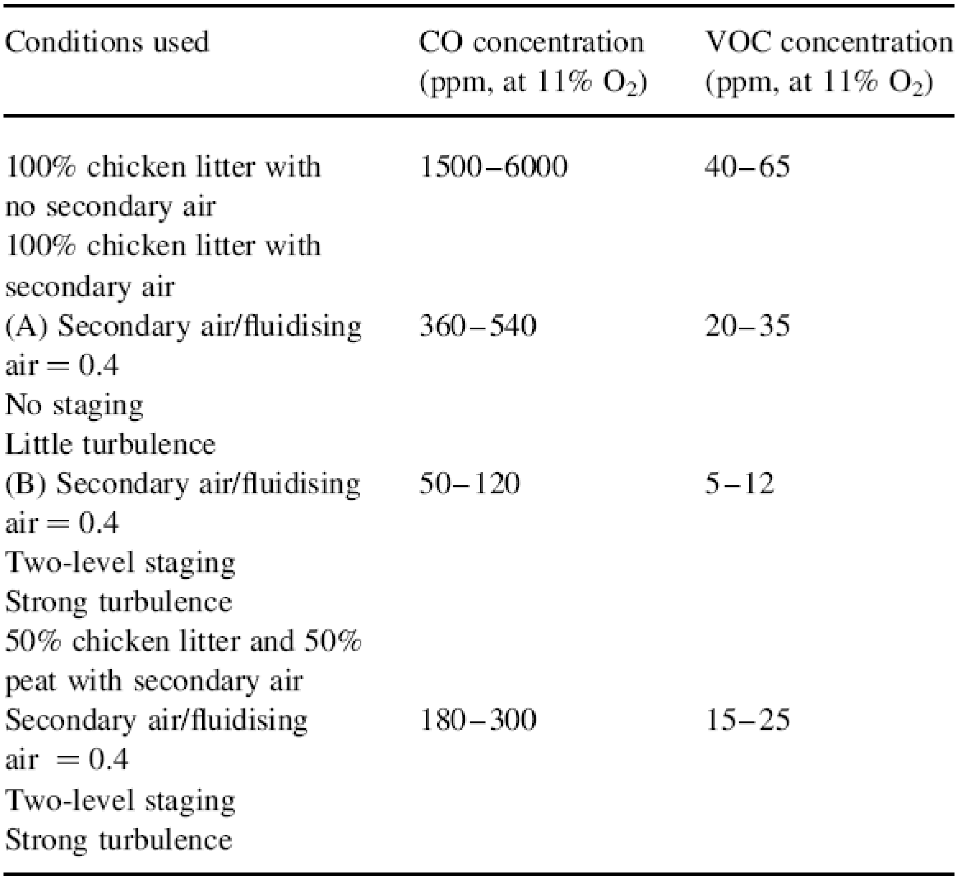
Elements	(wt% or wt/wt)
Ca	1.5%
K	3.1%
Fe	0.1%
Mn	596 μg/g
Zn	209 μg/g
Cu	71 μg/g
Cr	112 μg/g
Ni	<LL (LL = 10 μg/g)

LL: lower limit.

The primary problem Abelha et al. (2003) encountered was the feeding of the litter. The screw-type feeder that was used could not handle the litter when it had a moisture content greater than 25 percent. This could certainly cause problems in cement plant applications as well. In fact, the moisture content of litter is also a problem for other reasons. The most prominent of these is combustibility.

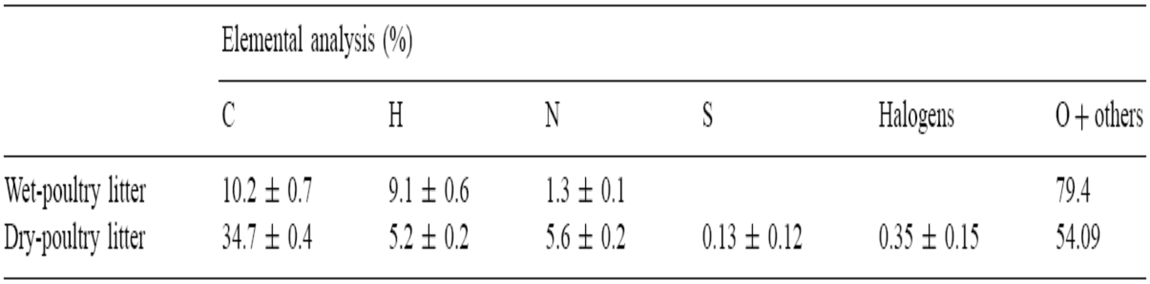
Dávalos et al. (2002) reported on a study in which combustion characteristics of poultry litter were evaluated for various moisture contents. Table 2.11 shows the elemental analysis of a wet sample (approximately 68 percent water content) and a dry sample. Figure 2.5 illustrates the energy content versus water content. A linear approximation is fitted to the experimental data. Based on this approximation, a completely dry sample will have a calorific value of 14,447 kJ/kg (6,211 BTUs/lb), and a sample has a calorific value of 4,000 kJ/kg (1,720 BTUs/lb) when its water content reaches 78 percent. These data clearly illustrate the detrimental effect that increasing moisture content has on the heating value of broiler litter.

Table 2.10: CO and VOC Concentrations for Various Chicken Litter/Peat Mixtures and Burning Conditions (Abelha et al. 2003)



Conditions used	CO concentration (ppm, at 11% O_2)	VOC concentration (ppm, at 11% O_2)
100% chicken litter with no secondary air	1500–6000	40–65
100% chicken litter with secondary air		
(A) Secondary air/fluidising air = 0.4 No staging Little turbulence	360–540	20–35
(B) Secondary air/fluidising air = 0.4 Two-level staging Strong turbulence	50–120	5–12
50% chicken litter and 50% peat with secondary air		
Secondary air/fluidising air = 0.4 Two-level staging Strong turbulence	180–300	15–25

Table 2.11: Elemental Analysis of Poultry Litter at Wet and Dry Moisture Conditions (Dávalos et al. 2002)



	Elemental analysis (%)					
	C	H	N	S	Halogens	O + others
Wet-poultry litter	10.2 ± 0.7	9.1 ± 0.6	1.3 ± 0.1			79.4
Dry-poultry litter	34.7 ± 0.4	5.2 ± 0.2	5.6 ± 0.2	0.13 ± 0.12	0.35 ± 0.15	54.09

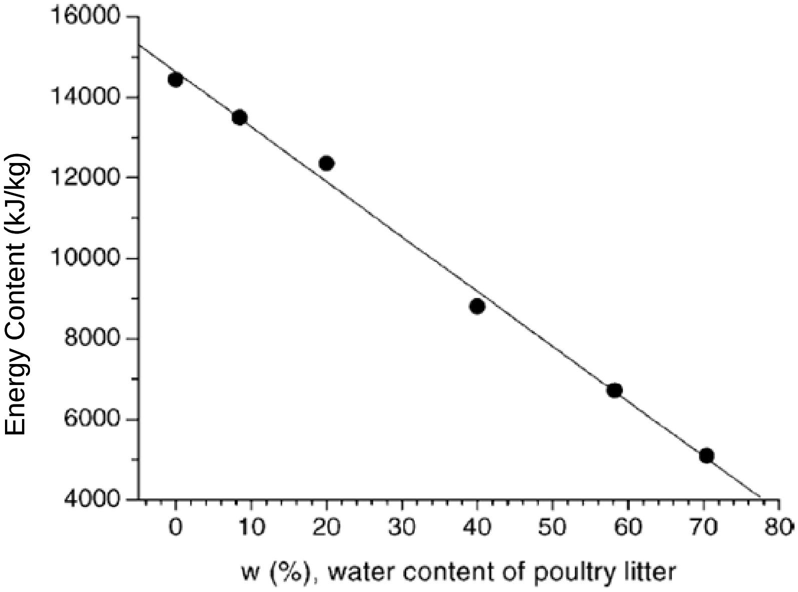
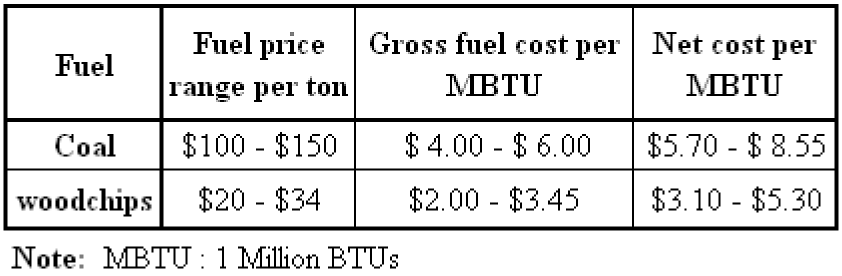


Figure 2.5: Energy Content Relative to Water Content of Poultry Litter (Dávalos et al. 2002)

2.3.4.4 Woodchips as fuel

Woodchips have been burnt to make heat for decades, but the use of this energy source has significantly increased over the past 20 years. At the heart of this new application of wood energy is the attraction of using a renewable, locally-produced energy source that is generally the least expensive fuel available (Maker 2004). Woodchips are solid fuels made from woody biomass in the process of woodchipping. They can be made from waste wood, brush, saplings, limbs, tree slash, logging operations, and from forestry and roadside maintenance operations (Redmond 2006). In Table 2.12, woodchip fuel costs are compared to coal, as reported by Maker (2004).

Table 2.12: Comparative fuel cost for woodchips (Maker 2004)



Fuel	Fuel price range per ton	Gross fuel cost per MBTU	Net cost per MBTU
Coal	$100 - $150	$ 4.00 - $ 6.00	$5.70 - $ 8.55
woodchips	$20 - $34	$2.00 - $3.45	$3.10 - $5.30

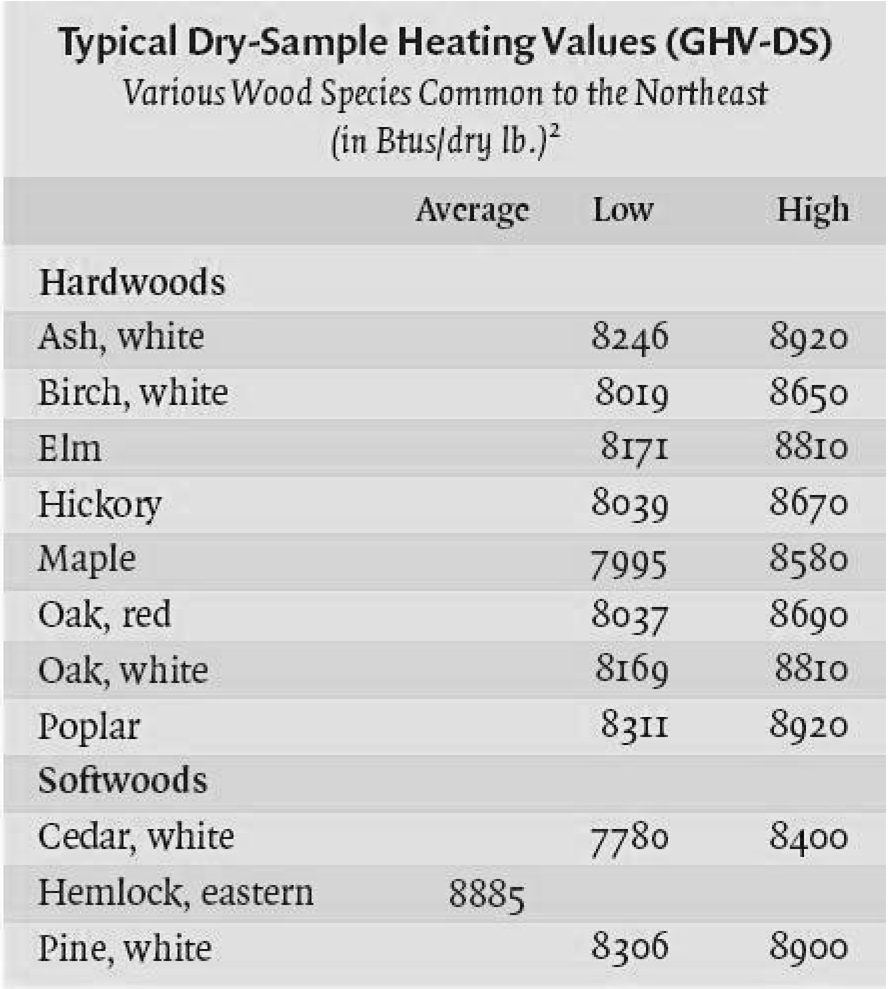
Note: MBTU : 1 Million BTUs

Woodchip prices are relatively stable. They can be transported and unloaded by dump trucks. Because they are available locally, long distance haulage, packaging, and energy consumption can be reduced. Fuel growing methods such as brush and coppice farming can produce ideal wood for chipping on a sustainable basis and hence may reduce dependence on fossil fuels (Redmond 2006).

Woodchips have primarily been used in commercial heating systems, manufacturing plants and power plants (Maker 2004). Since there is not much literature available for use of woodchips as fuel in cement production, only the characteristics and chemical composition of woodchips will be discussed in this section.

The heat content of woodchips mainly depends on their moisture content. As reported by Maker (2004), the average energy content of the bone-dry woodchips sample is typically about 19,771 KJ/Kg (8,500 BTUs/lb). But the actual energy content of any sample will depend on the mixture of species included in the sample and can only be determined in the laboratory (Maker 2004). Table 2.13 shows some typical dry-sample heating values for certain wood species.

Table 2.13: Dry sample heating values for woodchips (Maker 2004)



Typical Dry-Sample Heating Values (GHV-DS)

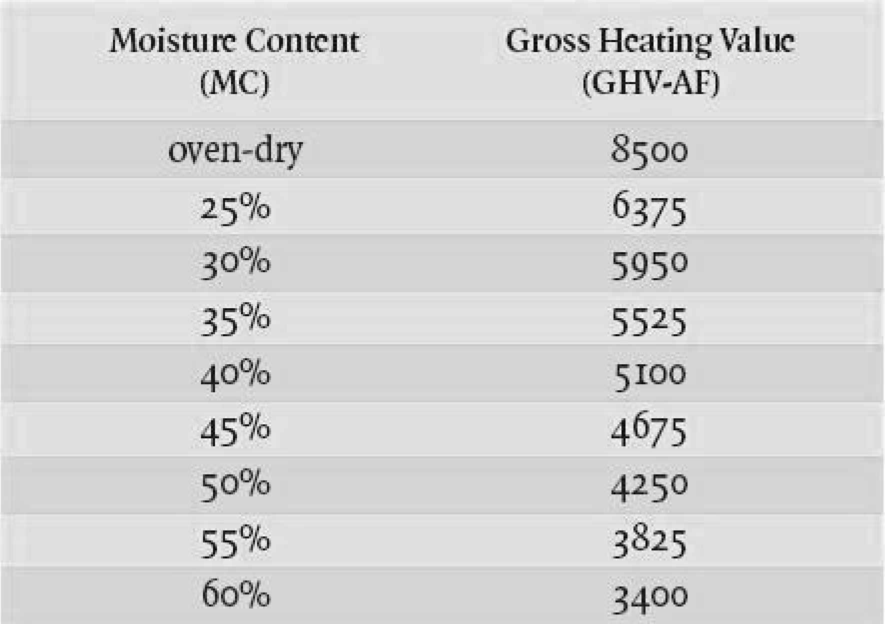
Various Wood Species Common to the Northeast

(in Btus/dry lb.)[2]

	Average	Low	High
Hardwoods			
Ash, white		8246	8920
Birch, white		8019	8650
Elm		8171	8810
Hickory		8039	8670
Maple		7995	8580
Oak, red		8037	8690
Oak, white		8169	8810
Poplar		8311	8920
Softwoods			
Cedar, white		7780	8400
Hemlock, eastern	8885		
Pine, white		8306	8900

However, woodchips fuel, as it is delivered, is never completely dry. The as-delivered or as-fired woodchips fuel can be characterized by its moisture content and the resulting heat content of the wood. Table 2.14 lists the average as-fired heating values of woodchips corresponding to the moisture content. The heating value of 11,863 KJ/Kg (5,100 BTUs/lb) corresponding to moisture content of 40 % is a good all-round figure to use for typical woodchips fuel (Maker 2004).

Table 2.14: As-fired heating values for woodchips corresponding to the moisture content (Maker 2004)

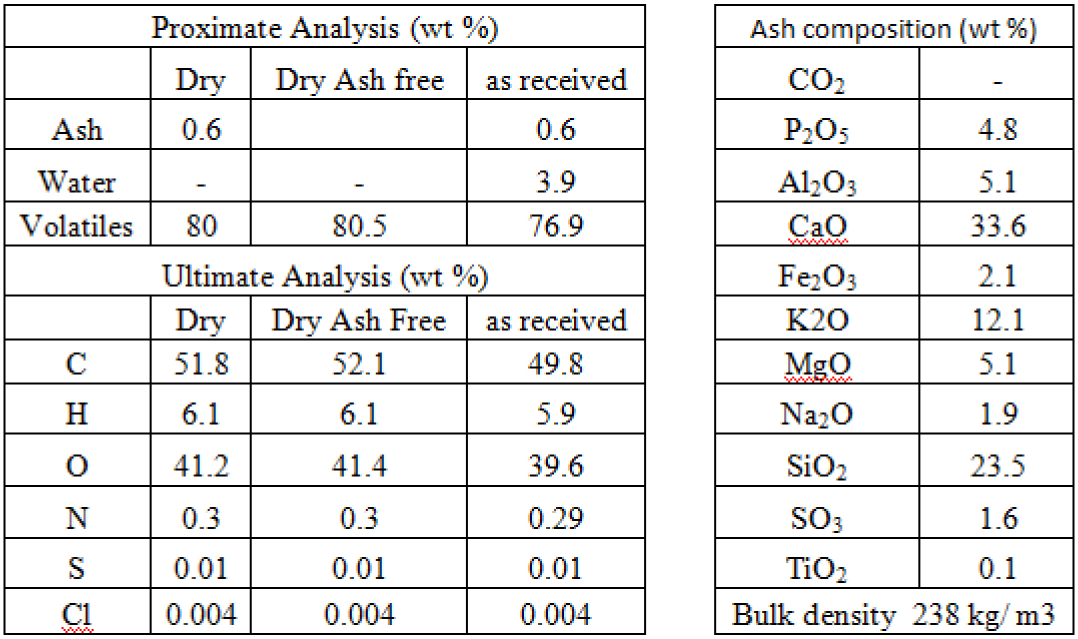


Moisture Content (MC)	Gross Heating Value (GHV-AF)
oven-dry	8500
25%	6375
30%	5950
35%	5525
40%	5100
45%	4675
50%	4250
55%	3825
60%	3400

Teislev (2002) reported that, typically, woodchips fuel contains 42% of moisture and has the following (dry) chemical analysis: Carbon 50.00%, Hydrogen 6.17%, Oxygen 42.64%, Nitrogen 0.17% and ash 1.00%. The high amounts of volatiles and low ash content of woodchips is suitable particularly for the cement kiln as the lower the ash incorporated into the clinker, the less effect it has on the clinker. Table 2.15 shows the typical chemical analysis of woodchips fuel reported by Wilen (1996)

Woodchips have practically no sulphur and so, unlike fossil fuels, produce no SO_x gases. Woodchips combustion does create NO_x, CO and VOC emissions, but at levels comparable to fossil fuels (Maker 2004).

Table 2.15: Chemical analysis of woodchips (Wilen et al. 1996)



Proximate Analysis (wt %)			
	Dry	Dry Ash free	as received
Ash	0.6		0.6
Water	-	-	3.9
Volatiles	80	80.5	76.9
Ultimate Analysis (wt %)			
	Dry	Dry Ash Free	as received
C	51.8	52.1	49.8
H	6.1	6.1	5.9
O	41.2	41.4	39.6
N	0.3	0.3	0.29
S	0.01	0.01	0.01
Cl	0.004	0.004	0.004

Ash composition (wt %)	
CO_2	-
P_2O_5	4.8
Al_2O_3	5.1
CaO	33.6
Fe_2O_3	2.1
K2O	12.1
MgO	5.1
Na_2O	1.9
SiO_2	23.5
SO_3	1.6
TiO_2	0.1
Bulk density 238 kg/ m3	

2.3.4.5 Switchgrass as fuel

Switchgrass is a warm-season grass and is one of the dominant species of the central North American tall prairie grass. In the United States, switchgrass is considered the most valuable native grass for biomass production on a wide range of sites. It can be found in remnant prairies, along roadsides, pastures and as an ornamental plant in gardens. It is noted for its heavy growth in late spring and early summer (Sami et al. 2001).

Switchgrass requires little fertilization and herbicide, and can be harvested twice a year with existing farm equipment. The grass is tough and has high productivity. Grown by farmers on marginal land, switchgrass could offer a cash crop and a boost to the farm economy (Boylan et al. 2000). It is also valuable for soil stabilization, erosion control, and for use as a windbreak (Sami et al. 2001).

Though switchgrass has not been used in cement kilns before, it has been co-fired successfully with coal in power generating plants. However, in power plants, some elements in switchgrass such as potassium, sodium, chlorine, silica, etc. cause problems when burned due to erosion, slagging and fouling, hence decreasing efficiency while increasing maintenance costs (Sami et al. 2001). In a cement kiln, such problems can be avoided since the ash is incorporated into the clinker. So, if it does not change the properties of the clinker drastically, use of a cement kiln can be a viable option for co-firing of switchgrass with coal.

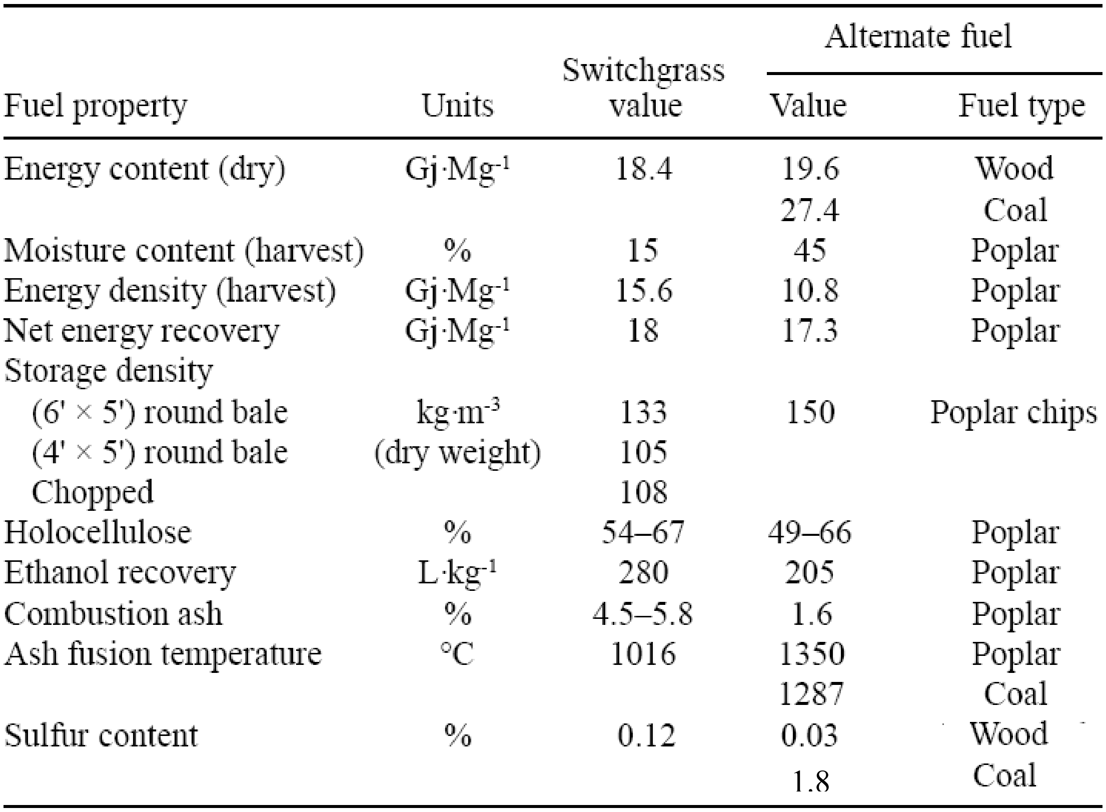
One of the major variables affecting economics of co-firing coal and switchgrass is the degree of preparation (shredding) necessary for the switchgrass material (usually transported as bales) before it is fed into the kiln. Some size reduction of the 8 to 10 foot stalks of grass will be required, and ways to minimize either the amount or the difficulty of pre-processing the grass are being investigated (Boylan et al. 2000).

McLaughlin et al. (1999) reported that the energy content of switchgrass is about 18,400 KJ/Kg (7,910 BTUs/lb), which is comparable to that of other bio-fuels such as wood. The ignition process of switchgrass and coal is similar to that for coal only except that there is more volatile matter available for reaction in such fuel. Therefore, it is more likely that homogeneous ignition will occur for such fuels (Sami et al. 2001).

Table 2.16 shows a list of physical and chemical properties of switchgrass compared to other common bio-fuels. As is typical with many other biomass fuels, handling issues appear to be the toughest problems. The bulk density of switchgrass is very low, and is considerably less dense than coal. As a result, a mixture of 10%

switchgrass with 90% coal (by mass) is a roughly 50% mixture of the two constituents by volume (Boylan et al. 2000).

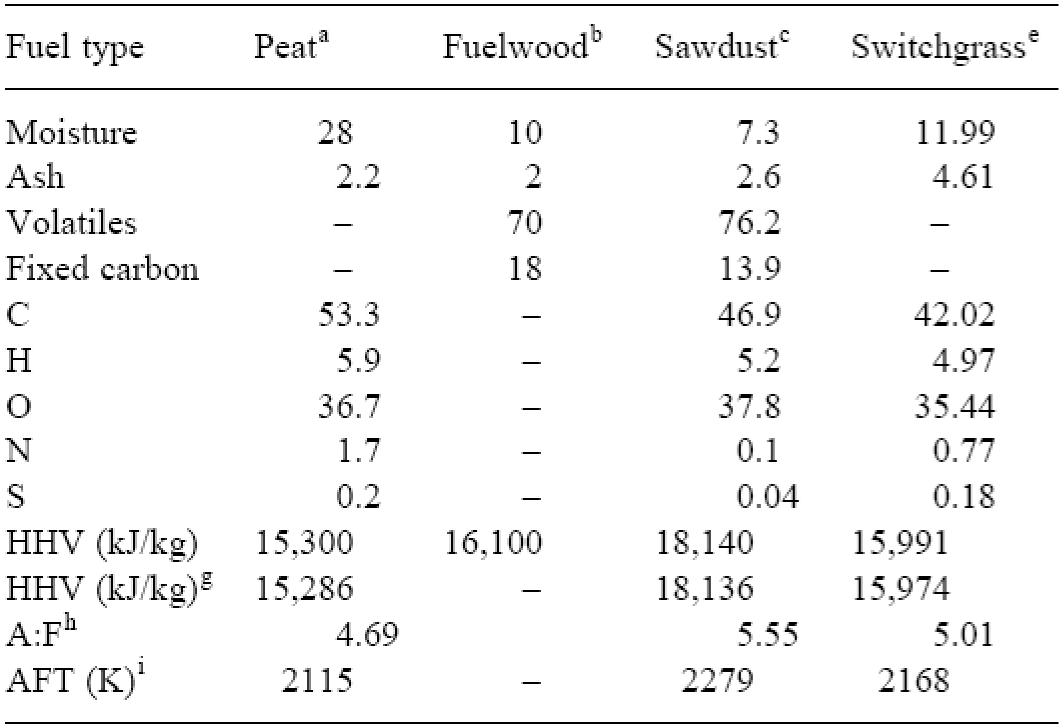
Table 2.16: Physical and Chemical properties of Switchgrass compared to other bio-fuels (McLaughlin et al. 1999)



Fuel property	Units	Switchgrass value	Alternate fuel Value	Fuel type
Energy content (dry)	Gj·Mg^{-1}	18.4	19.6	Wood
			27.4	Coal
Moisture content (harvest)	%	15	45	Poplar
Energy density (harvest)	Gj·Mg^{-1}	15.6	10.8	Poplar
Net energy recovery	Gj·Mg^{-1}	18	17.3	Poplar
Storage density				
(6' × 5') round bale	kg·m^{-3}	133	150	Poplar chips
(4' × 5') round bale	(dry weight)	105		
Chopped		108		
Holocellulose	%	54–67	49–66	Poplar
Ethanol recovery	L·kg^{-1}	280	205	Poplar
Combustion ash	%	4.5–5.8	1.6	Poplar
Ash fusion temperature	°C	1016	1350	Poplar
			1287	Coal
Sulfur content	%	0.12	0.03	Wood
			1.8	Coal

Table 2.17 shows the proximate and ultimate analyses of switchgrass fuel in comparison to other fuels as reported by Sami et al (2001). The ash content of switchgrass is notably higher than coal while moisture content is lower.

Table 2.17: Chemical analysis of Switchgrass compared to other fuels (Sami et al. 2001)



Fuel type	Peat[a]	Fuelwood[b]	Sawdust[c]	Switchgrass[e]
Moisture	28	10	7.3	11.99
Ash	2.2	2	2.6	4.61
Volatiles	–	70	76.2	–
Fixed carbon	–	18	13.9	–
C	53.3	–	46.9	42.02
H	5.9	–	5.2	4.97
O	36.7	–	37.8	35.44
N	1.7	–	0.1	0.77
S	0.2	–	0.04	0.18
HHV (kJ/kg)	15,300	16,100	18,140	15,991
HHV (kJ/kg)[g]	15,286	–	18,136	15,974
A:F[h]	4.69		5.55	5.01
AFT (K)[i]	2115	–	2279	2168

HHV- Higher heating value A: F – Air to Fuel ratio (dry ash free basis)

AFT – Adiabatic flame temperature (ultimate analysis)

Boylan et al. (2000) conducted combustion tests with 10% switchgrass – 90 % coal mixtures and compared the results to bituminous coal combustion tests. It was observed that there was no degradation of unburned carbon. There was a reduction in sulfur emissions which could be attributed to the low sulfur content of switchgrass. Also, there was a decrease in the NO_x emissions as well.

2.4 Emissions

A portland cement manufacturing facility that produces one million tons of cement annually will also produce roughly 1.5 billion cubic meters of gases in the process (Jackson 1998). The primary components of these gaseous emissions are CO_2,

NO_x, and SO_x. Lesser pollutants emitted into the atmosphere are carbon monoxide, dioxins, furans, particulate matter, and metals (Schuhmacher et al. 2003). Due to the highly variable nature of portland cement manufacturing, the specific composition of plant emissions will be unique to each facility. Although many factors affect the specific makeup of a plant's emissions, there are three fundamental aspects of the process, which the manufacturer can control, that ultimately determine their emissions state. These three parameters are the chemical composition of the raw materials, the chemical and physical properties of the fuel, and the kiln conditions (Marengo et al. 2006). Based on the focus of this project, a discussion of each of the primary emission components and their relationship with alternative fuels will be discussed in the following sections. Brief mention of the lesser emission compounds will also be made.

2.4.1 Carbon Emissions

Carbon dioxide (CO_2) and carbon monoxide (CO) are major emission components with which portland cement production facilities must be concerned. CO_2 is the primary agent responsible for the "greenhouse effect," and is therefore closely monitored by environmental agencies around the world. Portland cement production facilities are a significant contributor to atmospheric carbon dioxide worldwide. In 2000, global CO_2 emissions from portland cement production were estimated at 829 million metric tons, which accounts for 3.4 percent of all CO_2 emissions for that year (Hanle et al. 2004). On a more regional scale, in 1999 the portland cement industry in the United States was responsible for 22.3 million metric tons of carbon dioxide emissions, which accounted for 4 percent of the total CO_2 emissions in the United States in that year (Bhatty 2004).

Carbon dioxide emissions come from combustion of fossil fuels and the calcination of limestone, each of which contribute approximately half of the CO_2 during production (Worrell et al. 2001). Calcining is the process of heating limestone and converting $CaCO_3$ into CO_2 and CaO. This process is typically carried out in a preheater, which may also be known as a precalciner. The CO_2 is released into the atmosphere, and the CaO enters the kiln where it becomes a primary component in the formation of the clinker. Carbon monoxide is primarily produced when fuels are not completely consumed due to insufficient mixture of oxygen and fuel at the location of combustion and/or a rapid decrease in local temperature to levels below those required for ignition (Bhatty 2004).

The amount of CO_2 produced during combustion is a partially a function of the type of fuel being consumed (Worrell et al. 2001). The same can be said of carbon monoxide. In an experiment conducted at the Malogoszcz cement plant in Poland, up to 40 percent of the heat required for clinkerization was provided by two different alternative fuels called PASr and PASi. PASr fuel was a composite mixture of grain-sized particles made from paper, cardboard, foil, cloth, textile, plastic containers, tapes, cables and cleaning agent. The PASi fuel was composed of sawdust or tobacco dust mixed with wastes derived from paint, varnish, heavy post-distillation fractions, diatomaceous earth contaminated with petroleum-based waste, etc. The emissions data for the three major compounds are shown in Figure 2.6.

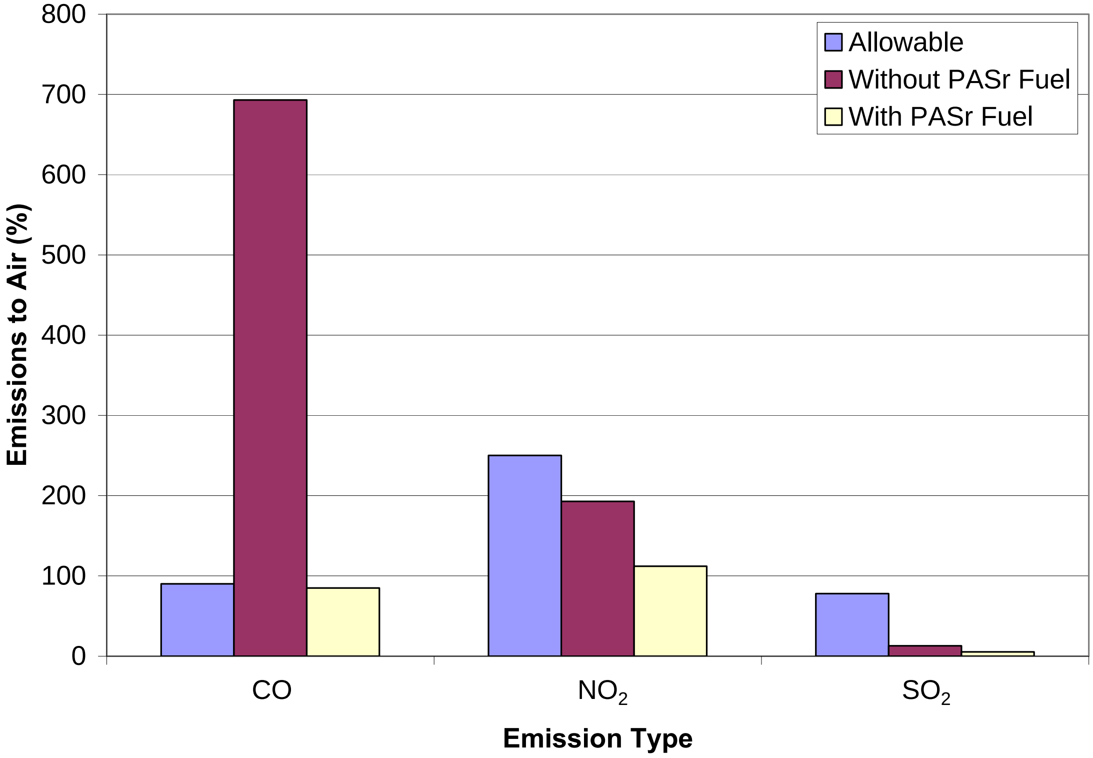


Figure 2.6: Emissions Data from a Plant Burning Alternative Fuels (modified from Mokrzycki et al 2003)

Prisciandaro et al. (2003) have also reported emissions results of tests run when comparing traditional fuels with alternative fuels. Two Italian cement plants were used for the study. Both plants used petcoke as their traditional fuel. Plant 1 replaced up to 20 percent of its energy with that from tires. Plant 2 replaced the same percentage of its energy with that from recycled oils. Figure 2.7 shows the change in emissions concentrations due to the changes in fuel types. CO levels remained approximately unchanged in Plant 1 and Plant 2.

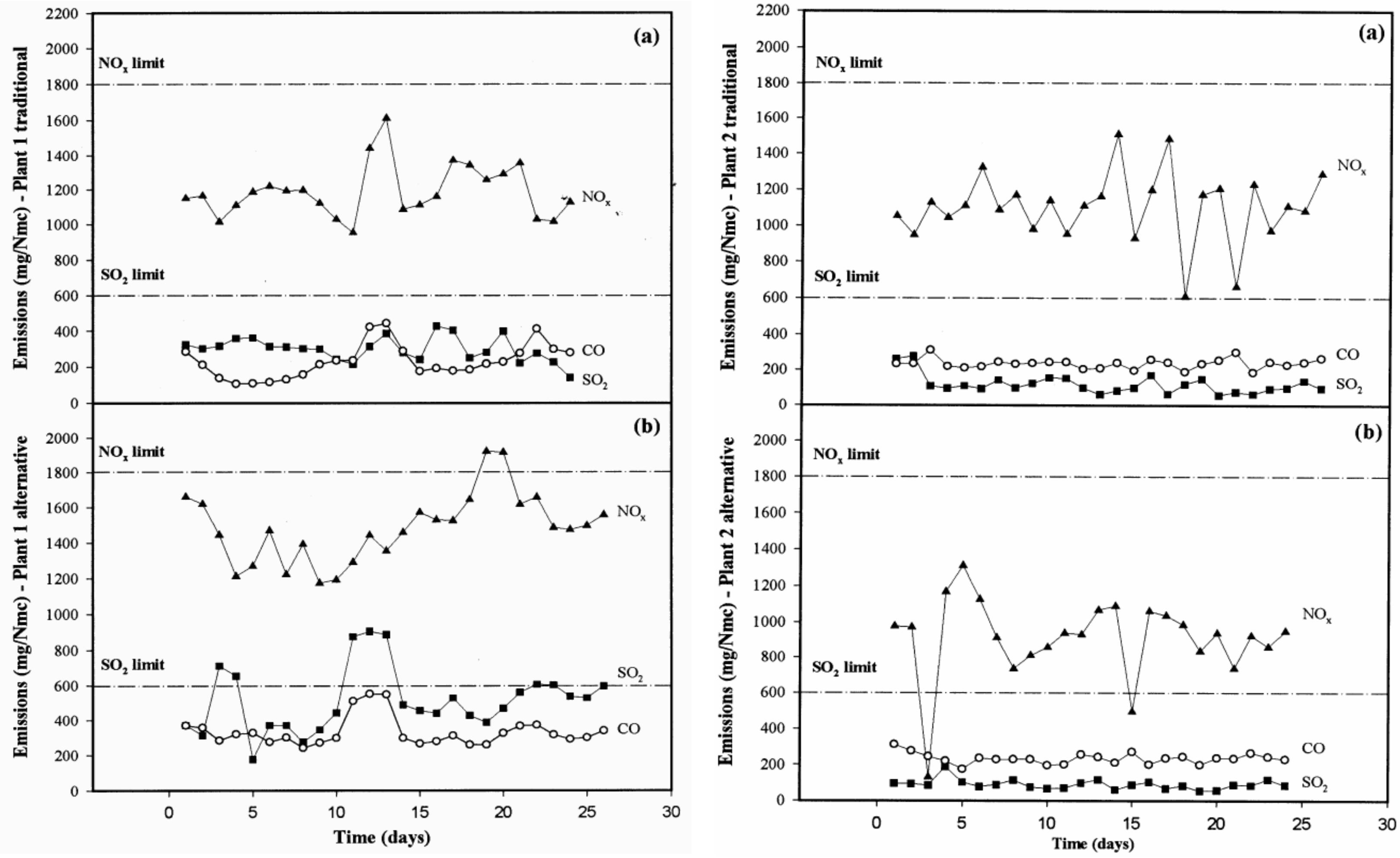


Figure 2.7: Change in Emission Levels due to Changes in Fuel Types (Prisciandaro et al. 2003)

2.4.2 Nitrogen Emissions

Nitrogen Oxides (NO_x) are a family of nitrogen-based compounds that are found in the stack emissions of a portland cement production facility. The two most common forms are NO and NO_2. Typically, more than 95 percent of exhaust gases produced by a cement kiln are NO, with the remainder of the gases mostly comprising NO_2 (Gardeik et al. 1984; Greer 1989). Just like carbon-based emissions, NO_x concentrations are also susceptible to the temperamental nature of cement kilns. The independent variables which have the greatest influence on NO_x levels are fuel type, feed rate, amount of air flow, and the temperatures in the burning zone of the kiln (Walters et al. 1999).

There are three mechanisms by which NO_x is formed in the kiln. In order of decreasing contribution to overall concentration, they are thermal NO_x, fuel NO_x, and feed NO_x (Young 2002). Thermal NO_x (primarily NO) is the most abundant source of NO_x in the kiln system. It is formed when atmospheric nitrogen present in the combustion air is oxidized in the presence of high temperatures. The threshold at which thermal NO_x begins to form is commonly thought to be around 1400°C, above which NO levels increase dramatically. The majority of the thermal NO_x are formed in the burning zone where flame temperatures easily reach 1600°C (Bhatty 2004; Greer 1989; Marengo et al. 2006; Young 2002).

Fuel NO_x is formed when chemically bonded nitrogen in the fuel is released and oxidized due to combustion. Therefore, as long as the temperatures are above the ignition temperature of the fuel, fuel NO_x is being formed (Gardeik et al. 1984). The quantity of nitrogen present in fuel is significantly less than that present in the combustion air, which means that the contribution of fuel NO_x in the burning zone is relatively small. However, in a system where a preheater is utilized, the temperature at the secondary combustion zone is much less than the threshold for thermal NO_x formation. This allows fuel NO_x to be the primary contributor at this location (Young 2002). Greer (1986) stated that if all the other factors controlling NO_x formation are held constant, the total amount of NO_x can be altered by controlling the content of nitrogen in the fuel (Greer 1986).

The final source of NO_x, is the raw material feeds. Feed NO_x is similar to fuel NO_x in that it is formed when the nitrogen that is chemically bonded within the feeds is released and oxidized. This process takes place at temperatures in the range of 300 °C - 800 °C (Marengo et al. 2006). An upper limit of 50 percent has been reported for the amount of feed nitrogen that may be converted to NO_x. Ratios this high will only occur when the raw materials are heated slowly (Gartner 1983). Considering this theoretical maximum along with the natural limit of the amount of nitrogen present in feeds, it is evident that the contribution of feed NO_x to the overall NO_x production in the kiln is minimal (Young 2002).

There are two major implications of large volumes of NO_x emitted into the atmosphere. The first is that NO_2 combines with moisture in the atmosphere to form either nitrous acid or nitric acid. These two compounds are the primary components of acid rain (Bhatty 2004). Although the majority of the NO_x produced in the kiln system is NO, it is largely converted into NO_2 in the atmosphere (Greer 1989). The second product that forms when NO_x is released into the atmosphere is smog. Smog is formed when NO_x combines with hydrocarbons in the presence of solar radiation (Bhatty 2004; Greer

1989). Therefore, it is important that all NO_x levels are monitored and limited throughout the portland cement industry.

Because the majority of the NO_x produced in cement kilns comes from thermal NO_x, alternative fuels cannot change its concentration substantially in either direction. However, the nitrogen concentration of fuels does have some effect on the amount of NO_x produced. The results of the study conducted by Mokrzycki et al. (2003) show that NO_2 emissions were decreased by 81 percent between traditional fuels and the PASr fuel, as shown in Figure 2.6. The study conducted by Prisciandaro et al. (2003) shows an increase in NO_x emissions in Plant 1, and a decrease in NO_x emission at Plant 2, as shown in Figure 2.7.

2.4.3 Sulphur Emissions

Sulphur Oxides (SO_x) are a family of sulphur-based compounds that are commonly released as emissions from industrial applications. In the portland cement industry, SO_2 and SO_3 are the most prevalent members of this family. Although both of these compounds are typically present in a cement kiln, it has been reported that as much as 99 percent of the SO_x emissions are in the form of SO_2 (Marengo et al. 2006). The SO_2 that is released from the kiln system is produced by the oxidation of sulphur compounds that enter the kiln in either the fuel or the raw materials. The quantity of SO_2 released is highly variable based on factors such as the form in which it enters the kiln, the presence of certain other elements, such as alkalies and chlorine, in the kiln, and the kiln operation and design (Miller and Hawkins 2000). Although significant quantities of sulphur are released via emissions, the majority of sulphur that enters the kiln is either incorporated into the clinker, usually as alkali-sulfates, or deposited in the kiln/preheater system in the form of deposits or kiln rings. Greer (1989) reported 50 to 90 percent of the sulphur that enters the kiln either remains in the kiln or is incorporated into the clinker.

When SO_x are emitted into the atmosphere, they typically take one of two forms. SO_2 readily combines with the moisture in the atmosphere to form H_2SO_4, also known as sulphuric acid, which is a major contributor to acid rain (Bhatty 2004). SO_x may also remain solid and become what is known as dry deposition, which is a solid reaction product (Greer 1989). The consequences of either of these phenomenons are certainly detrimental. The former speaks for itself in terms of potentially harmful effects. The latter exists as particles small enough to be inhaled by both animals and humans, where it is harmful to the respiratory system and potentially fatal (Schuhmacher et al. 2003).

Just as with NO_x and carbon-based emissions, the type of fuels used have a direct effect on the amount of SO_x in the emissions. This can be illustrated by examining the study by Mokrzycki et al. (2003), which was shown previously. It was reported that there was a decrease in SO_2 emissions by 7 percent between traditional fuel and PASr fuel as shown Figure 2.6.

2.4.4 Other Problematic Emissions

In addition to the three major types of emissions that have been previously discussed, many other compounds may be created in the kiln system and emitted into the atmosphere. Just as with NO_x, SO_x, and carbon-based emissions, the concentrations of each are affected, to some extent, by the type and quantities of fuels being used. Due to the lack of literature directly relating alternative fuels and the emission of these compounds, a brief discussion of their formation and potential dangers will be presented, and the ability of alternative fuels to affect their presence will be briefly discussed.

2.4.5 Dioxins and Furans

"Polychlorinated dibenzodioxins ($PCDD$) and polychlorinated dibenzofurans ($PCDF$) are halogenated aromatic hydrocarbons that are byproducts of combustion below 400°C and chemical processes in the presence of chlorine" (Kirk 2000). Although the formation of these compounds is not completely understood, many of the precursors can be readily identified. Many chlorine compounds, including polyvinyl chloride (PVC) and sodium chloride, are the primary harbingers of dioxins and furans (Bhatty 2004). The major concern with dioxins and furans is that they are extremely harmful to animals and humans when they are ingested. Human ingestion typically arises from the consumption of animals, such as fish, that have been contaminated. Some of the effects in humans are eye irritation, dermatitis, gastrointestinal disturbances, liver and kidney damage, and possibly cancer (Kirk 2000). Therefore, increases in dioxin and furan emissions due to implementation of alternative fuels would be a serious setback for the viability of those fuels.

2.4.6 Metals

Metals in the emissions from cement plants are also a concern. Many metals present in the kiln system are incorporated into the clinker and are not emitted in measurable quantities. However, some metals are extremely volatile in the kiln, and are present in the stack gases. Some of the metals of greatest concern are mercury, lead, cadmium, and chromium. Detailed discussion of each metal is presented in Section 2.6. The concentration of metals in the emissions is directly related to the concentration of that metal in both the fuel and raw materials. Therefore, if the concentration of a metal typically found in emissions is changed by utilizing an alternative fuel, the concentration of that metal in the stack gases may change by a similar amount. One example of this phenomenon is reported by Bhatty (2004), who reported that ZnO mass flow rates in stack emissions decreased from 2.97 mg/sec to 1.53 mg/sec in U.S. cement plants using traditional fuels and waste fuels, respectively.

2.4.7 Particulates

One final emissions component that must be considered is particulate matter. These solids are fine enough to remain suspended in the gases flowing through the kiln and into the stack. Although particulates are common in stack gases, they typically do not actually exit the stack in appreciable quantities. It is common practice for portland cement plants to have electrostatic precipitators installed in the stack, which filter out and collect this dust. A precipitator works by imparting an electrical charge to the dust particles as they pass, then these charged particles are attracted to oppositely charged plates to which they stick. When a plate becomes completely coated, the dust is removed and collected. The amount of particulates collected is dependent upon local regulations and how much the facility is willing to spend on removal devices. The price of a precipitator increases exponentially with a decrease in the size of the particles it is capable of removing. The implementation of electrostatic precipitators has significantly reduced the concern over particulate emissions from a portland cement facility (Jackson 1998).

2.5 Cement Kiln Dust

It has been mentioned previously that all products that enter the kiln are either incorporated into the clinker, or they are volatilized and become suspended in the gas flow. When these gases reach the cooler parts of the kiln, many of the suspended particles precipitate out and are absorbed into the incoming raw material stream. This is particularly true in kilns with a suspension preheater system. In this way, a cycle is established in which particularly volatile elements, such as K, Na, S, Cl, and some metals, are continuously redeposited into the raw material feed (Taylor 1997). The particles that remain aloft in the gases are collected by what are known as particulate matter control devices (PMCD) (Hawkins et al. 2004), thus removing them from the remainder of the emissions. These particulates are collectively referred to as cement kiln dust (CKD).

The amount of cement kiln dust produced by a portland cement facility varies based on the chemical composition, type, and quantity of raw materials and fuels present, as well as the type of kiln being used. Bhatty and Miller (2004) reported CKD production of a typical facility to be five percent of the total cement produced. Shoaib et al. (1999) report the production rate may be as high as 12 percent. The United States is responsible for producing over 4 million tons of CKD that must be disposed of yearly (Todres et al. 1992). On a global scale, there are about 30 million tons produced in the average year (Konsta-Gdoutos and Shah 2003). With quantities such as these produced annually, it is easy to see why CKD poses tremendous disposal problems for the industry.

Many portland cement facilities are able to reuse all, or at least a major portion of, the CKD they generate as a replacement for some of the raw material feed or the fuels (Taylor 1997). However, due to chemical composition limits related to concrete durability issues, particularly those associated with alkalies, sulfates, and chlorides, most facilities are forced to find other applications for this industrial waste (Bhattacharja 1999). Some common alternative applications, in lieu of landfilling, are use as a supplementary cementing material (Mishulovich 1999; Shoaib et al. 2000), for stabilization of soils (Bhatty et al. 1996), and as a waste stabilization/solidification agent (Hawkins et al. 2004).

2.5.1 Composition of Cement Kiln Dust

Cement kiln dust varies from plant to plant in chemical, mineralogical, and physical composition, based upon factors such as the feed raw materials, type of kiln operation, dust collection facilities, and the type of fuel(s) used (Klemm 1980). In Table 2.18, the chemical composition, as a percentage of total weight, of the *CKD* produced in three different types of kilns is shown (Bhatty et al. 1996). In Figure 2.8, the particle size distribution of the same three *CKD*s, where, “Dust G” is from the long-wet kiln, “Dust H” is from the long-dry kiln, and “Dust S” is from the alkali by-pass kiln is shown (Todres et al. 1992).

Table 2.18: Chemical Composition of CKD Produced in Various Kiln Types

(Bhatty et al. 1996)

Constituent	Long-wet kiln	Long-dry kiln	Alkali by-pass
SiO_2	15.02	9.64	15.23
Al_2O_3	3.85	3.39	3.07
Fe_2O_3	1.88	1.10	2.00
CaO	41.01	44.91	61.28
MgO	1.47	1.29	2.13
SO_3	6.27	6.74	8.67
Na_2O	0.74	0.27	0.34
K_2O	2.57	2.40	2.51
L.O.I.	25.78	30.24	4.48
Free CaO	0.85	0.52	27.18
Mean Particle Size (μm)	9 μm	3 μm	22 μm

2.5.2 Alternative Fuels and CKD

The type and quantity of fuel used to fire a cement kiln has a direct effect on the chemical composition of the kiln dust (Bhatty 2004). Eckert and Guo (1998) reported on a study conducted at numerous cement plants across the United States whose purpose was to determine the chemical composition of cement and CKD when waste-derived fuels (WDF) were used as a replacement for a portion of the traditional fuels. These chemical compositions were determined by means of X-ray fluorescence (XRF). Table 2.19 provides information about each of the plants, which includes whether it used waste-derived fuels as its primary (P) or alternate (A) fuel source.

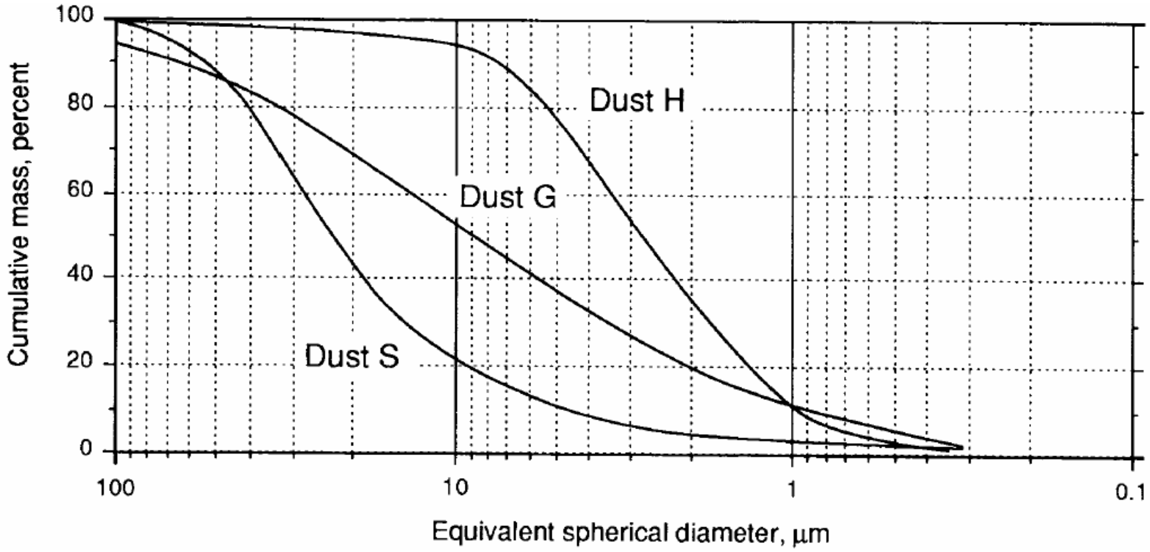


Figure 2.8: Particle Size Distribution of CKD Produced in a S (alkali by-pass kiln), G (long wet kiln), and H (long dry kiln) (Todres et al. 1992)

The results for seven of the seventeen kilns studied are shown in Table 2.20. Although these results provide only a snapshot of the effects that fuel has on CKD, they do provide some understanding of the link between these two components of portland cement manufacturing.

Table 2.19: Cement Plant Information (Eckert and Guo 1998)

Company Name	Plant Location	WDF use	Sample Designation
Giant	Harleyville, SC	P	Giant(SC)-1
Holnam	Holly Hill, SC	P	Holnam(SC)-1
Giant	Harleyville, SC	P	Giant(SC)-2
Holnam	Holly Hill, SC	P	Holnam(SC)-2
Texas Industries	Midlothian, TX	P	TXI(TX)-1
Texas Industries	Midlothian, TX	P	TXI(TX)-2
North Texas	Midlothian, TX	A	NTXC(TX)-1

WDF usage: P=Primary, A=Alternate

Table 2.20: CKD Composition (Eckert and Guo 1998)

Sample #:	Giant (SC)-1	Holnam (SC)-1	Giant (SC)-2	Holnam (SC)-2	TXI (TX)-1	TXI (TX)-2	NTXC (TX)-1
Oxide (Wt%)							
SiO_2	20.89	21.26	20.46	20.48	20.13	20.06	21.28
Al_2O_3	5.72	5.46	5.47	4.5	4.45	4.72	5.1
Fe_2O_3	2.89	2.6	2.61	3.34	3.78	4.24	3.12
MnO	0.01	0.02	0.01	0.02	0.23	0.17	0.3
MgO	1.11	1.06	1.05	1.28	1.03	0.98	0.89
CaO	68.22	66.4	68.6	67.87	67.35	65.6	67.84
Na_2O	0.17	0.16	0.16	0.13	0.28	0.27	0.14
K_2O	0.32	0.3	0.47	0.16	0.32	0.36	0.47
TiO_2	0.3	0.37	0.3	0.23	0.24	0.24	0.21
P_2O_5	0.14	0.14	0.15	0.14	0.15	0.16	0.19
LOI	< 0.01	1.32	< 0.01	0.41	0.54	0.74	0.22
TOTAL Wt.%	98.37	99.09	98.57	98.54	98.51	97.55	99.75
Element (ppm)							
Al	30273.1	28897.1	28950.0	23816.3	23551.7	24980.6	26991.8
Ti	1798.2	2217.8	1798.2	1378.6	1438.6	1438.6	1258.8
V	136.0	112.0	167.0	114.0	108.0	103.0	112.0
Cr	**87.0**	**112.0**	**118.0**	**143.0**	**315.0**	**176.0**	**63.0**
Mn	77.4	154.9	77.4	154.9	1781.3	1316.6	2323.4
Co	17.0	12.0	17.0	9.0	8.0	8.0	15.0
Ni	52.0	41.0	55.0	49.0	49.0	55.0	55.0
Cu	47.0	36.0	86.0	29.0	84.0	83.0	21.0
Zn	71.0	39.0	135.0	24.0	294.0	332.0	58.0
As	**29.0**	**9.0**	**24.0**	**13.0**	**10.0**	**10.0**	**10.0**
Pb	**< 5.0**	**< 5.0**	**< 5.0**	**< 5.0**	**< 5.0**	**< 5.0**	**< 5.0**

2.6 The Effects of Elements on Clinker, Cement, and Concrete

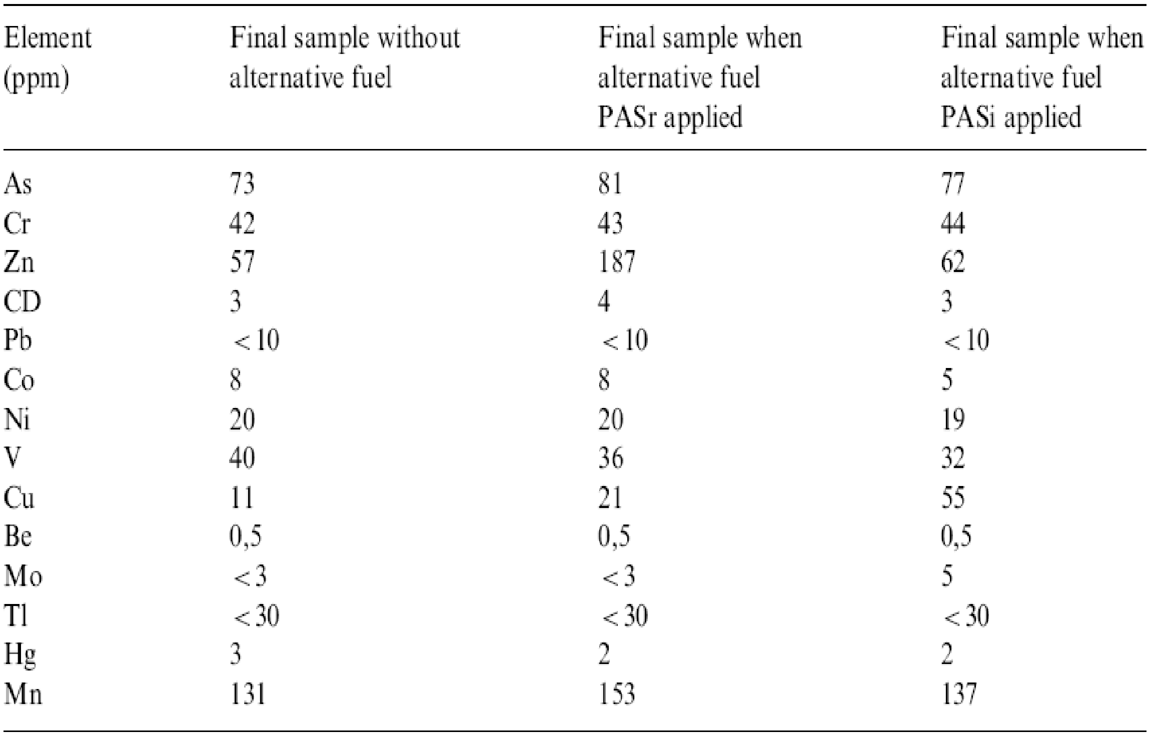
There are many elements that may be incorporated into portland cement throughout the manufacturing process that could alter the performance of the final product. The assimilation of these elements into the cement is highly complex, and depends on the kiln process conditions. The first aspect of their inclusion is the source of the element. It has previously been discussed that many materials must be fed into the kiln in order to produce cement. Raw materials, fuels, and air could potentially be sources of altered composition of the clinker (Bhatty 2004).

Another factor that determines whether an element will be detrimental is the concentration at which it is present. The concentration at which an element becomes harmful is unique to that element. In the case of many of the elements, it may not be known if there is any effect on the product or the process at any concentration.

A project conducted by Mokrzycki et al. (2003) was described in Section 2.1 of this document. In this research, a portland cement facility produced clinker using traditional fuels alone, as well as two different alternative fuels. In Table 2.21, the change in chemical composition of the clinker based on changes only in fuel types is shown. It is evident from these data that the chemical composition of the fuels has an effect on some of the chemicals in the clinker. In order for an alternative fuel to be implemented, it must be established that changes such as these will not adversely affect the properties of the final product (Gartner 1980).

One criterion that must be considered when evaluating data relating changes in chemical composition to cement or concrete properties, is the method by which the variation in chemical composition is brought about. Many tests are conducted in which specific elements are isolated and cement or clinker samples are artificially dosed with predetermined concentrations of the corresponding compound after the cement has been formed (Trezza and Scian 2000). In such cases, the results may be substantially different from those in which the concentration changes came about through the clinkering process. These results can serve illustrative purposes nonetheless.

Table 2.21: Elemental Composition of Clinker Produced with and without Two Alternative Fuels (Mokrzycki et al. 2003)



Element (ppm)	Final sample without alternative fuel	Final sample when alternative fuel PASr applied	Final sample when alternative fuel PASi applied
As	73	81	77
Cr	42	43	44
Zn	57	187	62
CD	3	4	3
Pb	< 10	< 10	< 10
Co	8	8	5
Ni	20	20	19
V	40	36	32
Cu	11	21	55
Be	0,5	0,5	0,5
Mo	< 3	< 3	5
Tl	< 30	< 30	< 30
Hg	3	2	2
Mn	131	153	137

Table 2.22 is a summary, based on previous research, of the effects that selected elements have on concrete properties. The effects shown resulted from an increase in the respective element concentration in the cement from which the concrete was made.

Many elements have been found to affect compressive strength, the predominant property of concrete, differently at different ages. Therefore, compressive strength is divided into three age groups: early strength (less than 28 days), strength at 28 days, and long-term strength (later than 28 days). In many cases, the literature was contradictory. In such cases, multiple effects are shown for the same element-property interaction.

Discussions of the source, resulting destination, and effect on the properties of the product for many selected elements are included in the following sections.

2.6.1 Alkalis (Sodium and Potassium)

These two elements are typically addressed together because their effects are so closely related in the cement/concrete industry. Sodium and potassium are both metals and are numbers 11 and 19 on the periodic table, respectively. Alkalis are present in both raw materials and fuels, particularly coal (Gartner 1980). Bhatty (2004) reported alkali concentrations of 0.13 percent for sodium and 0.47 percent for potassium in raw feeds.

When alkalis are present in the kiln process, they will primarily be incorporated into the clinker. They will most likely take the form of sulfates, if adequate sulphur is present, and will combine with the major clinker phases (Taylor 1997). The amount of alkalis in the major phases is dependent on the degree to which they can react with sulphur. This reaction will continue until all sulfates are consumed (Gartner 1980).

Alkalis are potentially detrimental to the kiln process. It is likely that some will volatilize in the hottest portions of the kiln and will condense in the cooler parts (Jackson 1998). This produces clogs in the preheater (when present) and rings in the kiln (Gartner 1980).

Table 2.22: Effects of Elements on Concrete Properties (Swart 2007)

Element	Property								Other
	Early Comp. Str. (< 28 days)	Comp. Str. (@ 28 Days)	Long Term Comp. Str. (> 28 Days)	Setting Time (↑ = accelerated)	Heat of Hydration	Shrinkage	Water Demand	Leaching Concerns?	
Alkalis	↑↑		↓↓	↑,↓		↑			
Antimony									
Arsenic								Y	
Barium		⬆⬆				↑	↓		
Beryllium									Possibly effects color of clinker/cement
Boron									
Bromine									
Cadmium	↓	↓	↓	↓				Y	
Carbon									
Chlorine									Promotes corrosion of reinforcing steel
Chromium	↑, ↓	↓↓		↓↓	↑, ↓	↑			
Cobalt	↓	↓	↓				↑		
Copper				↓↓	↓↓				Produces darker colored clinker/cement
Fluorine		↑, ↓		↓↓					
Lead		↑		↓↓				Y	Discourages Alkali-Silica Reaction
Lithium									
Magnesium	⬇	↓	↓						
Manganese	⬆, ⬇	↑, ↓	⬇						Effects color of clinker/cement
Mercury								Y	
Molybdenum		↑,↓		↓					
Nickel	↑↑,↓	↑↑	↑↑	↑					Produces brown color in clinker/cement
Nitrogen									
Phosphorus	↓↓	↓↓	↓↓	↓↓	↓	↑	↓		
Rubidium	↓	↓	↓			↑	↑		
Strontium	↓	↓	↓		↓	↑			
Sulfur	↓	↓	↓	↑, ↓					
Thallium								Y	
Titanium	↑, ↓		⬆	↓			↑		Produces yellow color in clinker/cement
Vanadium		↓↓		↓			↑		
Zinc	↑,↓	↑,↓	↑,↓	↓↓	↑↑	↓			Produces color changes in clinker/cement
Zirconium	↑	↑	↑		↑		↓		

Key

	Major Increase	Minor Increase	Major Decrease	Minor Decrease
Multiple Sources	⬆⬆	⬆	⬇⬇	⬇
Single Source	↑↑	↑	↓↓	↓

One method for avoiding this phenomenon is to by-pass the alkalies into the CKD. Many facilities do this, and CKD is usually high in alkali concentration because of this process (Bhatty 2004).

Alkalis incorporated into the cement typically produce high early strengths and lower long-term strengths (Gartner 1980; Taylor 1997). At alkali levels greater than 0.8 percent, Jackson (1998) reported increases in early strength of approximately 10 percent, with a corresponding decrease in 28-day strength of 10 to 15 percent. If alkalis are present at levels too large to completely combine with sulphur, they are detrimental to setting and hardening properties (Gartner 1980). The presence of alkalis, together with reactive silica in the aggregates, also promotes a reaction known as the alkali-silica reaction, which causes significant cracks in concrete (Bhatty 2004; Gartner 1980; Taylor 1997). Taylor (1997) also reported that if the concentration of alkalis is increased, the optimum amount of gypsum is also increased. Jackson (1998) reported high alkali cements exhibit higher drying shrinkage characteristics, accelerated rates of hydration, and decreased setting times.

The effects of alkalis on setting time and compressive strength are shown in Tables 2.23 and 2.24, as reported by Lawrence (1998). In Table 2.23, the initial and final setting times, in minutes, for concrete with various concentrations of alkalis are shown. In this study, it was found that as the concentration of Na_2O increased, so did both initial and final setting times. This contradicts what Jackson (1998) reported. As the concentration of K_2O increased, both initial and final setting times decreased.

In Table 2.24, the variation in compressive strength, at four ages, for the same concrete specimens as in Table 2.23, is shown. As the concentration of Na_2O increased, the compressive strength decreased at all ages. The compressive strength for the various concentrations of K_2O was more variable. For the concrete with 0.88 percent K_2O, the compressive strength, relative to the control sample, was increased at 1 and 3 days, but decreased at 7 and 28 days. The concrete strength with 1.48 percent K_2O was decreased at 1 and 3 days, and increased at 7 and 28 days relative to the strength of the concrete with 0.88 percent K_2O. This is consistent with what Gartner (1980) and Taylor (1997) reported.

Table 2.23: Setting Time of Cement Specimens with Various Alkali Contents (Lawrence 1998)

Cement + sodium or potassium oxide in clinker	Setting Time (min)		
	H_2O (%)	Initial	Final
Control	25	180	215
0.72% Na_2O in clinker	25	185	290
1.26% Na_2O in clinker	25	295	360
0.88% K_2O in clinker	25	150	205
1.48% K_2O in clinker	25	50	135

Table 2.24: Compressive Strength of Cement Specimens with Various Alkali Contents (Lawrence 1998)

Cement + sodium or potassium oxide in clinker	Compressive strength (MPa)			
	1 day	3 days	7 days	28 days
Control	20.0	41.5	61.8	74.2
0.72% Na_2O in clinker	19.5	39.8	59.6	68.7
1.26% Na_2O in clinker	18.4	39.2	57.5	68.2
0.88% K_2O in clinker	21.9	44.8	60.7	72.1
1.48% K_2O in clinker	20.0	43.1	61.0	73.2

2.6.2 Antimony (Sb)

Antimony is element number 51 on the periodic table, and is classified as a semi-metal. Typically, antimony is not found in large quantities in any of the components used to produce portland cement. However, it is not uncommon to find trace amounts, on the order of 0.08 ppm, in the raw materials (Bhatty 2004). Antimony could possibly be introduced by fuels, but more than likely it would be at levels even lower than those found in the raw materials (Bhatty 2004).

When antimony is introduced into the kiln, it is uncertain where it will establish itself. Bhatty (2004) stated that, "a considerable portion of antimony gets incorporated in clinker." It is also known that antimony has a tendency to be combined with the CKD (Gartner 1980).

Although it is possible to find antimony in portland cement, it is not known how its presence affects the properties of the final product. This is likely due to its very low concentration levels in cement.

2.6.3 Arsenic (As)

Arsenic is number 33 on the periodic table, and is classified as a nonmetal. It can generally be found in both raw materials and in fuels. Bhatty (2004) claimed that As can be present in levels up to 12 ppm in limestone, 23 ppm in clay, 50 ppm in coal, and 0.6 ppm in petroleum coke. Therefore, it is evident that some arsenic will be present in cement manufacture.

Although it is well known that As will almost certainly be present in at least one of the products introduced to the kiln, it is far less certain where that arsenic ends up.

Typically, arsenic takes the form of a volatile compound and would seemingly be incorporated into the CKD (Gartner 1980). It has been argued, however, that As enters into the clinker due to excess CaO, oxidizing conditions, and high temperatures within the kiln (Weisweiler and Krčmar 1989).

No significant results are known to have been collected on the effects of As on the properties of cement or concrete.

There is another concern with arsenic. Because it is a toxic and volatile element, its presence in emissions must be closely monitored in order to ensure the health of people, animals, and the environment (Moir and Glasser 1992).

2.6.4 Barium (*Ba*)

Barium, classified as a metal, is number 56 on the periodic table. Ba is typically found in the raw materials, particularly limestone or clay. In some instances, barium can also be found in fuels, such as coal, at levels up to 24.5 ppm (Bhatty 2004).

Because barium is not a volatile metal, it is generally incorporated into the clinker when introduced into the kiln.

Unlike many of the elements present in this study, links have been made between varying concentrations of Ba and the properties of the cement produced. It has repeatedly been reported that additions of barium have produced an increase in compressive strength of the concrete (Miller 1976; Gartner 1980). Specifically, Jackson (1998) reported that at small amounts, barium may increase 28-day strengths. Particularly, a 0.3 percent increase in BaO may increase 28-day strengths by up to 20 percent, and a 0.5 percent increase in BaO may increase 28-day strength by 10 percent.

It is also thought that cement paste shrinkage is affected by changes in barium concentrations. Both Miller (1976) and Gartner (1980) report that increases in Ba levels produced increases in paste shrinkage. Finally, it is also possible that additions of Ba produce a decrease in water demand (Miller 1976).

2.6.5 Beryllium (*Be*)

Beryllium is element number four and is classified as a metal. Although it is rarely present in any appreciable amounts, trace amounts can be found in the raw materials or in fly ash if it is being used as a raw material substitute (Bhatty 2004). Bhatty (2004) reported that Be can be found in levels up to 0.5 ppm in limestone, 3 ppm in clay, and 2.27 ppm in coal.

When beryllium is present in products introduced into the kiln, it is usually incorporated into the clinker. This is due to the fact that Be is a stable, nonvolatile element (Bhatty 2004; Gartner 1980).

Because beryllium is typically present in such low concentrations, its effect on cement and concrete is debatable. It is thought that additions of beryllium may cause the clinker to be blacker than without it. Also, Be could possibly have significant effects on the setting and strength properties of cement, but no data are reported (Bhatty 2004).

2.6.6 Boron (*B*)

Boron is element number five, and is a nonmetal. It is usually only found in small quantities in the raw materials, specifically the ones used as an iron source. In general, the upper limit on the concentration of boron is about 3 ppm. B is usually absorbed by the clinker when it is introduced into the kiln (Miller 1976).

The effects of boron addition are most notable in the chemical reaction of the raw materials. Gartner (1980) reported that quantities as low as 0.04 percent can be deleterious to cement properties, but its effects are highly unpredictable. Besides this, not much is known about the effect of boron on the properties of portland cement.

2.6.7 Bromine (*Br*)

Bromine is a nonmetal that is number 35 on the periodic table. Br is typically only found in appreciable amounts in the raw materials. Bhatty (2004) gives the following values as reasonable upper limits on the concentration of bromine: limestone (6 ppm), clay (58 ppm), and coal (11 ppm).

Due to the volatility of bromine, if it were introduced into the kiln, it is most likely to end up in either the emissions or the CKD. Negligible amounts of Br would be found in the clinker (Bhatty 2004).

Because bromine is volatilized in the kiln, it does not end up in the clinker. Therefore, the effects of Br on portland cement are unknown.

2.6.8 Cadmium (*Cd*)

Cadmium is element number 48, and is classified as a metal. Cd can be found in small amounts in the raw materials as well as the fuels. Bhatty (2004) gives possible concentration values for cadmium: limestone (0.035 to 0.1 ppm), clay/shale (0.016 to 0.3 ppm), coal (0.1 to 10 ppm), and used oil (4 ppm).

It is most likely that the majority of Cd introduced into the kiln will end up in the preheater cyclones, in facilities that have them, or in the CKD (Bhatty 2004; Taylor 1997). Bhatty (2004) claimed that, "in a cyclone preheater kiln, 74 to 88 percent of the total Cd entering the kiln is incorporated in clinker as opposed to 25 to 64 percent for that produced in the grate preheater kilns."

The most significant findings regarding the effect of Cd on the properties of portland cement were presented by Murat and Sorrentino (1996). They claim that cadmium in the clinker slows the setting time, and decreases the compressive strengths. Additionally, Gartner (1980) reported that the addition of $Cd(OH)_2$ to mortars produced a slight reduction in strength.

In addition to the effect that Cd may have on the final product, its introduction into the environment must be closely monitored due to its toxic nature. Therefore, emission levels must be observed in order to prevent Cd from being released. Additionally, the leachability of Cd from cement/concrete must be monitored. Murat and Sorrentino (1996) noted that no cadmium was detected in the leached material from concrete after one month. Although leaching of Cd is not typically a problem, its consequences are something that anyone placing concrete high in cadmium levels should be aware of.

2.6.9 Carbon (*C*)

Carbon is element number six on the periodic table, and is classified as a nonmetal. It is present in very large quantities in both the raw materials and in the fuels. Limestone is the major contributor of carbon to the raw materials. Any fuel that is used will contain carbon in high concentrations.

Almost without exception, any carbon that is introduced into the kiln will be released through the stack emissions as CO_2. This is one of the most significant problems that portland cement manufacturers have to deal with. A detailed discussion of carbon-based emissions can be found in Section 4.1.

Due to the fact that all of the carbon is released in the emissions, there is no C that is incorporated into the clinker. Therefore, its effect on cement and concrete is negligible.

2.6.10 Chlorine (Cl)

Chlorine is the 17th element, and a nonmetal. Chlorine is commonly found in both the raw materials and fuels. Bhatty (2004) has reported the following typical concentrations: less than 0.02 percent by weight in raw materials and 10 to 2800 ppm in traditional fuels. Limestone is quite often closely associated with Cl, as well as other $CaCO_3$ sources, particularly those derived from marine origins (Gartner 1980), which may contain chloride levels up to 240 ppm (Bhatty 2004). The tendency toward refuse-derived fuels, including scrap tires, is prone to contributing meaningful increases in chloride levels (Miller 1976).

Alkali chlorides that volatilize and condense in the kiln may lead to the formation of kiln rings. If the volatilized alkali chlorides escape into the preheater stack, they have a tendency to cause buildups which lead to poor performance of the facility (Bhatty 2004; Jackson 1998; Taylor 1997). It has been reported that as much as 99 percent of all chlorides in the preheater are recaptured by the incoming raw feeds (Ritzmann 1971). If no preheater stacks are present, these compounds are generally incorporated into the CKD, if they do not form kiln rings (Bhatty 2004). Jackson (1998) also claimed that chlorides will end up in emissions.

Due to the volatile nature of chlorine and its tendency to be deposited elsewhere, typical concentrations of Cl in clinker are not very high (Gartner 1980). These levels are generally less than 0.03 percent (Bhatty 2004). One effect of chlorides on concrete that is a cause of major concern in the concrete industry is the acceleration of corrosion of the reinforcing steel (Taylor 1997). If the reinforcing steel found in most structures is exposed to chlorides and oxygen, corrosion may occur over time. Overall, the greatest concern with increased levels of chlorine is the deleterious effect it has on the production process.

2.6.11 Chromium (*Cr*)

Chromium is element number 24 on the periodic table, and it falls into the metal classification. Cr is a common element that can be found in any of the materials introduced into the kiln. Reports have shown chromium levels from 1.2 to 16 ppm in limestone, as well as 90 to 109 ppm in clay and shale. Additionally, the levels of chromium in fuels are on the order of 80 ppm in coal and 50 ppm in used oils (Bhatty 2004). Bhatty also reported that it is not unusual to introduce meaningful levels of Cr into the cement during the grinding of the clinker. The grinding balls as well as the added gypsum may contain significant amounts of chromium.

The volatility of Cr is generally very low, thus it is primarily deposited in the clinker. However, if conditions in the kiln are right, Cr may volatilize and be concentrated in either the CKD or emissions at levels as high as 100 to 1000 ppm (Gartner 1980). One statistic that is particularly relevant to this study is that Bhatty (2004) reported Cr concentrations in the range of 0.01 to 299 ppm in CKD from facilities that use waste-derived fuels, which is as much as an 11 percent increase relative to facilities using traditional fuels.

The common presence of chromium has led to many studies on its effect on the properties of cement. Many researchers have found that chromium is directly related to concrete compressive strength. It has been reported that increased concentrations of Cr in the raw materials have shown improved early strength, but have resulted in a decrease in 28-day strength (Bhatty 2004; Gartner 1980; Miller 1976; Murat and Sorrentino 1996). Other effects attributed to increased Cr concentrations, as reported by Miller (1976), were higher heat of hydration, lower autoclave expansion, and increased 24-hour paste shrinkage. Gartner (1980) confirms that higher levels of Cr reduced autoclave expansion. Kakali, Tsivilis, and Tsialtas (1998) studied the effect of Cr on rate of hydration and found that it is slowed during the first two days, but the effect is negligible at 28 days. Stephan et al. (1999) reported decreases in setting time, as well as a lowered heat of hydration, for increased Cr concentrations, which contradicts Miller (1976).

In a study conducted by Stephan et al. (2000), clinker samples were prepared using a raw mix dosed with various concentrations of Cr_2O_3, NiO, and ZnO, ranging from 5000 to 25,000 ppm. It should be noted that these are very high dosages of these compounds. The chemical composition of the raw meal before dosing is shown in Table 2.25. Once the cement was produced, a number of physical tests were conducted**.** Figure 2.9 shows the heat of hydration for the samples dosed with 25,000 ppm of each of the oxides. The sample dosed with chromium exhibited an accelerated rate of heat liberation, and a decrease in total amount of heat released. Figures 2.10 and 2.11 show the penetration, which is related to initial setting time, for the samples dosed with 25,000 and

5,000 ppm, respectively. The samples dosed with chromium showed accelerated setting times in both cases. This phenomenon was significantly more pronounced in the sample containing 25,000 ppm, however.

The final tests conducted were compressive strengths on mortar cubes. Figures 2.12 and 2.13 show these results for the samples dosed with 25,000 ppm and 5,000 ppm respectively. In both cases, the compressive strength of the samples dosed with Cr_2O_3 decreased at both dosage levels. The difference between the strength effects of the two concentrations was minimal. The results of the samples dosed with the other elements will be discussed in the following appropriate sections.

Table 2.25: Chemical Analysis of Cement before Addition of Dosed Elements (Stephan et al. 2000)

Oxide	Portland Cement
SiO_2 (wt.%)	14.1
Al_2O_3 (wt.%)	3.5
Fe_2O_3 (wt.%)	2.2
CaO (wt.%)	41.3
MgO (wt.%)	1.7
K_2O (wt.%)	1.1
SO_3 (wt.%)	0.6
Cr (ppm)	51
Ni (ppm)	15
Zn (ppm)	88
Specific surface (m^2/cm^3)	1.71

One additional concern with chromium is that it is a toxic element. Many authors, including Murat and Sorrentino (1996), agree that Cr may be easily leached from concrete. Therefore, special considerations must be made in order to prevent harmful effects from concrete manufactured with portland cement with high concentrations of chromium.

2.6.12 Cobalt (*Co*)

Cobalt is the 27th element on the periodic table and a metal. Co is generally found in the raw materials as a trace element, with concentrations no more than 23 ppm (Bhatty 2004; Kolovos et al. 2002). It may also be found at levels significantly higher if fly ash is used a supplementary raw material (Bhatty 2004).

When cobalt is present in the kiln, it is typically incorporated into the clinker, where it may be found at concentrations up to 130 ppm (Bhatty 2004). At concentrations this high, it has been reported that the clinker may exhibit changes in its properties such as altered color and increased hardness (Gartner 1980).

Cobalt is typically found in cement at low levels, and the effects on the physical properties are therefore not well known. However, Miller (1976) reported that additions of Co might slightly reduce long-term strengths, as well as slightly increase water demand. Additionally, cobalt has been shown to retard hydration during the first two days (Kakali et al. 1998).

2.6.13 Copper (*Cu*)

Copper is a metal and is the 29th element on the periodic table. Cu is introduced into the kiln system predominantly by the raw materials. Approximate concentrations are on the order of 10 ppm in such components (Bhatty 2004).

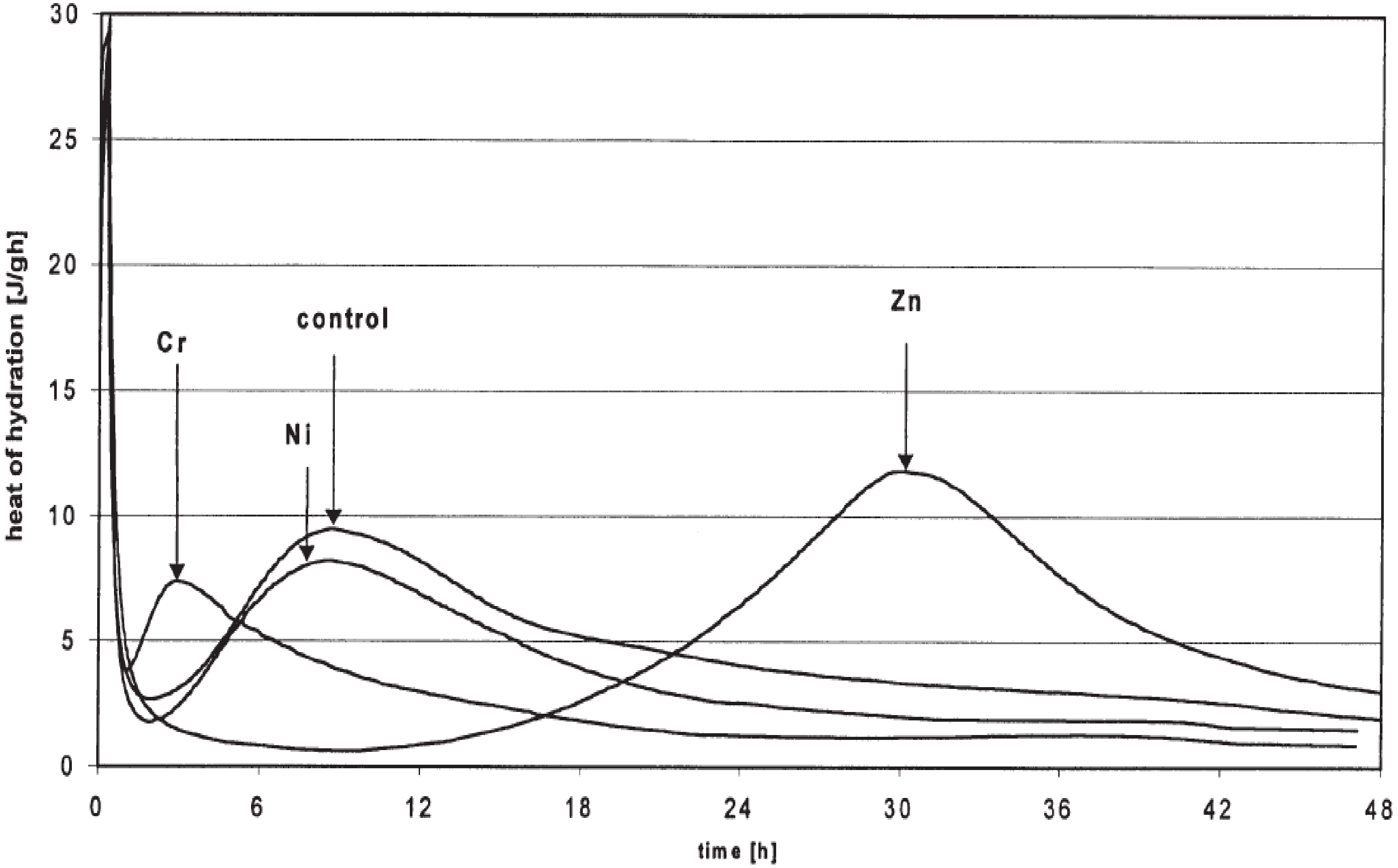


Figure 2.9: Heat of Hydration for Cement with Various Concentrations of Cr, Ni, and Zn (Stephan et al. 2000)

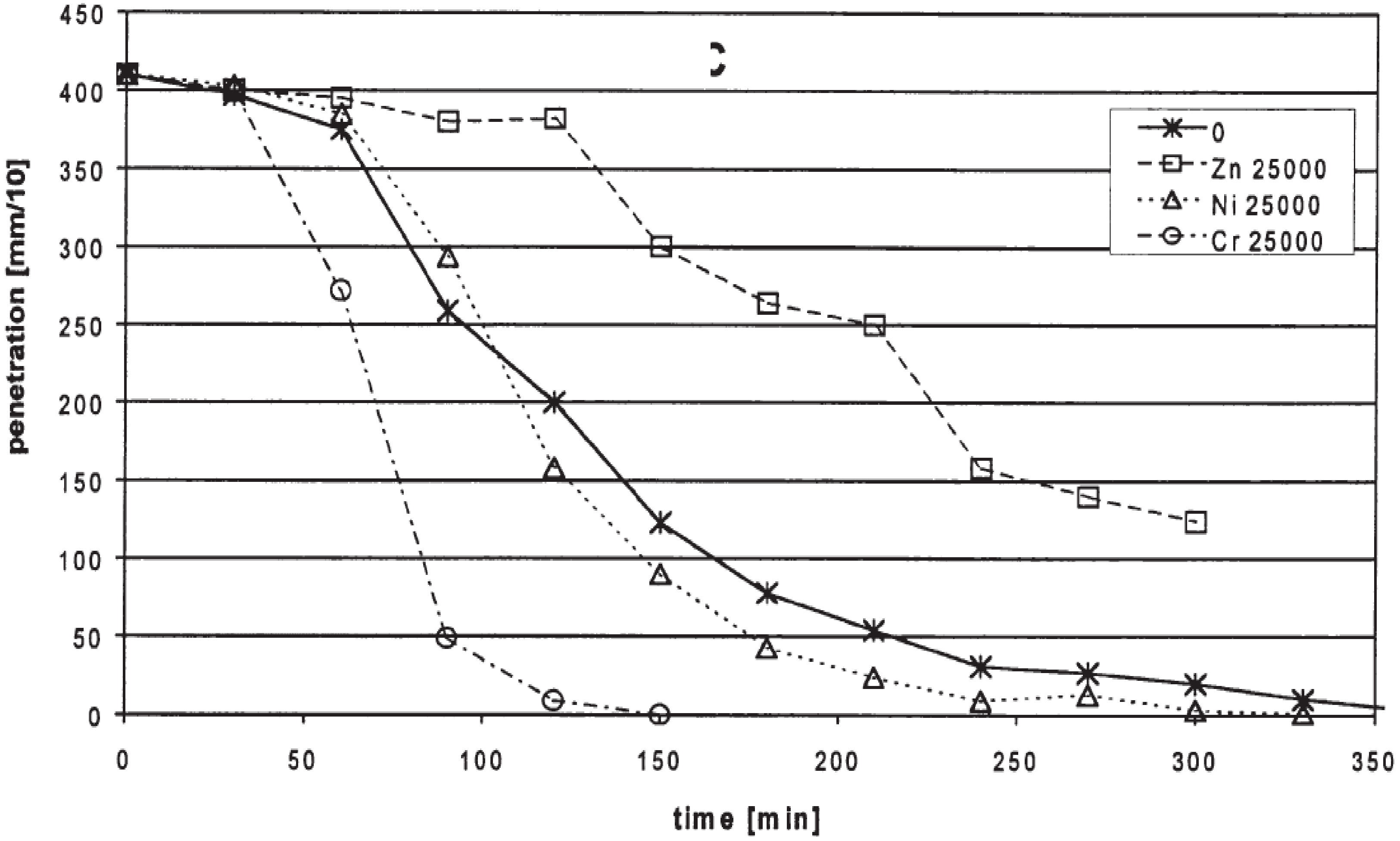


Figure 2.10: Penetration of Cements Dosed with 25,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

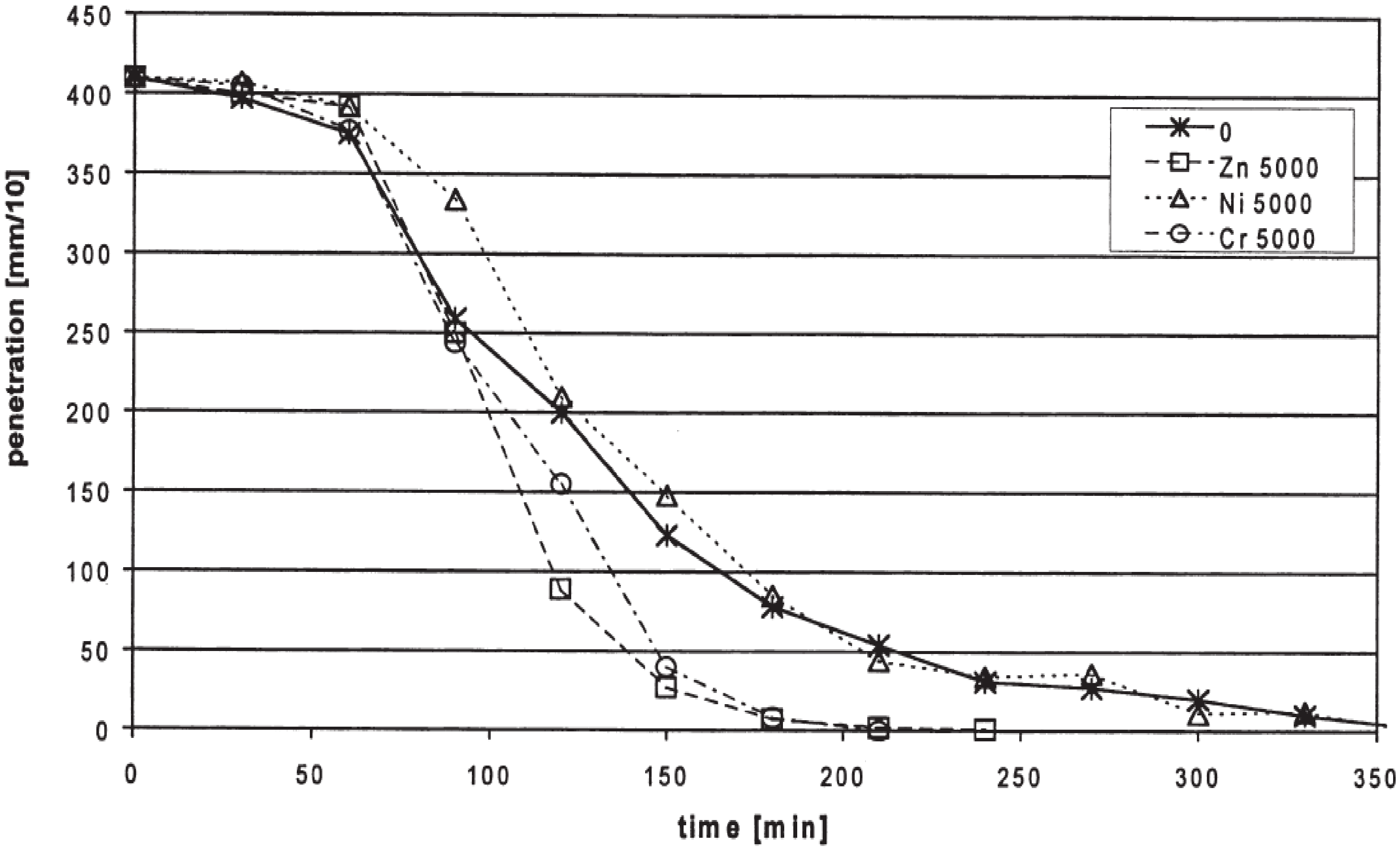


Figure 2.11: Penetration of Cements Dosed with 5,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

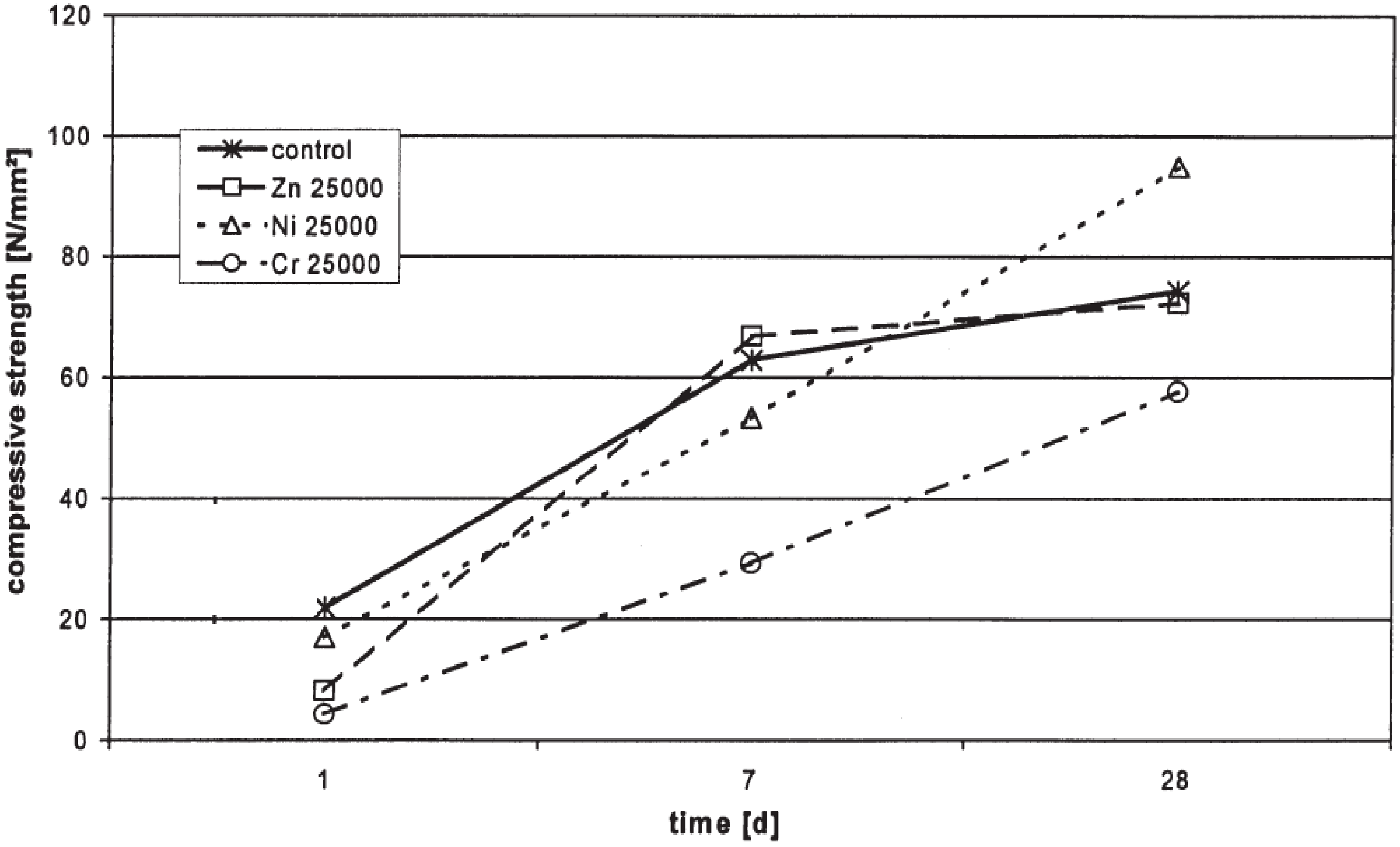


Figure 2.12: Compressive Strength of Cements Dosed with 25,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

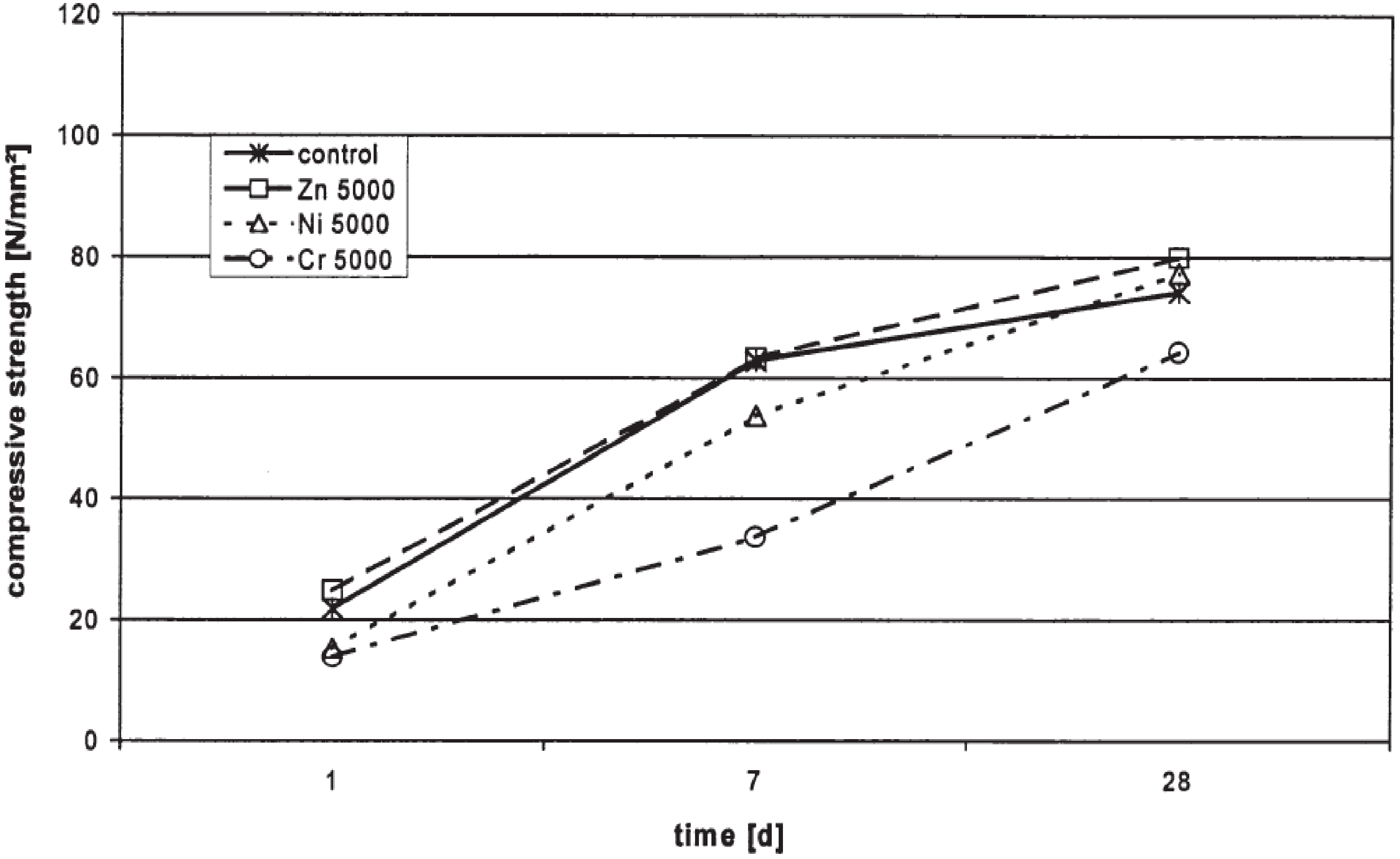


Figure 2.13: Compressive Strength of Cements Dosed with 5,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

Copper is a volatile element, and the majority therefore attaches itself to the CKD. In fact, Cu has been known to show up in the CKD at levels up to 500 ppm (Bhatty 2004). A much smaller amount of the element is incorporated into the clinker. Bhatty (2004) claimed concentrations of Cu in clinker may reach values as high as 90 ppm.

When copper is fused into the clinker, it has been known to influence a number of properties of the final product. First of all, copper in clinker has a tendency to produce a darker colored, sometimes tan, product (Bhatty 2004; Kolovos et al. 2002). Copper also affects the hydration properties of portland cement. Specifically, the addition of CuO to the raw mix has shown significant retardation of the hydration process, as well as a retardation of the amount of heat released during this hydration (Gartner 1980; Kakali et al. 1998; Miller 1976). In fact, Kakali et al. (1998) claim that CuO causes the greatest delay of hydration, even at 28 days, of all the transition elements.

2.6.14 Fluorine (*F*)

Fluorine is the 9th element and is a nonmetal. It is found in nearly all raw materials and fuels alike. Bhatty (2004) reported levels between 50 and 370 ppm in coal, and as much as 0.06 percent by mass in commercial raw materials.

Fluorine is a prominent element in the manufacture of portland cement. 88 to 98 percent of all F introduced into the kiln may be incorporated into the clinker (Bhatty 2004). However, fluorine may take a number of different forms during clinkering, each of which has a different melting point. Therefore, it is not uncommon to find fluorine in both CKD and emissions, almost without exception at levels lower than in the clinker (Bhatty 2004). Gartner (1980), Miller (1976), and Taylor (1997) all claim that if F is volatilized, it has a tendency to cycle in the CKD where it may lead to kiln rings or clogging of the precalciner.

One of the properties that may be affected by concentrations of fluorine over 0.2 percent, by mass, is setting time. When the ambient temperature is below 5 degrees Celsius, setting time may be significantly slowed (Jackson 1998). However, setting time is slowed by a decrease in temperature in all cement.

Miller (1976) reported that high levels of fluorine increase 28 day compressive strength. Jackson (1998) reported, however, that concentrations over 0.5 percent decrease compressive strength.

2.6.15 Lead (*Pb*)

Lead is element number 82 and is a semi-metal. It may be present in both raw materials and fuels, the latter of which has a tendency to exhibit higher concentrations. Lead is of particular concern with nontraditional fuels, such as used oils and tires, where its concentrations may be higher (Bhatty 2004).

Lead is a volatile element, which results in higher concentrations in the emissions and CKD (Bhatty 2004; Gartner 1980; Taylor 1997). Despite this fact, substantial concentrations of lead have been detected in the clinker (Bhatty 2004; Gartner 1980).

When lead is present in clinker, it has been shown to have a number of different effects. Many researchers have found that lead in portland cement has a direct retarding effect on setting time (Gartner 1980; Murat and Sorrentino 1996; Taylor 1997). This is especially true at levels above 0.2 percent by weight (Miller 1976). Although retarded setting times would generally be detrimental, Miller (1976) claimed that when setting time is not an issue, lead may actually increase the 28-day compressive strength.

In addition to the effects that lead may have on the properties of cement, its effects on the environment must also be considered. Lead is a toxic chemical, whose introduction into the environment must be closely monitored in order to ensure a healthy environment is sustained. Additionally, the leachability of the element must also be studied in order to prevent its introduction through the placement of concrete. Gartner (1980) and Murat and Sorrentino (1996) agree that at lead dosages as high as five percent it does not generally leach from concrete.

2.6.16 Lithium (*Li*)

Lithium is element number three, and is classified as a metal. Its presence in the kiln is usually attributed to raw materials, but in almost undetectable quantities. If wastes are being used as a fuel source, concentrations may be considerably higher (Bhatty 2004).

If Li is present in the kiln, it will be incorporated into the clinker since it is not a volatile element. However, this is generally at very low concentrations. If levels of Li are elevated, the most reported effect is that it may slow the rate of reaction between the alkalis and the aggregate in concrete (Gartner 1980). In fact, lithium has been proven very effective at reducing concrete's susceptibility to alkali-silica reaction. Figure 2.14 shows the results of a test conducted by Kawamura and Fuwa (2001) in which expansion due to alkali-silica reaction was monitored. The expansion of the concrete was reduced when 1 % and 1.5 % dosages of $LiCO_3$ compared to when no dosage was used.

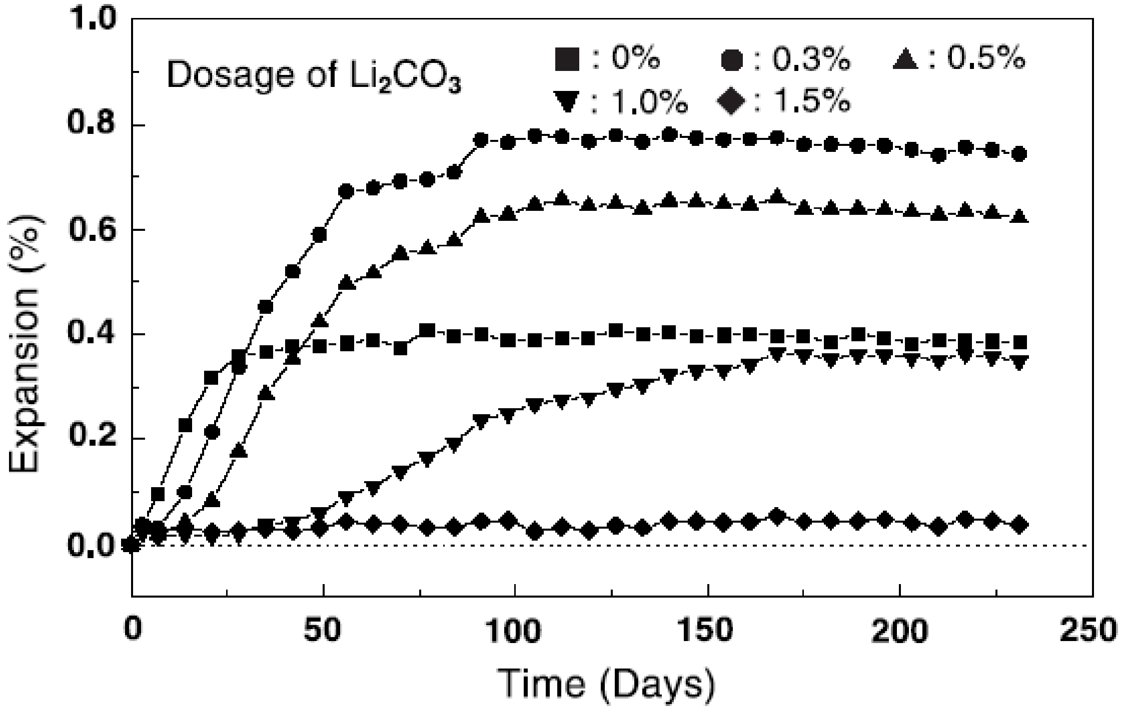


Figure 2.14: Effect of Various Doses of Li_2CO_3 on ASR Expansion (Kawamura and Fuwa 2001)

2.6.17 Magnesium (*Mg*)

Magnesium is element number 12 and classified as a metal. It is very common in most of the raw materials, where it may be present at concentrations as high as 0.63 percent (Bhatty 2004).

The Mg that is introduced into the kiln is almost exclusively incorporated into the clinker. Trace amounts may be found in the CKD or emissions. Bhatty (2004) reported that Mg may be found in the clinker at concentrations as high as 8900 ppm.

Magnesium concentrations of 0.5 percent, by mass, or greater can potentially decrease early strengths (Taylor 1997). Gartner (1980) claimed no dramatic changes in setting or hardening properties are brought about by high concentrations of Mg.

Generally speaking, Mg is regarded as a good thing in cement due to its benefits on the production process with minimal effects on the properties. ASTM C150 specifies an upper limit of six percent MgO in cement.

2.6.18 Manganese (*Mn*)

Manganese is element number 25 and is classified as a metal. Mn is a common element, and has a marked presence in the production of portland cement. Manganese can be found in both raw materials and fuels. It is not uncommon to find levels of Mn_2O_3 in limestone up to 1.91 percent, as well as up to 58.9 percent in shale and 36.7 percent in bauxite (Bhatty 2004). Nontraditional raw materials such as slag may contain higher levels of Mn than their traditional counterparts (Miller 1976).

It is highly unlikely that Mn will vaporize in the kiln process, and will therefore be incorporated into the clinker in most cases (Gartner 1980). The boiling point of Mn is 1960°C. It will therefore not typically volatilize and attach to CKD particles (Bhatty 2004.)

An increase in manganese has been reported to produce decreased compressive strengths (Bhatty 2004; Miller 1976). However, at levels of 0.7 percent or more, it has been shown to impart high early strength (Gartner 1980). Mn has also been found to cause various changes in color to clinker (Gartner 1980; Taylor 1997). In particular, “reddish-brown to blue casts have been observed in manganese-containing clinkers (Bhatty 2004; Miller 1976).”

2.6.19 Mercury (*Hg*)

Mercury is the 80th element and is classified as a metal. Hg may be found in very small quantities in both raw materials and fuels. Some typical concentrations, provided by Bhatty (2004), are limestone 0.03 ppm, clay/shale 0.45 ppm, and coal 0.27 ppm.

Mercury is a volatile element, and will therefore be found in the CKD and emissions. The concentrations in either place are primarily very low due to the low levels of the element entering the kiln. However, it has been found that plants that use waste fuels in place of traditional fuels have shown an increase in mercury emission mass flow rates from 0.984 mg/sec to 2.14 mg/sec (Mantus et al. 1992).

Due to the scarcity of substantial levels of mercury in the clinker, very little is known about its effect on the product. It is nevertheless necessary to monitor mercury levels due to its toxic nature. Gartner (1980) reported that if mercury forms the HgO compound and is incorporated into the clinker, it has a tendency to leach from concrete. This is certainly a concern, and must be closely observed.

2.6.20 Molybdenum (*Mo*)

Molybdenum is number 42 and is a metal. Mo can be present in both raw materials and fuels in significant quantities. One supplementary raw material of particular interest is coal fly ash, which has been shown to contain molybdenum at levels up to 1.5 percent by weight (Bhatty 2004).

Molybdenum is not a volatile element and, in conjunction with its abundant presence in the kiln components, can potentially be found at high concentrations in the clinker. Blaine, Bean, and Hubbard (1965) have reported that these concentrations could be as high as 0.05 percent.

Due to the potentially high levels of Mo in clinker, the effects that it may have on cement and concrete properties have been well documented. Taylor (1997) reported that concentrations up to 0.5 percent increase 28-day strength, but at concentrations above three percent that same strength may be significantly reduced. Another effect that has been attributed to high concentrations of Mo is the rate of setting. The effects of hydration are slightly retarded during the first two days (Kakali et al. 1997).

2.6.21 Nickel (*Ni*)

Nickel is element 28 and a metal. Oil and coal have been observed to have high levels of nickel (Miller 1976). These may be on the order of 3 to 30 ppm and 20 to 80 ppm, respectively (Bhatty 2004). Additionally, Bhatty (2004) reported levels of 1.5 to 7.5 ppm in limestone, 61 to 71 ppm in clay/shale, and 208 ppm in petroleum coke. Miller (1976) also reported higher levels of nickel in black shale as well as in refuse-derived fuels.

It has been shown that Ni may exhibit volatile characteristics when subjected to coal combustion, resulting in its incorporation into the CKD (Gartner 1980). However, nickel amounts of up to 0.02 percent in clinkers have also been reported (Blaine et al. 1965). Bhatty (2004) confirms that the location of Ni is dependent on the compound it forms, and may be incorporated in clinker or CKD.

Compressive strengths have reportedly been improved by higher concentrations of Ni. Levels of 0.5 to one percent have been responsible for increases in 1-day and 5-

year strengths (Gartner 1980). Another property that may be affected by nickel is hydration. Miller (1976) stated that water-soluble nickel is an accelerator for cement hydration, while nickel in clinker at levels up to 0.02 percent has very little effect on hydration. High levels of Ni may also produce a dark brown color in clinker (Bhatty 2004).

The results concerning nickel additions in the study conducted by Stephan et al. (2000) (as described in section 6.11) can be seen in Figures 2.9 through 2.13. From Figure 2.9, the rate of hydration and the total hydration energy were approximately unchanged due to nickel addition. Figures 2.10 and 2.11 show the rate of setting was also approximately unchanged for both levels of nickel addition. Finally, Figures 2.12 and 2.13 show that the compressive strength decreased at early ages and increased at later ages for both nickel addition levels.

2.6.22 Nitrogen (*N*)

Element number seven is nitrogen. In its natural state, nitrogen is a gas. N, in solid form as an oxide, can be found in both raw materials and fuels, and may be present at high levels. Specifically, nitrogen may be found at 0.01 percent in raw materials, and as high as two percent in fuels (Bhatty 2004).

Nitrogen is always present in kiln systems in the form of combustion air. However, it generally remains in the gaseous form and is released with the stack emissions. A detailed discussion of nitrogen emissions can be found in Section 2.4.2.

2.6.23 Phosphorus (*P*)

Phosphorus is element number 15 and is classified as a nonmetal. The most common form of phosphorus in the cement process is P_2O_5. Phosphorus is generally introduced into the kiln through limestone (Jackson 1998), but is present at some levels in most raw materials. It may exist at concentrations above one percent in many raw materials (Gartner 1980). Research conducted by the Portland Cement Association (PCA) has found that waste lubricating oil, as well as other refuse-derived fuels may exhibit substantial levels of phosphorus (Miller 1976).

P_2O_5 is not a volatile compound in the kiln process, and will usually be incorporated into the clinker. A typical concentration for P_2O_5 in cement clinker is 0.2 percent (Taylor 1997). Jackson (1998) agrees, reporting typical values of 0.03 to 0.22 percent.

Although Miller (1976) claimed that P_2O_5 at levels below 0.5 percent have no measurable effect, if that threshold is surpassed, phosphorus may produce a slight decrease in water requirements, slightly lower heat of hydration, and shows a tendency toward paste shrinkage. Gartner (1980) also reported serious decreases in strength at P_2O_5 levels above 2.5 percent. Concrete hardening becomes slower with high levels of P_2O_5. Figure 2.15 shows the effect of P_2O_5 content on compressive strength (Miller 1976). From this figure, it can be seen that there is an optimum P_2O_5 content at approximately 2.5 percent, above which compressive strength decreases. However, based on the P_2O_5 concentrations reported by Taylor (1997) and Jackson (1998), it may be concluded that most cements will contain less than this optimum P_2O_5 concentration.

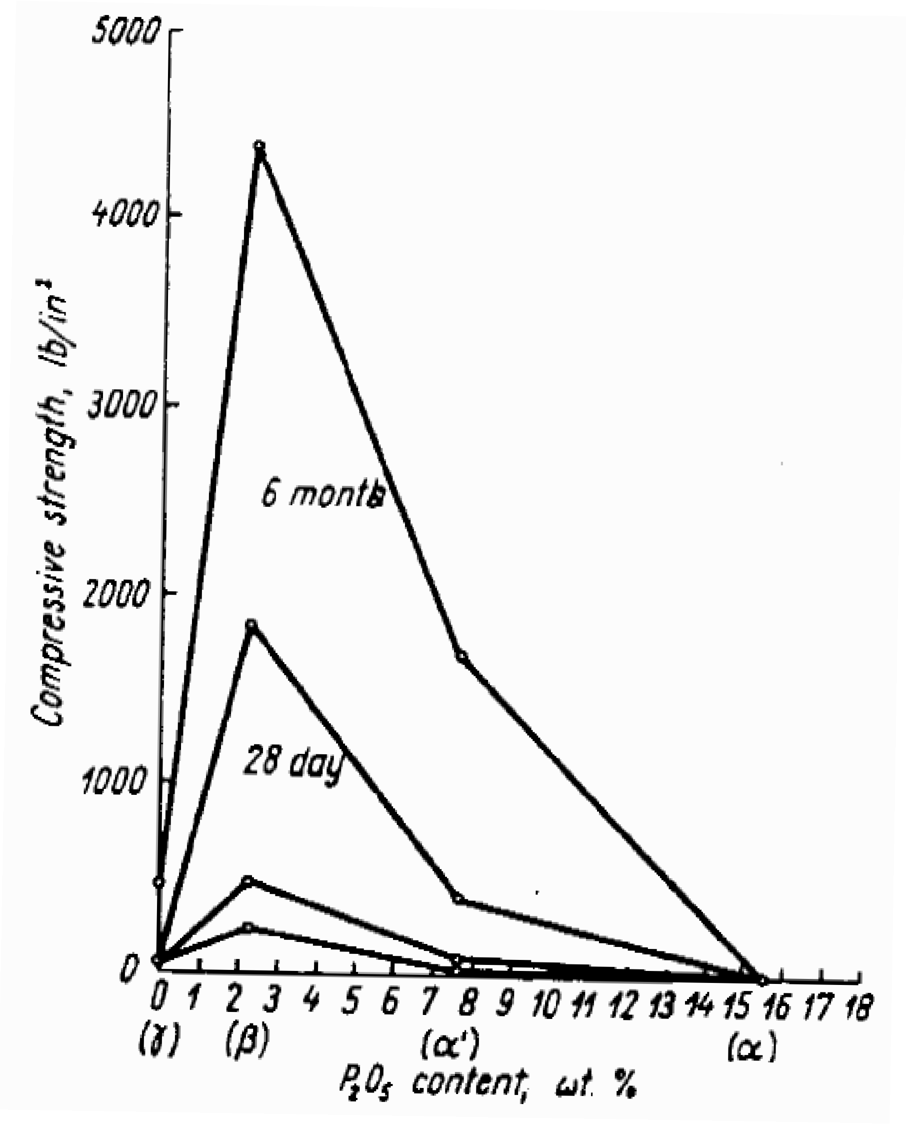


Figure 2.15: Compressive Strength for Different P_2O_5 Concentrations (Miller 1976)

2.6.24 Rubidium (*Rb*)

Rubidium is element number 37 and a metal. It is generally found only in small concentrations in the raw materials (Bhatty 2004). Gartner (1980) claimed that Rb acts similarly to potassium, in that it has a tendency to form rings in the kiln and to promote clogging throughout the system.

The levels at which rubidium is present in clinker are typically very low. Miller (1976) stated that although the concentrations may be low, Rb may affect cement in a number of ways. First, it may have a negative effect on compressive strength at all ages. Additionally, the paste may shrink more than a paste with lower concentrations of Rb. Rubidium may also be a culprit in the expansion of concrete, as well as in reducing its ability to resist freezing and thawing cycles. More water may also be required to properly hydrate cement with high levels of Rb (Bhatty 2004). More research is required to determine if these changes in properties can be accurately attributed to rubidium.

2.6.25 Strontium (*Sr*)

Strontium is the 38th element and a metal. The presence of Sr is not uncommon in the raw materials, particularly in $CaCO_3$ sources, such as limestone (Bhatty 2004). The concentrations are not especially high, however.

Because Sr is not volatile, it is generally trapped in the clinker, where it would not be uncommon to find strontium at levels on the order of 0.5 percent by weight (Bhatty 2004; Gartner 1980).

Although the concentrations at which strontium has been observed in the clinker are not high, researchers have reported that the effects on the physical properties may be many. Miller (1976), in particular, outlined a number of possible effects Sr may produce. Namely, lower strengths, higher autoclave expansion, lower heat of hydration at 28 days, and increased concrete shrinkage were observed. Gartner (1980) confirmed that strontium “is marginally deleterious to cement strength and other physical properties.”

2.6.26 Sulphur (*S*)

Sulphur is a nonmetal and element number 16. Sulphur may be introduced into the kiln through both raw materials and fuels (Jackson 1998). Fuels such as coal and oil are particularly prone to high levels of sulphur (Gartner 1980). Limestone, clayey sediments, and marl also contain appreciable quantities of sulphur (Bhatty 2004). The primary source of SO_3 in cement is the addition of gypsum during grinding of the clinker. The levels of SO_3 added are closely monitored in order to produce the desired effects in the cement, such as control of setting times. The optimum quantity of SO_3 added is on the order of three to five percent (Taylor 1997). ASTM C150 limits the amount of gypsum that may be added.

Some sulphur in the form of SO_2 is released through the stack emissions. A detailed discussion of sulphur emissions can be found in Section 2.4.3. The most common place for sulphur to be found is in the clinker. This is likely to occur because sulphur prefers to combine with alkalis (Gartner 1980), which are readily available in most kiln systems. As was mentioned in Section 2.6.1, alkali sulfates have a tendency to volatilize in high temperature areas, and condense in cooler temperature areas, where they may form kiln rings or clogs in the preheater system (Gartner 1980). This is obviously detrimental to the production process. Many production facilities have chosen to break the cycle of vaporization and condensation by removing alkali sulfates from the system in the CKD (Bhatty 2004; Gartner 1980).

“The effect of the presence of sulfates is intimately connected with those of the alkalis” (Jackson 1998). Gartner (1980) claimed that the presence of sulphur in clinker has no deleterious effects, so long as it is maintained at acceptable concentrations.

Otherwise, it may retard setting time and inhibit strength gain. If SO_3 is present at excessive levels, the cement paste will have a tendency to expand at an increased magnitude. The overall early hydration rate of portland cement is retarded as the levels of sulfate are increased (Jackson 1998). Jackson (1998) also reported that sulphur incorporated into the clinker phases has an accelerating effect on setting. There is an optimum gypsum content for all portland cements, which is specific to the chemical composition of that particular clinker. If SO_3 is added in excess of this optimum concentration, strengths, especially at early ages, are known to decrease (Jackson 1998).

2.6.27 Thallium (*Tl*)

Thallium is element number 81, and is classified as a semi-metal. Another trace element, Tl may be found in small quantities in both raw materials and fuels. The largest values reported were on the order of 1 ppm in coal (Bhatty 2004; Gartner 1980).

One of the most volatile of all elements introduced into the kiln, thallium almost certainly ends up in the CKD or emissions. Therefore, it has little to no effect on clinker properties. However, in a facility where the CKD is recycled without regular disposal, thallium has been shown to build up to concentrations as high as 10,000 ppm (Bhatty 2004). If this happens, serious problems may form in the kiln system such as clogging of the precalciner.

One additional concern with Tl is its high toxicity. Because of this, its levels must be monitored closely in order to ensure health and safety.

2.6.28 Titanium (*Ti*)

Titanium is the 22nd element and is classified as a metal. It may be found in concentrations on the order of 0.1 to one percent in most kiln feeds (Gartner 1980). Ti may also be found in certain auxiliary raw materials such as slag (Miller 1976). Bhatty (2004) reported TiO_2 levels in such materials of 1.7 percent in slag and two to eight percent in bauxite. Miller (1976) also claimed there may be substantial Ti content in some refuse-derived fuels.

Titanium is not volatile in the kiln system (Gartner 1980). Therefore, it is typically incorporated into the clinker (Bhatty 2004). Jackson (1998) claimed that the levels of TiO_2 in typical portland cement clinkers are between 0.14 percent and 0.43 percent.

Knofel (1976) reported that titanium concentrations in the range of one to two percent as TiO_2 produces improved cement strengths. Jackson (1998) reported TiO_2 levels up to one percent decrease one-to-two day strengths, but may improve strengths at ages greater than three days. Two percent Titanium has also been reported to slightly retard hydration during the first two days (Kakali et al. 1998). Miller (1976) reported that at Ti levels less than one percent there is little evidence to support any substantial deleterious effects. Titanium may lead to increased water demand as well as may give the cement a yellow color (Miller 1976). Taylor (1997) claimed the color change associated with Ti is of a darker nature.

2.6.29 Vanadium (*V*)

Vanadium is the 23rd element and a metal. V can be readily found in both raw materials and fuels. Limestone has been known to contain V at concentrations of 10 to 80 ppm, with even higher levels reported in clay and shale. Coal may have vanadium up to 50 ppm (Bhatty 2004). Gartner (1980) reported that vanadium may be found at “very high levels” in crude oil, and when introduced into the kiln at such levels, it has a tendency to deteriorate the kiln lining.

When vanadium is introduced into the kiln, its tendency is to combine with oxygen to form V_2O_5. This compound is mostly stable throughout the clinkering process, and will therefore be incorporated primarily into the clinker (Bhatty 2004). It is not uncommon, however, to be present in detectable quantities in both the CKD and emissions.

The effects of vanadium on cement and concrete are numerous. V has a tendency to produce increased expansion characteristics in the presence of sulfate (Gartner 1980; Miller 1976). It has also been suggested that vanadium additions result in a higher water demand (Miller 1976). In the study conducted by Kakali et al. (1998), concerning the effects of certain elements on hydration, it was determined that vanadium slightly retards hydration in the first 2 days. Jackson (1998) stated that 0.2 percent, by mass, may lead to a 10 percent reduction in the 28-day compressive strength.

2.6.30 Zinc (*Zn*)

The metal zinc is element number 30 on the periodic table. Zinc may be present in concentrations from 22 to 115 ppm in limestone and clay/shale, 16 to 220 ppm in coal, and as high as 10000 ppm in alternative fuels such as tires (Bhatty 2004). Certain byproduct raw materials such as fly ashes may have appreciably higher levels of zinc than more traditional materials (Miller 1976). Some refuse-derived fuels have shown high levels of zinc as well (Miller 1976).

About 10 to 20 percent of zinc is volatile in the kiln process. This portion has a tendency to be incorporated into the CKD (Miller 1976). Gartner (1980) claimed "virtually all of the ZnO is retained in the clinker if the kiln dust is recycled." In this case, zinc may be incorporated into the clinker at levels up to 0.2 percent (Blaine and Bean 1965). Barros et al. (2004) claimed that 90 percent of ZnO may be incorporated into the clinker. Bhatty (2004) reported that between 80 and 90 percent of ZnO in the kiln feed may end up in the clinker. If zinc is captured and recycled in the CKD, it is possible for it to form deposits in the preheater as well as in the kiln in the form of kiln rings (Taylor 1997). When this phenomenon occurs, serious problems may arise throughout the production process.

Blaine et al. (1965) have reported increased strength at five and ten years, decreased paste shrinkage at 1 and 28 days, and decreased concrete shrinkage due to increased levels of ZnO. Gartner (1980) claimed that additions of Zn in the raw mix decreased early strength while increasing long-term strength, and soluble Zn^{2+} leads to severe retardation of hydration. Miller (1976) also reported retarded setting times, decreased strengths, and changes in color when appreciable levels of zinc are present. Kakali and Parissakis (1995) agreed, reporting a brown color being imparted on the clinker. Zinc at concentrations on the order of 0.01 to 0.2 percent have been shown to lead to retardation of setting time, but when the level is maintained below 0.5 percent, there are no profound effects on other hydraulic properties (Jackson 1998). Murat and Sorrentino (1996) have shown that when extremely large quantities of ZnO (approximately ten percent) are mixed with cement, setting time is retarded and strengths are reduced.

The results of the study conducted by Stephan et al. (2000) concerning zinc additions can be seen in Figures 2.9 through 2.13. Figure 2.9 shows that zinc severely retards setting time, and increases the amount of heat released during hydration. Figures 2.10 and 2.11 show that zinc severely decreases setting time at concentrations of 25,000 ppm, but has little effect on setting at the 5,000 ppm level. Finally, Figures 2.12 and 2.13 show the effect of zinc on compressive strength. At both concentrations reported, the effects were negligible.

2.6.31 Zirconium (*Zr*)

Zirconium is the 40th element on the periodic table. It is classified as a metal. Although the raw materials are the most meaningful source of Zr, the concentrations there are not very high. Miller (1976) reported zirconium levels of 0 to 0.5 percent by weight in the raw materials.

A number of possible effects of zirconium on the properties of cement have been reported. Modestly higher compressive strengths at all ages, a reduction in water requirements, and higher heat of hydration were all mentioned by Miller (1976). Additionally, Gartner (1980) reported that zirconium may increase early strengths, but admits the effects of high concentrations are unknown.

2.7 Conclusion

The production of portland cement is a tremendously fuel-intensive process. Typically, the cost of fuel accounts for 30 to 40 percent of the total production costs (Mokrzycki et al. 2003). Because of this, cement producers are turning to cost-efficient alternative fuels at an increasing rate. Typically these fuels are derived from byproducts from other industries. Using such fuels allows the cement industry to save substantial amounts of money. Additionally, the use of wastes is beneficial to the environment. By reducing the amount of fossil fuels consumed, reducing landfill demand, and typically decreasing harmful greenhouse gases, the implementation of wastes in this way benefits us all.

Although the benefits of using waste fuels in the cement industry are significant, there are issues that must be considered in order to fully utilize these fuels. Primarily, the composition and performance of the cement must not be compromised. If it is, the use of these fuels is not a viable option. Additionally, it has been shown that, in some cases, emissions of potentially harmful elements have increased due to the incineration of some material waste. If alternative fuels are to be used, these emissions must be monitored and effectively controlled.

Careful consideration of alternative fuel implementation must be made by the cement industry. If the appropriate fuels are selected in the appropriate situations, the producers, the environment, and the world will benefit from this technology.

CHAPTER 3

TEST METHODS

3.1 Introduction

The production of portland cement is a complex process, involving many materials and complex systems working in tandem. In Section 2.2 the production process is discussed in detail. In order to satisfy the objectives of this project, a thorough sampling and testing program was developed. The program described in the following sections was used to collect and analyze samples of every material used in the production of portland cement at this particular facility.

The scope of this project included eight distinct collection and testing periods, which are referred to as burns. They are as follows:

1. **C** burn utilized only coal as fuel.
2. **CT1** burn utilized coal and tires. This is the standard fuel combination used at the cement plant, and was therefore considered the baseline for comparison purposes. This is the first baseline burn.
3. **CTP** burn used coal, tires, and waste plastics. These plastics were considered alternative fuel one.

4. **CT2** burn utilized coal and tires. Again, the standard fuel combination was used, and this is the second baseline burn.
5. **CTB** burn used coal, tires, and broiler litter. Broiler litter was the second alternative fuel tested.
6. **CT3** burn utilized coal and tires. Again, the standard fuel combination was used, and this is the third baseline burn.
7. **CTW** burn used coal, tires, and woodchips. Woodchips was the third alternative fuel tested.
8. **CTS** burn used coal, tires, and switchgrass. Switchgrass was the fourth alternative fuel tested.

All these burns, here onwards in this document, will be referred to by their respective lettered names as indicated above.

In each burn, all materials were sampled and tested in accordance with the program described in the following sections. A schematic of the overall sampling and testing plan is shown in Figure 3.1

The first phase in the testing program was to collect samples of all of the materials involved in the process. The cement plant already had a program in place for collecting samples of these materials as a part of their quality control process. Due to their established collection frequencies and for convenience, it was decided to collect samples at the same frequencies as were used by the plant. These frequencies, as well as the particular materials and sample quantities, are discussed in the following sections.

The second half of the testing program was the actual testing of the materials that were collected. Many different tests were implemented in this program to be as thorough as possible. This was particularly true for the testing of the portland cement itself. The specific tests that were conducted are discussed in the appropriate sections that follow.

3.1.1 Definitions

The process of sampling refers to the method by which a quantity of material is collected at the cement plant. A specimen is the material on which a test is conducted. A discrete sample is a batch of material collected at a specific time and location at the cement plant. A composite specimen is prepared, in accordance with Section 3.3.2, using discrete samples taken over a given period of time. A daily composite is a composite specimen that is prepared from discrete samples that were collected over a 24-hour period. A three-day composite is a composite specimen that is prepared using discrete samples taken over a 72-hour period.

3.2 *General Test Planning and Overview*

The comprehensive testing plan, presented in tabular form, is given in Appendix A**.** This testing plan presents an overview for the materials that were sampled, sampling frequency, specimen preparation methods, tests conducted, as well as other pertinent information concerning sampling and testing.

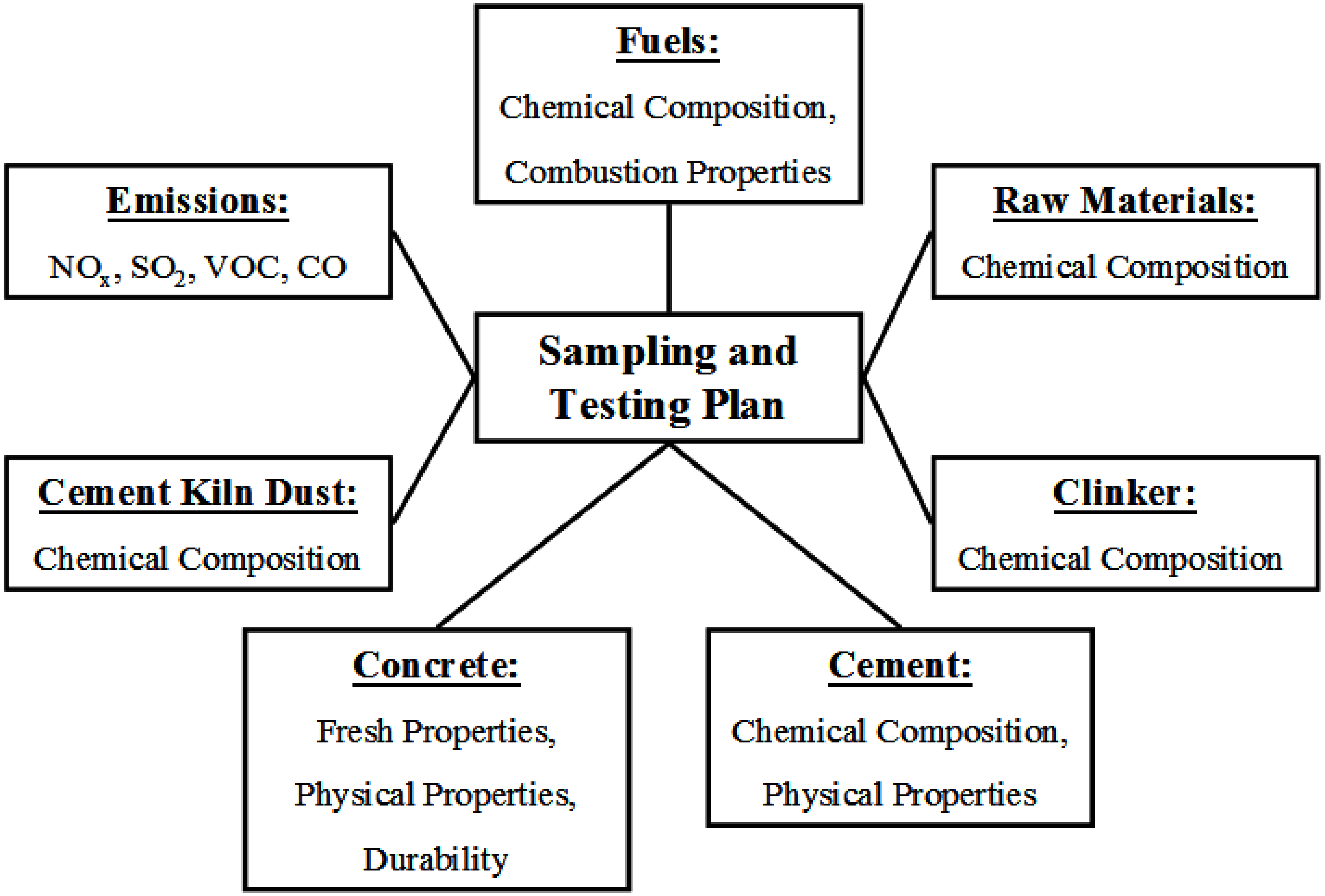


Figure 3.1: Sampling and Testing Plan

Sampling frequency refers to the frequency at which discrete samples were collected at the cement plant. Specimen preparation method describes the manner in which samples were prepared for testing, that is, whether the discrete samples were tested directly , or if composite specimens were prepared from the discrete samples collected. Discussion of specimen preparation methods is given in Section 3.3.2. The actual dates of burns conducted are given in chapter 4. A graphical timeline for the typical sampling period of all the burns can be found in Figure 3.2.

3.2.1 Collection of Materials

All of the materials used in the production process were sampled and tested for various properties. All of these materials (except cement kiln dust) can be divided into two categories. These categories are process inputs and process outputs.

Process input materials are those that are used to produce portland cement. The inputs at this specific cement plant were six raw materials and the different fuels. The sources of the raw materials were classified as proprietary information by the cement plant and hence cannot be revealed, however, they shall be referred to as Raw Materials One to Six in this document Five of the six raw materials were combined in strictly controlled proportions in order to produce a material known as kiln feed. The kiln feed is the material that is sent into the kiln, where in the presence of high temperatures produced by the combustion of the fuels, it is chemically transformed into clinker. The sixth raw material is combined with the clinker prior to grinding to produce portland cement. Each of these process input materials was sampled and tested for various properties as described in the following sections.

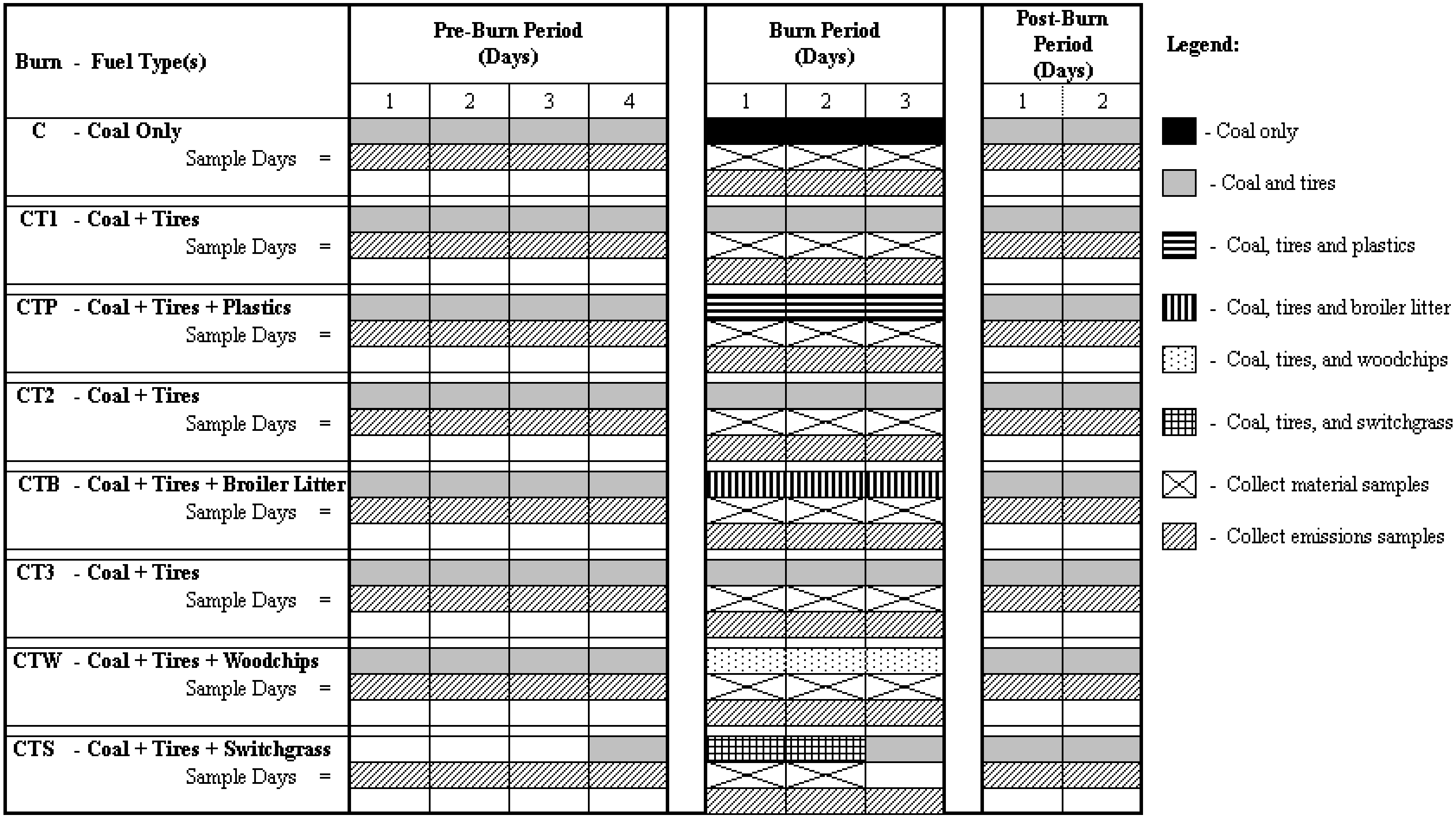


Figure 3.2: Sampling Timeline

The process output materials are clinker, portland cement, and emissions. Each of these process output materials was sampled and tested for various properties as described in the following sections. However, an emphasis was placed on the primary output of the plant, portland cement.

The cement kiln dust (CKD) is primarily composed of fine particulate matter that does not combine with the other materials in the kiln to become clinker. It is discussed in detail in Section 2.3. What distinguishes CKD from the other materials is that it is both an output and an input of the process. It is a byproduct of the clinkering process, but it is recycled back into the kiln feed just before entering the kiln. CKD was sampled and tested for various properties as described in Section 3.3.5.

It must be noted that the CTS burn had a pre-burn period of coal and tires as fuel for only one day and the burn itself lasted for only two days due to insufficient supply of switchgrass.

3.2.2 Types of Tests

The primary test conducted on all materials was a chemical analysis. The chemical compounds were determined by X-Ray Fluorescence (XRF), and the components were reported either as percent by weight (wt. %), or as parts per million (ppm). The former is the percentage of the total unit weight of the chemical or component in question. Parts per million (ppm) is actually measured as μg/g. PPM units were used for many of the elements that had a relatively small presence in the material being examined.

XRF was used to determine the chemical compositions at the cement plant and the external laboratory, with one exception. Raw Material Three was not tested by XRF at the cement plant. In this case, the chemical composition was determined by a Prompt Gamma Neutron Activation Analyzer (PGNAA). The testing of the emissions did not include a chemical analysis and the details of this testing are discussed in Section 3.3.10.

The cement plant and the external laboratory both tested the chemical composition of the materials; however, the standard elements tested for differed somewhat between the two testing entities. In Table 3.1, the standard parameters that were examined by personnel the cement plant and by those at the external laboratory are shown. Each of the parameters shown in Table 3.1 was determined by XRF, except for Na_2O_{eq}, which was calculated from the concentrations of Na_2O and K_2O by the formula presented in ASTM C 150. The approximate detection limits for the XRF used at the external laboratory are shown in Table 3.2.

Concrete was made from the portland cement collected during each of the burns. The specific tests associated with concrete are described in Section 3.3.9. Any other tests that were specific to only one material are discussed in the section pertaining to that material.

Table 3.1: Standard Chemical Parameters

Standard Cement Plant Parameters	Standard External Lab Parameters	
(wt. %)	**(wt. %)**	**(ppm)**
Al_2O_3	Al_2O_3	Arsenic (As)
CaO	CaO	Barium (Ba)
Fe_2O_3	Fe_2O_3	Cadmium (Cd)
K_2O	K_2O	Chlorine (Cl)
MgO	MgO	Cobalt (Co)
Na_2O	Na_2O	Chromium (Cr)
Na_2O_{eq}	P_2O_5	Copper (Cu)
SiO_2	SiO_2	Mercury (Hg)
SO_3	SO_3	Manganese (Mn)
Moisture	TiO_2	Molybdenum (Mo)
Loss On Ignition	Moisture	Nickel (Ni)
	Loss On Ignition	Lead (Pb)
		Tin (Sb)
		Selenium (Se)
		Strontium (Sr)
		Vanadium (V)
		Zinc (Zn)

Table 3.2: Approximate Detection Limits for XRF used at the External Laboratory

Parameter	Lower Limit of Detection
Al_2O_3 (wt. %)	0.01
CaO (wt. %)	0.01
Fe_2O_3 (wt. %)	0.01
K_2O (wt. %)	0.01
MgO (wt. %)	0.01
Na_2O (wt. %)	0.01
P_2O_5 (wt. %)	0.01
SiO_2 (wt. %)	0.02
SO_3 (wt. %)	0.01
TiO_2 (wt. %)	0.01
Moisture (wt. %)	0.01
LOI (wt. %)	0.01
As (ppm)	2
Ba (ppm)	40
Cd (ppm)	3
Cl (ppm)	5
Co (ppm)	10
Cr (ppm)	16
Cu (ppm)	13
Hg (ppm)	0.01
Mn (ppm)	12
Mo (ppm)	9
Ni (ppm)	9
Pb (ppm)	4
Sb (ppm)	20
Se (ppm)	1
Sr (ppm)	16
V (ppm)	20
Zn (ppm)	9

3.3 Detailed Test Procedure

3.3.1 Plant Layout, Sample Collection Locations, and Collection Methods

Figure 3.3 shows a schematic layout of the cement plant, including material paths, sample collection points, and important facilities. As mentioned earlier, due to the proprietary nature of the raw materials, they can only be identified as Raw Material One through Six. The main raw material, Raw Material Three, is mined from the quarry and unloaded into the primary crusher where it is reduced to a manageable size. From the primary crusher, Raw Material Three is sent by conveyor through the Prompt Gamma Neutron Activation Analyzer (PGNAA) for determining its chemical composition, which is discussed in Section 3.3.3. Once it is analyzed by the PGNAA, it is either stockpiled for later use, or sent directly to the proportioning equipment. Based on the chemical analysis of Raw Material Three, Raw Materials One, Two, Four, and Five are added to the stream by the proportioning equipment in order to meet the chemical requirements to produce portland cement. Sample Points One through Four in Figure 3.3 apply to Raw Materials One, Two, Four, and Five respectively. These raw material samples were collected by removing approximately one gallon of material directly out of the stream just before they were added to Raw Material Three. The one gallon tin pail in which they were collected is referred to as the typical container from this point forward. Figure 3.4 shows a typical sample point for the raw materials.

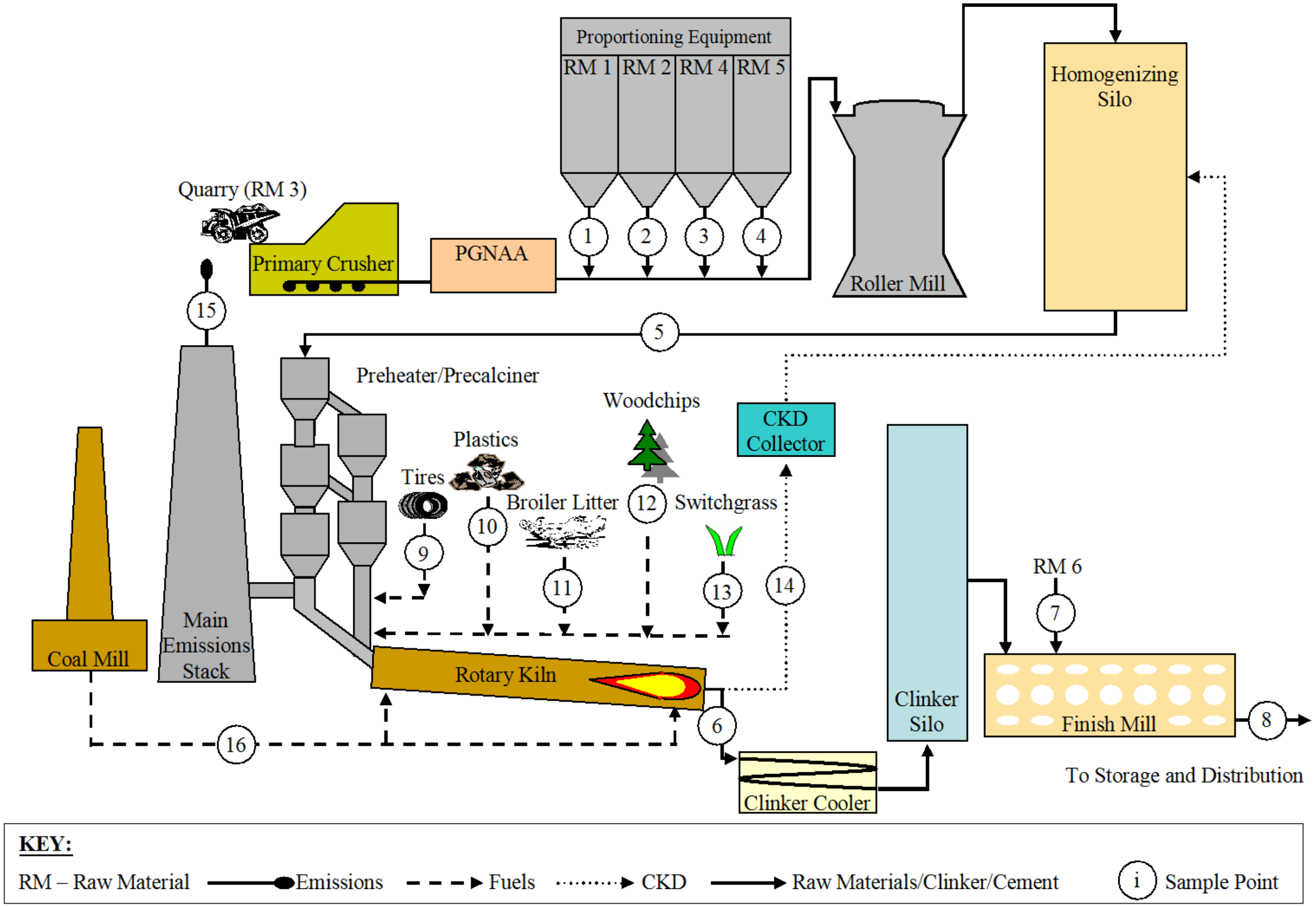


Figure 3.3: Diagram of the Cement Plant (Adapted from Swart 2007)

Figure 3.4: Raw Material Sample Point

Once the raw materials have been proportioned, they are sent to the roller mill, which grinds the material to the desired particle size distribution. They are then sent to the homogenizing silo. Just before the raw materials enter the homogenizing silo, recycled cement kiln dust (CKD) is added. Once the materials enter the silo, they are mixed to produce a homogeneous mixture known as the kiln feed. After the kiln feed was blended, a sample was taken at Sample Point Five in Figure 3.3, by inserting a pint-sized tin container directly into the stream, as shown in Figure 3.5. Before the CKD was added to the raw materials, a sample was collected at Sample Point 14 in Figure 3.3, in the same manner as for the kiln feed.

From the homogenizing silo, the kiln feed is sent to the preheater/precalciner. Once the kiln feed makes its way completely through the preheater/precalciner, it goes into the rotary kiln where it is chemically fused to produce clinker. The clinker then exits the kiln and is sent directly to the clinker cooler. The clinker was sampled at Sample Point Six immediately after it exited the kiln, as shown in Figure 3.3. A rod with the top half partially removed to form a trough was inserted directly into the clinker stream, where a small volume of clinker was removed and collected into the typical container as shown in Figure 3.6.

Figure 3.5 : Kiln Feed Sampling

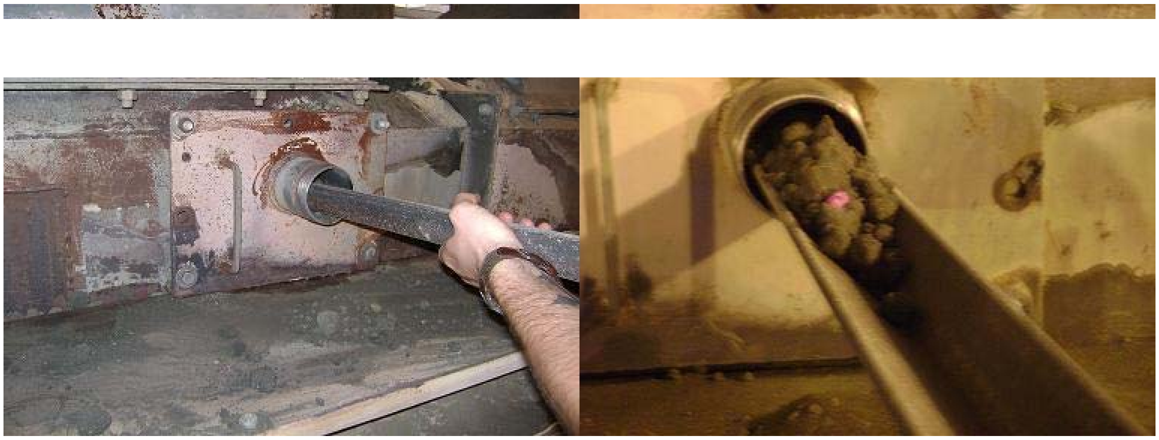


Figure 3.6 : Clinker Sampling

The preheater/precalciner-rotary kiln system has two locations at which fuel is introduced. The back end is considered to be the upper end of the kiln. This is where approximately 60 percent of the coal is consumed at this particular plant. Additionally, because of their large size, all of the alternative fuels are introduced at this end of the kiln. The remaining 40 percent of the coal is injected at the front end of the kiln, which is the lower end. The coal was sampled at Sample Point 16 in Figure 3.3 by an automated plunger system that removes material from the stream, and empties it into the typical container, as shown in Figure 3.7. The tires are sent into the kiln through a conveyor system that drops them directly in one at a time. This process is shown in Figure 3.8 and Figure 3.9.

Figure 3.7: Automated Plunger Removing Coal Samples

The broiler litter, plastics, woodchips and switchgrass are injected just below the tires' injection point using a conveyor and screw system as shown in Figure 3.10**.** The tires, plastics, broiler litter, woodchips and switchgrass were sampled at Sample Points Nine, Ten, Eleven, Twelve and Thirteen in Figure 3.3, respectively. Tires were sampled by removing a single tire from the conveyor at a time. Preparation of tire samples is discussed in Section 3.3.2**.** All other alternative fuels were sampled by inserting the typical container directly into the feed stream.

Figure 3.8: Tires Transported to Kiln

Figure 3.9: Tire Entering Kiln

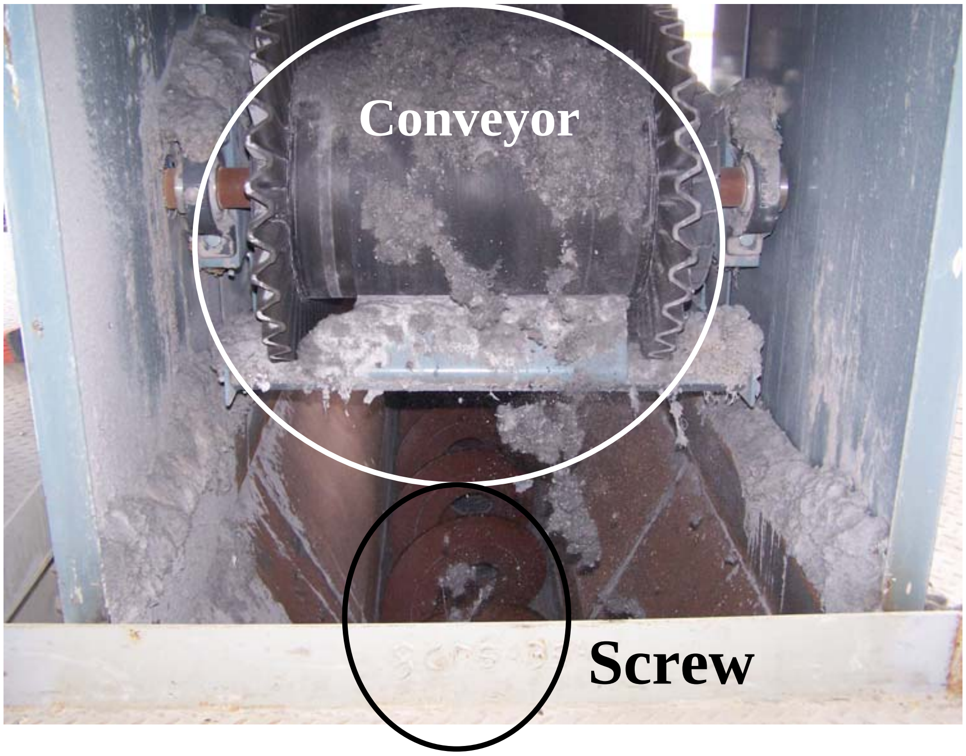


Figure 3.10: Alternative Fuel Kiln Injection System

Once the clinker has cooled, it is sent, along with Raw Material Six, which was sampled at Sample Point Seven in Figure 3.3, to the finish mill. The finish mill grinds these two materials together to form the final product, portland cement. After the materials are ground, the portland cement was sampled at Sample Point Eight in Figure 3.3, by an automated plunger that removes the product from the mill, and empties it into a five-gallon plastic bucket. This process is shown in Figure 3.5. Finally, the finished product is either sent to storage, placed in bags, or loaded directly into trains or trucks for distribution.

Figure 3.11: Automated Plunger Collecting Cement Samples

3.3.2 Sample Preparation, Shipping, and Storage

Once all of the samples were collected for a given sampling period, the samples were prepared for shipping or testing. Containers that were filled with samples were each emptied into a two-gallon, heavy-duty, plastic bag, which was labeled with the material type, date of sampling, and time of sampling.

In many cases, single discrete specimens were tested by the external laboratory. In this case, a small portion (approximately two kilograms) was removed from the sample bag, placed into a separate bag, labeled with a sample identification number, and sent directly to the external laboratory. Many of the samples were not tested as discrete specimens, but as composite specimens produced over either an entire day of sampling, or over a three-day period of sampling. In order to produce composite specimens, a small quantity (approximately one half kilogram) was taken from each of the sample bags pertaining to the composite period, and placed into a five-gallon bucket. Once the bucket was filled with all the appropriate samples, it was rolled on its side 60 feet in one direction and back again along same path. This method was used to minimize the human interference in the composite specimen creation process. Once the material had been thoroughly mixed, two kilograms were removed, placed in a plastic bag, and labeled.

Once all of the composite specimens were produced, and all necessary specimens (both composite and discrete) had been bagged and labeled, they were placed into boxes and sent to the external lab for testing. For the sake of possible future testing, the samples originally collected at the plant were only partially used for testing. Approximately two kilograms of each sample were stored in a cool, dry place indefinitely. The specimens that were tested by the cement plant were not prepared by Auburn University staff.

3.3.3 Analyzing the Chemical Composition of Raw Materials

There were seven raw materials that were tested. The raw materials' sources and names were not used, because that information is proprietary information of the cement plant. The primary raw material sampled and tested was known as the kiln feed(labeled Raw Material Seven), which was produced by combining Raw Materials One through Five in closely controlled proportions. The kiln feed, Raw Material Seven, was sampled at a frequency of two times a day over the standard sampling period. Each of the discrete samples was tested by the cement plant as described later in this section. Additionally, after each of the discrete samples was collected, a single composite specimen was prepared, in accordance with Section 3.3.2, over each three-day period during the standard sampling period. These composite specimens were tested by the external laboratory as described below.

In addition to the kiln feed, each of the individual raw materials from which it is composed, Raw Materials One through Five,was sampled and tested. The samples of these individual raw materials were collected less frequently than the kiln feed. A single discrete sample of each was collected during every burn. Both the cement plant and the external laboratory tested these discrete specimens as described below.

The final raw material collected and tested was Raw Material Six, which was mixed with the clinker, prior to grinding, to produce portland cement. The frequency of sampling for Raw Material Six was one discrete sample collected during the grinding process for each of the burn phases. A single discrete specimen was tested by both the cement plant and the external laboratory as described below.

The test specimens for each of the raw materials were analyzed for the standard parameters shown in Table 3.1 by XRF, with the exception of Raw Material Three. The chemical composition of Raw Material Three was not determined by XRF, but instead by a Prompt Gamma Neutron Activation Analyzer (PGNAA), which was capable of determining these concentrations in real time. This device determined the concentration of all of the standard cement plant parameters shown in Table 3.1, except for moisture and loss on ignition (LOI).

3.3.4 Analyzing the Chemical Composition of Fuel Sources

Each of the six fuel sources was sampled at different frequencies. Although the quantity of testing was different for each of the fuels, the actual tests conducted were the same.

Coal, the primary fuel source, was sampled twice a day over the standard sampling period. Three-day composites were then prepared from the discrete samples in accordance with Section 3.3.2. These composites were tested by the external laboratory as described below. A single discrete specimen was tested by the cement plant as described below.

Tires were sampled by collecting eight different tires during each burn. From these tires, eight discrete radial sections were removed, one section from each tire. These radial sections were then cut down into one inch square pieces, which were made into individual composite specimens to be tested by the external laboratory alone. Tires were sampled once during each burn in which they were used.

Sampling of all the alternative fuels was the same. Eight discrete samples were taken for each fuel in a single day. These samples were collected only in the burn phase to which they applied. Each of the discrete specimens was tested by the external laboratory only. In addition, two of the discrete samples from each day were tested in duplicate in order to ensure accuracy.

The testing of the fuel sources at the external laboratory was the same for all of the fuels. First, an XRF scan was conducted on the specimen. Then, proximate and ultimate analyses were conducted on each sample. A detailed list of the data collected in each of these analyses is shown in Table 3.3. In addition to the proximate and ultimate analyses, a combustion analysis was conducted to determine the energy content (BTU/lb) of the fuel. Once this test was completed, the ash was analyzed, by XRF, in order to determine the concentration of the standard parameters shown in Table 3.1. The cement plant did not conduct any tests on the tires, plastics, broiler litter, woodchips or switchgrass. For the coal, the cement plant conducted the same tests as the external laboratory.

Table 3.3: Proximate and Ultimate Analysis Details

Proximate Analysis (wt %)	Ultimate Analysis (wt. %)
Moisture	Hydrogen
Ash	Carbon
Volatile Matter	Nirtogen
Fixed Carbon	Sulphur
	Oxygen
	Ash
	Moisture

3.3.5 Analyzing the Chemical Composition of Cement Kiln Dust

The cement kiln dust (CKD) was sampled twice a day over the standard sampling period. These discrete specimens were tested without making composite samples.

The standard parameters shown in Table 3.1 were determined by XRF at the cement plant and at the external laboratory. At the cement plant, moisture and loss on ignition were not determined. The standard external laboratory parameters were all tested for, with no exceptions or additions.

3.3.6 Analyzing the Chemical Composition of Clinker

Clinker was sampled at the cement plant twelve times per day in accordance with Section 3.3.1. The standard sampling period was used for collection of clinker samples.

The standard cement plant parameters, as shown in Table 3.1, were determined for each of the discrete specimens collected. In addition to the standard cement plant elements, the equivalent alkali content and Bogue compounds content were calculated in accordance with ASTM C 150. The cement plant also determined the free lime (FCaO) content in each of these discrete specimens.

In addition to the tests conducted at the cement plant, Rietveld Analysis was also conducted on clinker samples by the cement plant's specialty lab**.** Reitveld Analysis is a procedure used to determine the Bogue compounds more accurately than the formulas given by ASTM C 150. This test was conducted on one composite specimen per day, which was created in accordance with Section 3.3.2**,** using each of the twelve discrete samples collected during that day.

Finally, the standard external laboratory parameters, as shown in Table 3.1, were determined by XRF. These determinations were made on single-day composite specimens, prepared in accordance with Section 3.3.2, using all twelve of the discrete samples from that day. Each of the daily composite specimens was tested for the standard external laboratory elements twice.

3.3.7 Analyzing the Chemical Composition of Cement

Portland cement was sampled at the cement plant eight times per day, in accordance with Section 3.3.1. The standard sampling period was used for collection of cement samples.

The standard cement plant parameters, as shown in Table 3.1, were determined on each of the discrete specimens collected, as well as on daily composites made from each of the discrete samples. In both cases, the equivalent alkali content and Bogue compounds content were calculated in accordance with ASTM C 150. Additionally, the free lime content and Blaine specific surface area were determined.

In addition to the tests conducted at the cement plant, Rietveld Analysis was conducted on cement samples by the cement plant's specialty lab. This test was conducted on one composite specimen per day, which was created by the process described in Section 3.3.2**,** using each of the eight discrete samples collected during that day.

Finally, the standard external laboratory parameters, shown in Table 3.1, were determined by XRF. These determinations were made on single-day composite specimens prepared using all eight of the discrete samples from that day. In addition to the standard external laboratory elements, the total organic carbon (TOC) content was determined on each of the daily composites using a TOC analyzer.

3.3.8 Analyzing the Physical Properties of Cement

The cement samples collected were also used to conduct physical property testing. The physical properties of cement were tested by three different entities: the cement plant, Auburn University, and the cement plant's specialty lab. All of the tests conducted by the cement plant were conducted on one-day composite specimens prepared from the eight daily discrete samples. Auburn University tested a single composite specimen prepared for each of the burns. The physical property tests of cement performed by Auburn University, the cement plant, and the cement plant's specialty laboratory are shown in Tables 3.4, 3.5, and 3.6 respectively. These tables also show the specifications and units associated with each test.

Table 3.4: Cement Physical Property Tests Performed by Auburn University

Property	Units	ASTM Specification
Autoclave Expansion	%	C 151
Cube Flow	%	C 230
Compressive Strength at	MPa	C 109
Normal Consistency	%	C 187
Gillmore Initial Set	Min	C 266
Gillmore Final Set	Min	C 266
Vicat Initial Set	Min	C 191
Vicat Final Set	Min	C 191
Drying Shrinkage Development	%	C 596

Table 3.5: Cement Physical Property Tests Performed by Cement Plant

Property	Units	ASTM Specification
Air in Mortar	%	C 185
Blaine Specific Surface Area	m^2/kg	C 204
Autoclave Expansion	%	C 151
Cube Flow	%	C 230
Compressive Strength at 1, 3, 7, and 28 days	MPa	C 109
Normal Consistency	%	C 187
Gillmore Initial Set	Min	C 266
Gillmore Final Set	Min	C 266
Vicat Initial Set	Min	C 191
Vicat Final Set	Min	C 191

Table 3.6: Cement Physical Property Tests Performed by Cement Plant's Specialty Laboratory

Property	ASTM Specification
Particle Size Distribution	Laser Diffraction

3.3.9 Analyzing the Properties of Concrete

For each of the burns, cement was used to make concrete in an attempt to establish any links between the fuels and the properties of concrete. The bulk cement from C burn was collected at the end of the grinding period through the typical bagging process used at the cement plant. The cement from each of the subsequent burns was collected by making a composite specimen over the entire burn using the samples taken at each of the discrete sampling times.

There were two different mixture designs from which concrete was made using the cement from each burn. The primary mixture design, named Mix A, is shown in

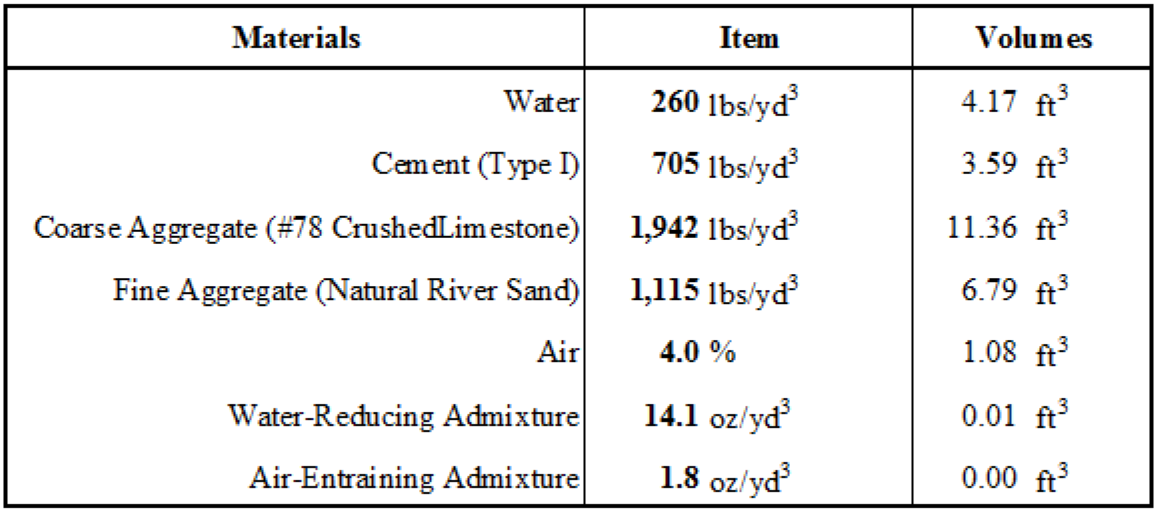
Table 3.7. Mix A had a water-to-cement ratio of 0.44, and used #57 crushed limestone and a natural river sand as the aggregate. The secondary mixture design, named Mix B, is shown in Table 3.8. The water-to-cement ratio in Mix B was 0.37, and utilized #78 crushed limestone and a natural river sand as the aggregate. In an attempt to eliminate the variability in aggregates, enough of each was collected from the same source on the same date to make all the concrete for all burns.

Table 3.7: Mix A Proportions (w/c = 0.44)

Materials	Item	Volumes
Water	**273** lbs/yd^3	4.38 ft^3
Cement (Type I)	**620** lbs/yd^3	3.15 ft^3
Coarse Aggregate (# 57 Crushed Limestone)	**1,900** lbs/yd^3	10.61 ft^3
Fine Aggregate (Natural River Sand)	**1,272** lbs/yd^3	7.78 ft^3
Air	**4.0** %	1.08 ft^3
Air-Entraining Admixture	**1.2** oz/yd^3	0.00 ft^3

Mix A was produced by Auburn University and the cement plant's specialty lab. The aggregate used by the cement plant for Mix A was collected and provided by personnel at Auburn University. All the tests conducted by both entities, as well as those conducted only by Auburn University are listed in Table 3.9. The specification associated with each test is also shown.

Table 3.8: Mix B Proportions (w/c = 0.37)



Materials	Item	Volumes
Water	**260** lbs/yd^3	4.17 ft^3
Cement (Type I)	**705** lbs/yd^3	3.59 ft^3
Coarse Aggregate (#78 CrushedLimestone)	**1,942** lbs/yd^3	11.36 ft^3
Fine Aggregate (Natural River Sand)	**1,115** lbs/yd^3	6.79 ft^3
Air	**4.0** %	1.08 ft^3
Water-Reducing Admixture	**14.1** oz/yd^3	0.01 ft^3
Air-Entraining Admixture	**1.8** oz/yd^3	0.00 ft^3

The typical concrete mixture at Auburn University was made by preparing enough material, in the proportions shown in Table 3.7 or Table 3.8, to produce 6.5 ft^3 of concrete. Once the concrete had been mixed, a slump test and total air content test were conducted in accordance with ASTM C 143 and ASTM C 231, respectively. Next, a setting time test specimen was prepared in accordance with ASTM C 403. The following step was to prepare three 3 x 3 x 11.25-inch bars to be used in the drying shrinkage development test (ASTM C 157). Finally, one 6-in. x 12-in. cylinder was prepared for the heat of hydration under semi-adiabatic conditions test, along with ten 6-in. x 12-in. cylinders for both compressive strength (ASTM C 39) and splitting tensile strength (ASTM C 496) tests. Two cylinders were tested at each age for each test. Additionally, six 4-in. x 8-in. cylinders were prepared in order to conduct the rapid chloride ion permeability (RCPT) test at 91 and 365 days. The various concrete tests that were conducted are listed in Table 3.9.

Table 3.9. Concrete Tests

Tests Conducted by Both Entities	
Test	**Specification**
Slump	ASTM C 143
Setting Time	ASTM C 403
Total Air Content	ASTM C 231
Compressive Strength at 1, 3, 7, 28, and 91 days	ASTM C 39
Drying Shrinkage Development	ASTM C 157
Permeability (RCPT)	ASTM C 1202

Tests Only Conducted at Auburn University	
Test	**Specification**
Heat of Hydration (Semi-Adiabatic)	Rilem 119-TCE
Splitting Tensile Strength at 1, 3, 7, 28, and 91 days	ASTM C 496

3.3.10 Analyzing the Emissions

The emissions were collected by the cement plant using a Continuous Emissions Monitoring System (CEMS). Although the emissions were continuously monitored, they were reported as an hourly average. The sampling period for emissions was four days before, during, and two days after each burn as shown in Figure 3.2.

The emissions that were monitored from the main stack were carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOC).

3.4 Conclusion

The test procedure described in the previous sections was developed to provide the most complete data possible regarding the effects of the alternative fuels on the production process, as well as on the products themselves. All materials involved in the production process were sampled and tested. These included the raw materials, fuels, and CKD. Also, all of the products of the process were sampled. These included clinker, portland cement, and emissions. A chemical analysis was conducted on each of the materials listed above in order to determine any variations that may be attributed to the utilization of the alternative fuels. Additionally, special testing was conducted to determine any effects that the fuels may have had on concrete produced using the portland cement collected from each burn.

CHAPTER 4

PRESENTATION AND ANALYSIS OF DATA

4.1 Introduction

This chapter presents the collected data along with an analysis and discussion of the results. The data pertaining to each material tested follow the same order described in Chapter Three. For the discussion of each material, there are three objectives to be met: presentation of data, analysis of data, and discussion of results. For each material, the results presented by the various testing laboratories are discussed separately. Comparisons are made between results from different testing laboratories when it is deemed necessary.

Since this effort is a continuation of the research initiated by Swart (2007), the data and results from his thesis are directly used for study and comparison. Swart only investigated the use of scrap tires and waste plastics as fuels in cement manufacturing; in this study, broiler litter, woodchips and switchgrass are also being investigated. In order to gain better insight into the potential of alternative fuel options through comparison, the data from all the alternative fuel burns including scrap tires and waste plastics fuel burns are presented and discussed in this document.

Swart (2007) had remarked that due to the delays between the trial burns and the changes introduced into the production process at the cement plant in those delay periods, it had become difficult to conclusively evaluate the possible effect of alternative fuels on the various process outputs (i.e. clinker, cement, CKD and emissions). To address this concern to an extent, two additional baseline burns (coal and tires burns) closer to the alternative fuel trial burns were conducted, whenever it was found to be necessary. All non-baseline burns will be referred to as Fuel Burns from here onwards. As already mentioned in Section 3.1, the following notations shall refer to the different trial burns conducted:

1. **C** burn utilized only coal as fuel.
2. **CT1** burn utilized coal and tires. This is the standard fuel combination used at the cement plant, and was therefore considered the baseline for comparison purposes. This is the first baseline burn. This is the baseline burn exclusively for the **C** burn.
3. **CTP** burn used coal, tires, and waste plastics. Waste plastics were the first alternative fuel tested.
4. **CT2** burn utilized coal and tires. Again, this is the second baseline burn with standard fuel combination. This is the baseline burn exclusively for the **CTP** burn.
5. **CTB** burn used coal, tires, and broiler litter. Broiler litter was the second alternative fuel tested.
6. **CT3** burn utilized coal and tires. Again, the standard fuel combination was used and this is the third baseline burn. This is the baseline burn for the **CTB**, **CTW**, and **CTS** burns.

7. **CTW** burn used coal, tires, and woodchips. Woodchips was the third alternative fuel tested.
8. **CTS** burn used coal, tires, and switchgrass. Switchgrass was the fourth alternative fuel tested.

Due to economic constraints and lack of availability of adequate storage for isolation and grinding of the produced clinker, cement was not sampled or tested for CT2 and CT3 burns. However, all the raw materials, fuels, CKD, emissions and the primary product, clinker, were sampled and tested for chemical properties.

Over the project period, it was realized that the emissions were actually more sensitive to the raw material and fuel composition changes than the clinker or cement properties. This could be due to the fact that certain volatile compounds or elements present, even if in trace amounts, in the process inputs may directly end up in emissions as a major constituent of emissions, which are in amounts in the order of one millionth ton per hour, whereas the same constituents may not have as significant an effect on clinker or cement, which is produced in amounts in the order of 200 tons per hour.

To estimate the effects of alternative fuels on the process outputs at different levels, a new analysis approach was developed, based on the available budget constraints, data limitations, and the individual product sensitivities to the fuels. Figure 4.1 depicts the actual analysis methodology adopted for studying the effects on various process inputs and outputs in the alternative fuel trial burns. In the figure, the baseline burn for the individual fuel or group of fuels is represented by gray shading in its box. The results for all the process inputs and outputs except fuels and cement for all the fuel burns were compared to the respective baseline burns. Fuel data will be presented for all burns in Section 4.3.3. Comparisons were made for all burns, wherever applicable. Cement and concrete properties for all the fuel burns were analyzed using CT1 burn as the baseline burn (Swart 2007).

In this chapter, graphical representations are presented showing the difference in means between each of the burns relative to its own baseline burn (coal and tires burn). Since the cement plant, during its normal operations, uses coal and scrap tires as the fuel, it was decided to use this fuel combination as the baseline for comparison.

The final objective of this chapter is to discuss the results. In this section, an emphasis is placed on the tests or parameters that showed the greatest change in means. Any conclusions that can be drawn for the cause of these changes are presented. A discussion of whether the findings of this project agree or disagree with the literature presented in Chapter Two is given.

The previous chapters in this document address the utilization of four alternative fuels. It was the aim of this study to produce portland cement using all the alternative fuels and to evaluate the properties of concrete made from these cement. However, certain results concerned with long-term durability of concrete like later-age drying shrinkage and permeability for later trial burns could not be obtained within the timeframe necessary to be presented and discussed in this document. Since this study will continue, the complete data associated with those burns will be presented in future documentation related to this project.

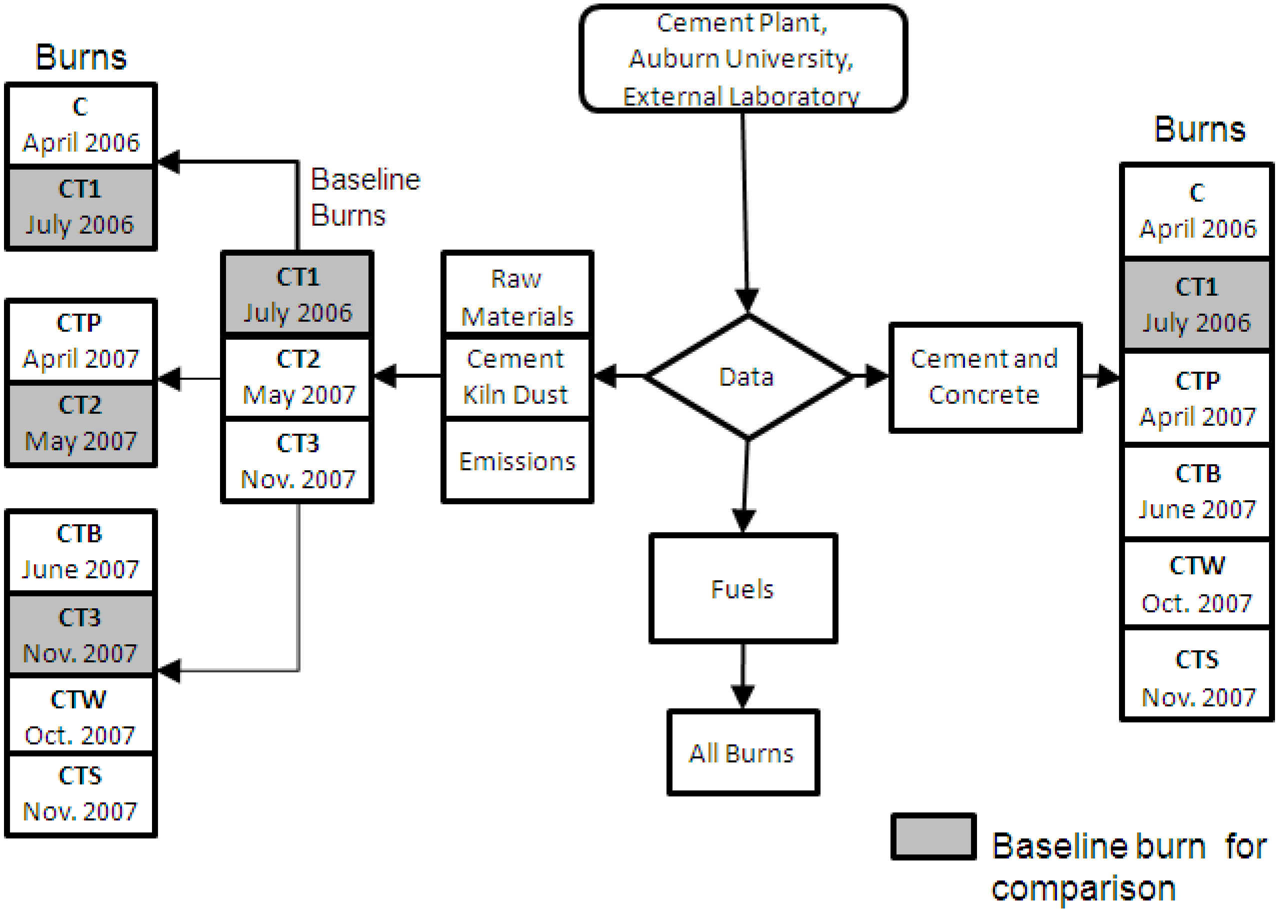


Figure 4.1: Analysis method for the burn data

4.2 Use of Statistics to analyze data

In this chapter, the data pertaining to each test or parameter for every material are presented. When there are ten or more data points for a set of results, a complete set of summary statistics is also presented along with the data

The summary statistics consist of the average, coefficient of variation (as a percentage), and an indication of how well the data are represented by a normal distribution based on Anderson-darling statistic (Section 4.2.1). The coefficient of variation is calculated by dividing the standard deviation of the data set by the average (arithmetic mean), and is reported as a percentage. If the minimum requirement for summary statistics is not met, only the average value is presented. The complete data sets for which only summary statistics are given are shown in Appendices B.1 through B.8. Further, when ten or more data points for two comparable set of results are available, they are tested for significance of the difference (Two-sample t-test) in the means of each data set.

Both the Anderson-Darling test and the Two-sample t-test are based on the *Test of hypotheses* method in which there are two competing hypotheses under consideration. Initially, one of the hypotheses, the *Null Hypothesis* (H_0), is assumed to be correct. Then evidence from the sample data is obtained and the null hypothesis is rejected in favor of the competing claim, called the *Alternative Hypothesis* (H_a), only if there is convincing evidence against the null hypothesis (Devore 2005).

The evidence obtained is in form a p-value, which represents the probability of failing to reject the null hypothesis. A small p-value is an indication that the null hypothesis is false and hence can be rejected in favor of the alternative hypothesis (Minitab 2006).

4.2.1 Anderson-Darling Normality Test

The Anderson-Darling normality test is used to assess whether the data comes from a normal distribution. It uses a sample's p-value to measure whether sample data is normal. P-value is the probability that the sample being tested was drawn from a population with a normal distribution.

The hypotheses in Anderson-Darling test (Minitab 2006) are defined as:

H_0: The data follow a normal distribution.

H_a: The data do not follow a normal distribution

where, H_0 – Null Hypothesis

H_a– Alternative Hypothesis

The p-values are obtained from running the test in Minitab 15.1.0.0 software. If the p-value is less than 0.10, which corresponds to 90% confidence level, the null hypothesis is likely to be false and differences between the sample data sets (one being the test sample data and the data from a pre-defined normal distribution) are likely to exist, and hence the data cannot be assumed to be normally distributed, which is the alternative hypothesis (Romeu 2003).

As the P-value obtained for the normality test decreases, the coefficient of variation becomes less meaningful (Devore 2005). For this reason, when the P-value is below the limiting value of 0.10, the data are considered not normally distributed, and the coefficient of variation is noted with a superscript.

4.2.2 Test for Significant difference

To assess the difference in means of various parameters obtained from each burn with respect to its baseline burn, the Two-sample t-test was run on the sample data sets. The test assumes null and alternative hypotheses and produces a p-value corresponding to the sample data, which as discussed earlier, represents the probability of failing to reject the null hypothesis (i.e. in this particular case, the probability of the null hypothesis being true).

The hypotheses of the test in the context of the experiment (Minitab 2006) are defined as:

H_0: The means of two sample data sets are equal

H_a: The means of two sample data sets are not equal

where, H_0 – Null Hypothesis

H_a– Alternative Hypothesis

In this context, the p-value is a measure of how much evidence we have *against* the assumption that the two data sets that are being compared are identical. The limiting p-value used for determination of statistical significance was selected to be 0.10, which corresponds to 90 % confidence level. This was done because the sample sizes for all materials except emissions were considered to be small to very small. It means that any p-value above this limiting value will imply that the difference in means for that specific result is *not* statistically significant or a p-value of less than 0.10 will help reject the null hypothesis and suggests that there is a significant difference in means of the two sample data sets (Devore 2005).

While using this test in the context of the experiment, it must be noted that just because some sample data sets for any parameter show a statistically significant difference, it may not mean that the parameter shows a difference of practical significance. Practical significance is determined by the performance of the cement, and whether a statistically significant difference in a parameter significantly alters the behavior of the cement.

4.3 Plant Operations

Each of the trial burns lasted a total of three days, with the exception of the CTS burn, which lasted only for two days due to insufficient in-time supply of switchgrass. Considerable time elapsed between each burn, which allowed the cement plant to establish its typical production process without the influence of the additional testing and fuel usage associated with this study. Furthermore, because the cement plant is concerned with its production, many aspects of the production process like kiln feed rate, fuel feed rates, and production rates were changed relative to each burn, in order to assure maximum production. Since these aspects of the production process are proprietary information, the ranges for each of these parameters are given, instead of the averages. A summary of plant conditions during each of the burns is presented in Table 4.1.

The cement plant was able to start using alternative fuels with minimal impact on its operations. Equipment had to be installed to help shred, store, meter (by weight), and feed the various alternative fuels into the precalciner. The quantity of tires that could be burned was limited by the development of sulfur build-ups within the system, which limited the airflow, and effectively choked the system. These build-ups were primarily composed of sulfur-derived compounds, and were directly responsible for limiting the air flow through the kiln, which reduced oxygen levels necessary for good combustion in the kiln. The feed rates of tires for the CTS burn reported in Table 4.1 are unusually high, which may be an anomaly arisen from malfunctioning of the weighing scale, as suggested by the cement plant personnel.

The introduction of waste plastics into the system was affected by the ability of the fuel feed equipment to convey the low-density material into the precalciner. The average density of waste plastics was measured to be 5.26 lb/ft^3, which is very low and resulted in low feed rates for the waste plastics. Broiler litter handled easily and did not cause any problems while in use. The major concern with woodchips was the high moisture content. However, woodchips burned well and did not cause any problems in the plant operation. Switchgrass preprocessing was labor-intensive, especially with the shredding of huge bales, before feeding into the system. But it flowed smoothly once shredded and did not cause any problems. The feed rate was limited due to its low density.

4.4 Data Presentation and Analysis

For all of the tables and figures presented in this chapter, a specific terminology will be implemented in order to designate the origin of the data.

- Cement plant results (CPR) refers to data that were obtained from the cement plants laboratory.
- Auburn University results (AUR) refers to data that were collected at Auburn University.
- External laboratory results (ELR) are those that were collected at the external laboratory.
- Specialty laboratory results (SLR) are those that were collected at the cement plant's specialty laboratory.

The external laboratory provided results concerning all chemical compositions. Although more parameters were reported by the external laboratory than by the cement plant, only the major parameters (those which are measured as percent by weight) are discussed in most cases. The major parameters were determined by both the cement plant and the external laboratory.

In all tables that present summary statistics, the abbreviation C.V. stands for coefficient of variation and % Diff. stands for a percent difference. This percent difference is relative to the results of the baseline burn, from the testing agency in question. For instance, in any given table of results as presented by the cement plant (or external laboratory), the percent difference is relative to the baseline, as reported by the cement plant (or external laboratory).

As discussed earlier in Section 4.2, the summary statistics do not include the coefficient of variation or the p-value from the normality test for data sets that contain less than ten data points. The same limit is utilized for determining statistically significant differences relative to a baseline burn. Even though statistical significance is not reported for such small data sets, a graphical representation of percent difference between *means relative to baseline burn* is given. These percent difference plots may show the results from different testing agencies. Once again, these differences are relative to the baseline burn as reported by the testing agency in question. In the plots of percent difference for chemical compositions, the same major parameters are plotted. These major parameters are Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, SiO_2, and SO_3.

First, for every material composition and property discussed, the results of the baseline burns, CT2 burn and CT3 burn are compared to those from CT1 burn. This helps in determining if the plant conditions have indeed changed between the burn conditions that used the same fuel, i.e. coal and scrap tires (baseline burns). Then, the fuel burns are compared to the respective baseline burns to determine if any observable changes occurred in the properties.

Table 4.1: Summary of plant conditions during each trial burn

Item	Burn Type							
	C	CT1 [b]	CTP	CT2 [b]	CTB	CT3 [b]	CTW	CTS
Period	April 18 to 21, 2006	July 11 to 14, 2006	April 3 to 7, 2007	May 16 to 19, 2007	June 19 to 22, 2007	Aug. 13 to 16, 2007	Oct. 16 to 19, 2007	Nov. 27 to 29, 2007
Kiln Feed Rate (tons/hr)	250 to 310	90 to 330	260 to 330	266 to 336	215 to 345	275 to 328	248 to 307	266 to 300
Clinker Production Rate (tons/hr)	160 to 200	100 to 200	170 to 240	147 to 275	127 to 249	119 to 223	118 to 228	133 to 219
Coal Feed Rate (tons/hr)	18 to 20	10 to 20	10 to 20	14 to 21	11 to 18	13 to 22	10 to 17	12 to 18
Tire Feed Rate (tons/hr)	-	0.0 to 1.4	0.3 to 4.0	0.1 to 3.0	0.1 to 1.0	0.1 to 6.1	0.1 to 2	0.1 to 17
Tire-to-Fuel Replacement Rate (%) [a]	-	1 to 10	2.0 to 8.0	0.1 to 4.5	0.1 to 4.4	0.1 to 4.8	0.5 to 13	0.3 to 52
Plastics Feed Rate (tons/hr)	-	-	2.5 to 3.5	-	-		-	-
Plastics-to-Fuel Replacement Rate (%) [a]	-	-	12 to 22.5	-	-		-	-
Broiler Litter Feed Rate (tons/hr)	-	-	-	-	1.7 to 3.0	-	-	-
Broiler Litter-to-Fuel Replacement Rate (%)	-	-	-	-	5.0 to 7.5	-	-	-
Woodchips Feed Rate (tons/hr)	-	-	-	-	-	-	2.1 to 3.6	-
Woodchips-to-Fuel Replacement Rate (%) [a]	-	-	-	-	-	-	2.8 to 9.7	-
Switchgrass Feed Rate (tons/hr)	-	-	-	-	-	-	-	1.9 to 2.5
Switchgrass-to-Fuel Replacement Rate (%)	-	-	-	-	-	-	-	2.6 to 9.1

[a] Reported as an energy replacement basis

[b] Baseline burns

4.3.1 Chemical Composition of Raw Materials

The chemical compositions of the raw materials were tested using XRF by both the cement plant and the external laboratory. The kiln feed is obtained by blending various raw materials, and it becomes the primary material entering the kiln; therefore, only a single specimen of each of the individual raw materials was tested during each burn. In Tables 4.2 to 4.5, the percentage difference in chemical composition of Raw Materials One, Two, Three, Four, Five and Six from CT2 and CT3 burns relative to CT1 burn are shown. These raw materials are not identified because the cement plant considered this to be confidential information. In the tables, the percentage difference value is reported as NA (not applicable) wherever the data is not available or was not detected. The raw material data for CTS burn from the cement plant is not reported since it was not collected by the cement plant. The cement plant also did not test for the compositions of Raw Material Three for some of the burns. However, all the raw material data is tested for and reported by the external laboratory.

From the data it can be deduced that the raw material composition used in the baseline burns are varied greatly. This justifies the use of different baselines for comparison of data collected from different trial burns. Although the percent change of each parameter is presented for the raw materials, no conclusions can be drawn based on these data alone.

Table 4.2: CPR- Baseline Burns, Percentage change in Raw Materials One, Two and Three relative to CT1 burn

Parameter	Percent Difference Relative to CT1 burn					
	Raw Material One		Raw Material Two		Raw Material Three	
	CT2 burn	CT3 burn	CT2 burn	CT3 burn	CT2 burn	CT3 burn
Al_2O_3	4.8	-3.9	130.0	183.7	NA	NA
CaO	-31.1	65.1	-2.0	-2.8	NA	NA
Fe_2O_3	-76.9	-59.1	-100.0	-100.0	NA	NA
K_2O	12.5	-10.1	700.0	860.0	NA	NA
MgO	-11.0	33.9	26.3	89.5	NA	NA
Na_2O	-25.0	-26.0	NA	NA	NA	NA
SiO_2	28.5	16.3	115.3	149.4	NA	NA
SO_3	-23.1	-46.4	-84.8	-89.8	NA	NA
Moisture	51.9	-33.4	72.2	100.0	NA	NA
LOI	-40.7	-26.1	1.2	-0.2	NA	NA

Notes: NA - Not Applicable

Table 4.3: CPR- Baseline Burns, Percentage change in Raw Materials Four, Five and Six relative to CT1 burn

Parameter	Percent Difference Relative to CT1 burn					
	Raw Material Four		Raw Material Five		Raw Material Six	
	CT2 burn	CT3 burn	CT2 burn	CT3 burn	CT2 burn	CT3 burn
Al_2O_3	68.8	68.8	102.6	23.2	-60.4	-58.4
CaO	-9.7	-3.4	132.4	-36.6	48.5	40.9
Fe_2O_3	-32.8	-43.2	NA	NA	63.3	NA
K_2O	400.0	160.0	18.8	13.1	-52.6	-38.4
MgO	23.1	17.3	384.2	-57.4	-63.6	-58.7
Na_2O	NA	NA	NA	NA	NA	NA
SiO_2	44.2	41.2	-4.9	2.8	-58.1	-60.6
SO_3	52.6	55.7	252.7	86.6	14.2	12.6
Moisture	NA	61.4	14.0	55.8	187.4	190.8
LOI	NA	19.6	-72.4	-74.4	-77.9	-58.6

Notes: NA - Not Applicable

Table 4.4: ELR- Baseline Burns, Percentage change in Raw Materials One, Two and Three relative to CT1 burn

Property	**Percent Difference Relative to CT1 burn**					
	Raw Material One		**Raw Material Two**		**Raw Material Three**	
	CT2 burn	**CT3 burn**	**CT2 burn**	**CT3 burn**	**CT2 burn**	**CT3 burn**
Al_2O_3	11.5	11.50	2611	822.1	-40.1	-11.39
CaO	3.1	9.60	64.0	71.82	99.1	80.36
Fe_2O_3	12.6	10.51	560.7	71.85	-18.2	-3.87
K_2O	24.8	12.85	399.7	86.96	25.5	14.54
MgO	36.8	35.64	115	145.4	105.3	48.79
Na_2O	-12.3	-11.91	133.2	375.9	-51.9	70.74
P_2O_5	1.3	7.98	NA	NA	-79.4	-21.60
SiO_2	17.4	18.16	826.6	363.4	-12.4	11.37
SO_3	14.8	75.98	33.7	-2.02	-43.3	-2.00
TiO_2	25.8	18.69	NA	NA	-77.0	-72.33
Moisture	-8.9	-33.12	14807	15529	128.3	490.5
LOI	-45.3	-29.99	-6.1	0.23	11.6	14.88
As	18.9	20.16	NA	NA	-72.5	-11.14
Ba	52.3	39.03	465.8	126.3	-13.6	2.45
Cd	NA	NA	NA	NA	NA	NA
Cl	-39.2	-27.20	-85.3	-86.79	-81.0	-76.58
Co	47.8	41.62	NA	NA	NA	NA
Cr	17.3	25.39	NA	NA	-27.8	4.99
Cu	-8.1	-27.28	NA	NA	NA	NA
Hg	NA	34100	NA	6300	NA	4267
Mn	65.7	132.0	1010	455.0	162.4	211.1
Mo	NA	NA	NA	NA	NA	NA
Ni	6.1	0.13	NA	NA	NA	-40.55
Pb	18.8	-13.33	NA	NA	NA	-79.67
Sb	NA	NA	NA	NA	NA	NA
Se	NA	-23.12	NA	NA	NA	NA
Sr	45.6	38.33	166.9	122.4	54.7	93.33
V	20.4	16.17	NA	NA	-65.5	-47.46
Zn	4.3	-2.90	-68.8	-61.76	-91.6	-25.40

Notes: NA - Not Applicable

Table 4.5: ELR- Baseline Burns, Percentage change in Raw Materials Four, Five and Six relative to CT1 burn

Property	Percent Difference Relative to CT1 burn					
	Raw Material Four		Raw Material Five		Raw Material Six	
	CT2 burn	CT3 burn	CT2 burn	CT3 burn	CT2 burn	CT3 burn
Al_2O_3	15.5	73.60	-28.6	-73.91	-27.3	11.70
CaO	10.1	-1.02	1005.7	-4.23	39.5	30.77
Fe_2O_3	-23.8	-27.76	195.1	-63.93	40.0	49.81
K_2O	-5.4	86.08	-53.8	-61.20	-7.8	-5.38
MgO	7.3	15.26	723.1	-17.23	-14.9	-12.17
Na_2O	57.6	-68.99	-71.2	-73.40	-1.2	-5.38
P_2O_5	-21.5	-18.00	34.4	-100	-100	26.16
SiO_2	-6.5	9.57	-6.7	3.63	-4.1	-2.34
SO_3	54.3	188.9	303.1	-100	21.1	26.42
TiO_2	-5.4	15.37	-36.5	-34.48	31.7	26.16
Moisture	667.3	1282	-18.7	3.16	2327	1029
LOI	NA	NA	-55.2	-76.93	-64.6	-33.69
As	NA	NA	-28.0	NA	NA	NA
Ba	ND	NA	NA	NA	NA	NA
Cd	NA	NA	NA	NA	NA	NA
Cl	-87.4	-44.12	-28.8	-79.66	-84.8	-81.90
Co	NA	NA	NA	NA	NA	NA
Cr	-22.2	-18.11	NA	NA	NA	NA
Cu	-46.0	-24.68	NA	162.7	NA	NA
Hg	NA	1820	NA	6700	NA	477.8
Mn	124.7	103.9	8742	284.4	143.7	21.84
Mo	58.0	-37.53	NA	NA	NA	NA
Ni	209.5	365.2	NA	-60.09	NA	NA
Pb	NA	NA	-37.0	62.95	-65.8	NA
Sb	NA	NA	NA	NA	NA	NA
Se	NA	94.87	279.3	NA	NA	NA
Sr	77.2	77.15	-18.3	-18.25	41.4	94.40
V	-0.9	-1.26	NA	NA	NA	NA
Zn	-39.4	22.16	-100.0	0.87	NA	NA

Notes: NA - Not Applicable

Tables 4.6 to 4.11 present the percentage change in each parameter of raw materials one to six, for each burn relative to its *own baseline burn*.

Table 4.6: CPR- Fuel Burns, Percentage change in Raw Material One composition from each burn relative to its baseline burn

Parameter	**Percent Change Relative to Baselines**				
	Raw Material One				
	C burn[1]	**CTP burn[2]**	**CTB burn[3]**	**CTW burn[3]**	**CTS burn[3]**
Al_2O_3	13.2	-2.8	16.4	16.4	NA
CaO	-9.8	41.4	-58.6	-62.1	NA
Fe_2O_3	10.0	573.4	-86.8	88.7	NA
K_2O	23.6	-8.1	40.6	20.9	NA
MgO	11.0	127.8	-30.1	-29.5	NA
Na_2O	-5.0	40.0	26.7	28.4	NA
SiO_2	-2.7	-25.4	8.8	-4.0	NA
SO_3	-45.5	-86.0	12.3	-58.3	NA
Moisture	-54.2	15.0	140.2	140.2	NA
LOI	-22.0	2.9	-14.0	2.3	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.7: CPR- Fuel Burns, Percentage change in Raw Material Two composition from each burn relative to its baseline burn

Parameter	Percent Change Relative to Baselines				
	Raw Material Two				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	10.0	-43.5	8.1	-53.0	NA
CaO	-0.2	-0.3	-2.3	-1.4	NA
Fe_2O_3	-17.6	NA	NA	NA	NA
K_2O	600.0	-12.5	-19.8	-27.1	NA
MgO	21.1	-19.2	-5.6	-46.1	NA
Na_2O	NA	NA	NA	NA	NA
SiO_2	12.9	11.5	6.1	-5.7	NA
SO_3	-82.9	-37.5	-41.1	21.5	NA
Moisture	222.2	-3.2	-16.7	-2.8	NA
LOI	1.7	0.5	2.6	-0.5	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.8: CPR- Fuel Burns, Percentage change in Raw Material Three composition from each burn relative to its baseline burn

Parameter	Percent Change Relative to Baselines				
	Raw Material Three				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	-15.2	NA	NA	NA	NA
CaO	1.5	NA	NA	NA	NA
Fe_2O_3	14.0	NA	NA	NA	NA
K_2O	5.9	NA	NA	NA	NA
MgO	0.6	NA	NA	NA	NA
Na_2O	-85.7	NA	NA	NA	NA
SiO_2	-2.4	NA	NA	NA	NA
SO_3	-14.3	NA	NA	NA	NA
Moisture	NA	NA	NA	NA	NA
LOI	NA	NA	NA	NA	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.9: CPR- Fuel Burns, Percentage change in Raw Material Four composition from each burn relative to its baseline burn

Parameter	Percent Change Relative to Baselines				
	Raw Material Four				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	-32.8	-28.3	-11.0	-41.9	NA
CaO	-17.7	20.2	13.6	-2.2	NA
Fe_2O_3	38.8	-13.7	-3.5	93.6	NA
K_2O	850.0	-50.0	130.8	-61.5	NA
MgO	-15.4	0.8	-1.6	-5.5	NA
Na_2O	NA	NA	NA	NA	NA
SiO_2	-6.7	3.4	2.6	-44.5	NA
SO_3	110.6	-55.4	-15.9	-28.6	NA
Moisture	79.4	NA	-36.1	NA	NA
LOI	62.5	NA	-86.4	96.8	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.10: CPR- Fuel Burns, Percentage change in Raw Material Five composition from each burn relative to its baseline burn

Parameter	Percent Change Relative to Baselines				
	Raw Material Five				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	135.5	-26.0	13.2	22.9	NA
CaO	-59.7	-66.9	-34.1	16.8	NA
Fe_2O_3	18.6	NA	NA	NA	NA
K_2O	100.0	47.4	-17.1	10.5	NA
MgO	-57.9	-79.3	4.9	146.9	NA
Na_2O	NA	NA	NA	NA	NA
SiO_2	1.6	9.4	1.1	1.1	NA
SO_3	-66.1	-94.7	-33.0	-90.4	NA
Moisture	79.1	-30.6	-38.8	-47.8	NA
LOI	-69.2	-7.0	25.0	0.0	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.11: CPR- Fuel Burns, Percentage change in Raw Material Six composition from each burn relative to its baseline burn

Parameter	Percent Change Relative to Baselines				
	Raw Material Six				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	-53.5	254.2	-3.9	221.3	NA
CaO	26.5	-24.6	5.9	-23.2	NA
Fe_2O_3	50.0	-49.0	NA	NA	NA
K_2O	-42.1	177.8	-19.7	113.7	NA
MgO	-25.0	517.6	6.4	462.3	NA
Na_2O	NA	NA	NA	NA	NA
SiO_2	-51.1	297.7	-9.0	323.7	NA
SO_3	6.6	-26.6	0.6	-29.7	NA
Moisture	41.4	-58.4	4.3	-60.0	NA
LOI	-30.6	192.3	-31.5	57.8	NA

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

The proportion of each material that was combined to produce the kiln feed was not provided by the cement plant, because it is proprietary information. This is the reason for emphasizing the chemical composition of the kiln feed above that of the individual raw materials. This is also the reason that no graphical representation of the percent changes is presented in this report.

Tables 4.12 to 4.17 present the percentage change in Raw Materials One to Six compositions for each burn relative to the appropriate baseline burn as reported by the external laboratory. The actual raw data for all the burns can be found in Appendix B.

Table 4.12: ELR- Fuel Burns, Percentage change in Raw Material One composition from each burn relative to its baseline burn

Property	Percent Difference Relative to Baseline burns				
	Raw Material One				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	2.9	0.10	1.9	-12.5	-3.7
CaO	7.8	13.32	0.7	-1.8	-16.4
Fe_2O_3	-9.2	-0.03	-4.6	-21.7	-14.3
K_2O	-0.3	-4.38	8.7	-8.0	-5.7
MgO	18.4	4.14	-3.3	-23.3	-15.0
Na_2O	-4.2	23.33	4.2	-12.0	59.5
P_2O_5	11.3	10.31	-2.0	-14.6	-11.3
SiO_2	0.8	-0.79	-1.0	-15.9	-6.3
SO_3	106.8	-46.82	54.7	-34.5	-46.0
TiO_2	4.4	-1.12	11.2	-8.2	-7.4
Moisture	-25.2	3.26	32.5	38.3	45.9
LOI	-5.0	63.17	-12.7	60.2	-26.9
As	26.5	83.57	3.4	-16.8	9.9
Ba	23.6	-13.04	14.3	-4.8	-4.8
Cd	NA	NA	NA	NA	NA
Cl	-81.6	-67.11	-80.2	-60.4	-15.4
Co	-5.3	-3.95	5.3	0.2	15.9
Cr	3.0	27.96	-2.2	29.7	-7.4
Cu	34.4	19.00	28.0	-0.5	-4.6
Hg	600.0	NA	NA	-97.1	-98.7
Mn	-7.3	100.00	-42.9	-42.9	-14.3
Mo	NA	122.47	8.7	76.9	-64.6
Ni	-1.1	1.19	8.7	-0.6	13.4
Pb	-6.1	145.83	21.8	26.2	83.2
Sb	NA	NA	NA	NA	NA
Se	34.0	NA	100.0	50.0	NA
Sr	4.3	-10.00	10.5	-26.3	-31.6
V	12.1	-0.23	4.5	-1.7	5.6
Zn	-44.2	131.90	-3.2	-2.5	4.3

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.13: ELR- Fuel Burns, Percentage change in Raw Material Two composition from each burn relative to its baseline burn

Property	Percent Difference Relative to Baseline burns				
	Raw Material Two				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	179.7	-53.24	-6.8	-52.6	-58.9
CaO	-8.1	2.01	0.0	-43.2	-43.1
Fe_2O_3	-13.7	-53.93	46.2	-39.7	-62.3
K_2O	-2.3	-53.35	10.6	-46.6	-55.5
MgO	-6.8	71.71	9.8	-50.5	-31.7
Na_2O	-100.0	683.1	-74.7	-83.7	-10.2
P_2O_5	NA	-77.78	NA	NA	NA
SiO_2	4.7	-36.88	-8.2	-47.0	-70.4
SO_3	-15.9	2.54	-34.8	-37.0	-23.0
TiO_2	NA	-100.0	NA	NA	NA
Moisture	16650	29.61	-88.6	20.3	-31.2
LOI	10.2	5.52	-4.5	0.3	0.4
As	NA	99.95	NA	NA	NA
Ba	-23.4	-40.00	0.0	-50.0	-50.0
Cd	NA	NA	NA	NA	NA
Cl	-90.9	-25.64	31.4	14.3	34.3
Co	NA	-20.02	204.1	-51.0	-2.0
Cr	NA	-11.13	-17.6	210.2	79.6
Cu	NA	299.9	-32.4	NA	NA
Hg	-66.7	NA	NA	-94.8	-95.6
Mn	33.2	50.00	100.0	0.0	0.0
Mo	NA	NA	NA	NA	NA
Ni	NA	NA	NA	NA	-13.8
Pb	-2.3	NA	NA	NA	NA
Sb	-59.9	NA	NA	NA	NA
Se	NA	NA	NA	NA	NA
Sr	-23.4	-33.33	20.0	-40.0	-60.0
V	NA	-33.35	-49.3	-61.4	-52.5
Zn	NA	246.58	373.0	NA	NA

Notes: NA - Not Applicable

[1] Relative to CT1 burn

[2] Relative to CT2 burn

[3] Relative to CT3 burn

Table 4.14: ELR- Fuel Burns, Percentage change in Raw Material Three composition from each burn relative to its baseline burn

Property	**Percent Difference Relative to Baseline burns**				
	Raw Material Three				
	C burn[1]	**CTP burn[2]**	**CTB burn[3]**	**CTW burn[3]**	**CTS burn[3]**
Al_2O_3	-39.3	153.71	42.9	-13.0	24.9
CaO	19.4	-38.94	-25.6	-39.5	-47.9
Fe_2O_3	-31.4	58.06	148.8	-29.0	-0.6
K_2O	-16.2	36.33	39.4	49.4	97.0
MgO	-1.2	-23.44	140.4	86.8	6.2
Na_2O	-100.0	189.78	59.3	-70.3	100.4
P_2O_5	-43.5	216.12	73.5	-79.2	-37.6
SiO_2	-28.0	112.40	30.4	-40.9	-2.8
SO_3	20.0	-13.79	-15.7	16.4	-41.8
TiO_2	-78.4	78.86	44.6	-51.5	-16.9
Moisture	1250.9	750.37	21.2	97.5	209.1
LOI	10.2	-19.74	-29.1	0.9	-14.7
As	-62.3	354.42	23.9	-38.9	-14.4
Ba	8.0	18.58	59.0	-33.3	0.0
Cd	NA	NA	NA	NA	NA
Cl	-73.4	13.33	13.5	67.6	21.6
Co	NA	7.77	54.9	-22.1	120.8
Cr	52.6	85.55	238.0	93.7	25.2
Cu	NA	202.95	-18.4	NA	NA
Hg	33.3	NA	NA	-92.4	-94.7
Mn	730.2	374.31	1000	-66.7	0.0
Mo	NA	NA	-38.0	55.9	NA
Ni	NA	NA	71.6	-20.1	83.9
Pb	-63.4	NA	135.5	-58.4	222.2
Sb	176.2	NA	NA	NA	NA
Se	NA	NA	NA	NA	NA
Sr	-7.2	0.00	20.0	-60.0	-80.0
V	-51.8	108.87	66.0	-7.2	13.2
Zn	-70.3	584.93	-38.0	-54.0	-48.0

Notes: NA - Not Applicable [1] Relative to CT1 burn
[2] Relative to CT2 burn [3] Relative to CT3 burn

Table 4.15: ELR- Fuel Burns, Percentage change in Raw Material Four composition from each burn relative to its baseline burn

Property	Percent Difference Relative to Baseline burns				
	Raw Material Four				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	-6.7	-5.18	-16.0	-17.7	-54.1
CaO	-82.4	-16.83	5.6	110.5	14.1
Fe_2O_3	31.2	10.89	-2.3	-90.0	3.6
K_2O	2465.4	586.9	1.4	1017	-82.5
MgO	-86.1	-5.15	-11.0	-85.8	-5.3
Na_2O	555.0	167.9	204.2	737.8	1156.6
P_2O_5	-7.0	-1.17	-8.3	-91.9	30.9
SiO_2	9.3	32.00	10.0	30.6	-6.6
SO_3	253.3	-0.28	4.9	-45.0	-27.2
TiO_2	-37.8	3.04	-8.4	-5.4	-18.9
Moisture	3867	148.8	23.1	64.4	0.0
LOI	NA	-336.6	110.5	68.8	-85.4
As	NA	-58.78	30.4	94.5	4.7
Ba	NA	-31.03	0.0	50.0	-50.0
Cd	91.0	NA	NA	NA	NA
Cl	-52.1	233.3	-24.1	0.8	-27.1
Co	NA	-62.53	-11.3	-54.2	24.4
Cr	-89.3	56.36	-1.6	-93.3	12.2
Cu	2426	423.8	252.0	NA	NA
Hg	-80.0	NA	NA	-79.2	-67.7
Mn	-59.5	-11.99	5.0	-98.0	-12.5
Mo	-74.3	-20.74	7.9	NA	15.9
Ni	1604	114.7	-29.9	-86.7	12143
Pb	3269.4	NA	NA	NA	NA
Sb	NA	NA	NA	NA	NA
Se	-18.1	NA	NA	NA	NA
Sr	-25.1	-33.33	0.0	33.3	-33.3
V	-85.8	-11.22	-12.7	-90.0	13.9
Zn	4707.4	142.88	15.6	-77.5	-40.9

Notes: NA - Not Applicable

[1] Relative to CT1 burn

[2] Relative to CT2 burn

[3] Relative to CT3 burn

Table 4.16: ELR- Fuel Burns, Percentage change in Raw Material Five composition for each burn relative to its baseline burn

Property	Percent Difference Relative to Baseline burns				
	Raw Material Five				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	-23.3	-27.06	32.3	25.8	69.7
CaO	-48.5	-89.95	14.6	1.8	-54.7
Fe_2O_3	-21.9	-82.92	70.0	-26.6	-64.5
K_2O	68.8	45.41	21.9	52.8	42.6
MgO	56.3	-88.48	23.0	-61.8	-49.1
Na_2O	-100.0	88.18	228.1	1.8	1784.0
P_2O_5	-62.5	-100.00	NA	NA	NA
SiO_2	0.9	10.14	-0.6	-0.3	-0.6
SO_3	2263.7	-100.00	NA	NA	NA
TiO_2	50.1	10.69	-11.2	1.8	7.2
Moisture	2.7	-32.90	-35.2	-31.6	-57.0
LOI	-51.4	-15.55	37.6	-15.7	40.5
As	NA	-24.73	NA	NA	NA
Ba	NA	NA	NA	NA	NA
Cd	NA	NA	NA	NA	NA
Cl	-27.1	-69.05	483.3	700.0	625.0
Co	NA	-5.91	NA	NA	NA
Cr	NA	-95.91	724.8	1081.3	409.2
Cu	-23.6	NA	-69.2	NA	NA
Hg	0.0	NA	NA	-85.3	-91.5
Mn	96.2	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ni	NA	NA	NA	NA	NA
Pb	378.4	69.36	74.1	NA	74.6
Sb	NA	NA	NA	NA	NA
Se	NA	NA	NA	NA	NA
Sr	-59.2	NA	NA	NA	NA
V	NA	-88.24	17.2	-4.5	-30.0
Zn	528.4	NA	-78.4	NA	NA

Notes: NA - Not Applicable

[1] Relative to CT1 burn

[2] Relative to CT2 burn

[3] Relative to CT3 burn

Table 4.17: ELR- Fuel Burns, Percentage change in Raw Material Six composition from each burn relative to its baseline burn

Property	Percent Difference Relative to Baseline burns				
	Raw Material Six				
	C burn[1]	CTP burn[2]	CTB burn[3]	CTW burn[3]	CTS burn[3]
Al_2O_3	61.5	391.79	-36.2	-19.6	NA
CaO	7.8	-9.99	6.3	-18.5	NA
Fe_2O_3	192.0	41.44	-15.0	24.2	NA
K_2O	-15.1	78.62	-9.7	-6.3	NA
MgO	140.6	424.28	-5.3	57.1	NA
Na_2O	-46.9	156.48	4.2	100.9	NA
P_2O_5	324.7	NA	4.2	0.4	NA
SiO_2	29.6	201.08	-15.5	-11.2	NA
SO_3	-7.9	-18.72	-2.7	-17.8	NA
TiO_2	218.5	380.90	-47.9	50.7	NA
Moisture	162.0	-79.03	76.9	-100.0	NA
LOI	-11.1	145.90	-49.1	24.5	NA
As	NA	NA	NA	NA	NA
Ba	NA	NA	NA	NA	NA
Cd	NA	NA	NA	NA	NA
Cl	-93.3	87.50	21.1	-42.1	NA
Co	NA	236.63	NA	NA	NA
Cr	NA	NA	NA	693.5	NA
Cu	NA	NA	NA	NA	NA
Hg	0.0	NA	NA	-90.4	NA
Mn	314.5	NA	NA	NA	NA
Mo	NA	NA	NA	NA	NA
Ni	NA	NA	NA	NA	NA
Pb	-64.6	216.02	NA	NA	NA
Sb	NA	NA	NA	NA	NA
Se	NA	NA	NA	NA	NA
Sr	1.3	NA	NA	NA	NA
V	NA	57.39	30.3	84.1	NA
Zn	NA	NA	NA	NA	NA

Notes: NA - Not Applicable

[1] Relative to CT1 burn

[2] Relative to CT2 burn

[3] Relative to CT3 burn

4.3.2 Chemical Composition of Kiln Feed

The kiln feed is the primary input to the production process. The chemical composition of the kiln feed, reported by the cement plant, was obtained by sampling twice a day during each burn. The average percent by weight (wt. %) and the coefficient of variation (C.V. %) for all the samples collected for each burn as reported by the cement plant are tabulated in Table 4.18.

Since the number of data points for kiln feed composition was about six on average, the p-values for the test for normality of the distribution may not be valid and hence have not been reported. Nevertheless, the coefficient of variation can provide a measure of variation in the distribution and the nature of the data, i.e. the higher the C.V. value, the higher the variability of data. However, the coefficient of variation does not provide meaningful conclusions when the mean is a small number (Devore 2005), as in the case of Na_2O or SO_3 in Table 4.18. The data for all other parameters in the kiln feed have small C.V. values, which suggest limited variability in these data.

The percentage difference in the parameters of kiln feed composition as reported by the cement plant for the baseline burns relative to CT1 burn is shown in Table 4.19. The same data as reported by the external laboratory is presented in Table 4.20. The kiln feed was analyzed by the external laboratory in the form of a single composite sample collected during each burn.

The cement plant results for the kiln feed composition for the baseline burns in Table 4.19 does not show much variability, despite the variation in the actual raw materials noticed in Section 4.3.1.

This perhaps reflects the effort of the cement plant operators that try to maintain the kiln feed composition by varying the proportions of raw material. However, the external laboratory results of the same material reported in Table 4.20 show a completely different picture. The variation in the proportions of major parameters, CaO and SiO_2, over the baseline burns is quite significant.

As observed from the percentage differences in Table 4.20, it can be seen that the kiln feed compositions were different for each baseline burn. It only validates the method of applying different baseline references for analysis of fuel burns data.

The percentage differences found in the kiln feed composition of the fuel burns relative to the respective baseline burns as reported by the cement plant is presented in Table 4.21.The percentage differences in the major components in the kiln feed for the burns from Table 4.21 are plotted and presented in Figure 4.2. The high values of percentage difference in Na_2O_{eq} and SO_3 are not of practical significance since the mean values are so small that even a slight difference gets projected as a large percentage.

The major parameters of the kiln feed, CaO and SiO_2, from fuel burns showed less than 5% variation relative to their respective baseline burns. Kiln feed being the primary process input, keeping its composition fairly comparable to the control burn (baseline burn) renders the experimental setup valid for studying the effect of fuels on process outputs through comparison with the baseline burn results.

The results of the XRF scan conducted by the external laboratory, along with the percent differences relative to respective baseline burns are shown in Table 4.22.

Table 4.18: CPR- All burns, kiln feed composition

Parameter	C burn		CT1 burn		CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)	Average (wt. %)	C.V. (%)
Al_2O_3	3.11	2.4	3.23	2.6	3.02	2.1	3.07	2.1	3.12	0.8	2.97	2.4	2.97	2.6	3.11	2.6
CaO	43.95	0.5	43.05	0.8	43.74	0.6	43.71	0.2	43.42	0.4	43.41	0.6	43.03	0.2	42.70	0.4
Fe_2O_3	2.04	3.9	2.02	3.2	1.90	4.0	2.01	3.2	1.88	1.0	1.98	3.8	1.91	2.5	2.03	0.9
K_2O	0.33	2.9	0.30	5.3	0.29	1.7	0.32	6.7	0.40	4.0	0.29	5.7	0.34	7.1	0.38	3.3
MgO	1.92	2.4	2.51	6.6	2.07	2.9	2.09	4.6	1.96	5.8	1.93	4.0	1.96	2.2	1.89	0.9
Na_2O	0.05	14.4	0.10	18.6	0.04	17.8	0.03	15.0	0.05	18.6	0.03	0.0	0.16	7.7	0.05	16.3
Na_2O_{eq}	0.27	4.2	0.30	5.3	0.23	3.9	0.25	6.5	0.31	3.2	0.23	12.5	0.39	3.9	0.30	5.4
SiO_2	13.67	1.1	14.38	1.7	13.67	1.4	13.18	1.5	13.04	1.2	13.09	1.2	13.44	1.3	13.70	0.5
SO_3	0.29	12.4	0.29	12.1	0.12	18.3	0.17	12.9	0.22	5.3	0.26	7.5	0.21	3.6	0.21	2.8
LOI	36.59	0.4	35.05	1.2	34.73	0.7	NR	NA	36.21	0.7	35.04	0.3	35.00	0.0	35.00	0.0

Notes: NR - Not Reported NA - Not Applicable

These results are comparable to the cement plant results except for the results from CTW and CTS burns. Kiln feed from CTW burn and CTS burn, tested at the external laboratory, seem to have lowered content for almost all the parameters except moisture.

Table 4.19: CPR- Baseline Burns, Percentage difference in kiln feed composition relative to CT1 burn

Parameter	CT1 burn	CT2 burn		CT3 burn	
	Average (wt. %)	Average (wt. %)	Percent Difference	Average (wt. %)	Percent Difference
Al_2O_3	3.23	3.07	-5.09	2.97	-8.01
CaO	43.05	43.71	1.54	43.41	0.83
Fe_2O_3	2.02	2.01	-0.29	1.98	-1.64
K_2O	0.30	0.32	9.60	0.29	-3.15
MgO	2.51	2.09	-16.94	1.93	-22.96
Na_2O	0.10	0.03	-67.74	0.03	-70.97
Na_2O_{eq}	0.30	0.25	-16.76	0.23	-22.52
SiO_2	14.38	13.18	-8.39	13.09	-8.99
SO_3	0.29	0.17	-40.91	0.26	-11.85
LOI	35.05	NR	NA	35.04	-0.04

Table 4.20: ELR- Baseline Burns, Percentage difference in kiln feed composition relative to CT1 burn

Parameter	**CT1 burn**	**CT2 burn**		**CT3 burn**	
	Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Al_2O_3	2.75	4.09	48.4	4.46	62.0
CaO	40.23	64.08	59.3	63.62	58.1
Fe_2O_3	1.92	3.11	61.9	3.03	57.8
K_2O	0.29	0.46	57.5	0.42	45.2
MgO	2.08	3.18	52.6	3.41	63.4
Na_2O	0.03	0.08	134.2	0.08	129.6
P_2O_5	0.04	0.05	7.1	0.07	60.7
SiO_2	17.00	24.18	42.2	23.84	40.2
SO_3	0.24	0.26	9.9	0.53	121.4
TiO_2	0.21	0.26	28.3	0.27	29.1
Moisture	0.19	0.31	66.3	0.14	-23.5
LOI	35.19	33.30	-5.4	34.70	-1.4
	Value (ppm)	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**
As	13	23	78.4	23	76.0
Ba	257	200	-22.0	300	17.0
Cd	ND	ND	NA	ND	NA
Cl	76	97	27.6	105	38.2
Co	21	14	-33.1	10	-52.2
Cr	60	96	60.6	106	77.1
Cu	ND	28	NA	56	NA
Hg	0.10	ND	NA	1	430.0
Mn	317	1800	469	2000	532
Mo	ND	ND	NA	ND	NA
Ni	15	5	-68.5	16	8.0
Pb	9	ND	NA	17	77.4
Sb	88	NR	NA	NR	NA
Se	ND	3	NA	ND	NA
Sr	229	500	118.3	500	118.3
V	48	61	26.7	72	49.6
Zn	106	21	-80.6	300	182.3

Notes: ND - Not Detected NA - Not Applicable

Table 4.21: CPR- Fuel Burns, Percentage difference in kiln feed composition relative to baseline burns

Parameter	C burn	CTP burn	CTB burn	CTW burn	CTS burn
	Percent Difference[1]	Percent Difference[2]	Percent Difference[3]	Percent Difference[3]	Percent Difference[3]
Al_2O_3	-3.72	-1.53	18.38	0.00	4.75
CaO	2.09	0.07	3.75	-0.87	-1.63
Fe_2O_3	1.10	-5.33	-10.07	-3.46	2.13
K_2O	13.22	-11.19	2.80	20.50	33.88
MgO	-23.45	-0.54	0.41	1.40	-2.16
Na_2O	-54.52	32.86	0.08	428.57	66.67
Na_2O_{eq}	-9.15	-5.75	2.50	69.17	31.25
SiO_2	-4.95	3.74	-4.36	2.66	4.68
SO_3	-0.11	-32.42	-0.70	-19.89	-20.72
LOI	4.38	NA	NA	-0.11	-0.11

Notes: NA - Not Applicable

[1] Relative to CT1 burn

[2] Relative to CT2 burn

[3] Relative to CT3 burn

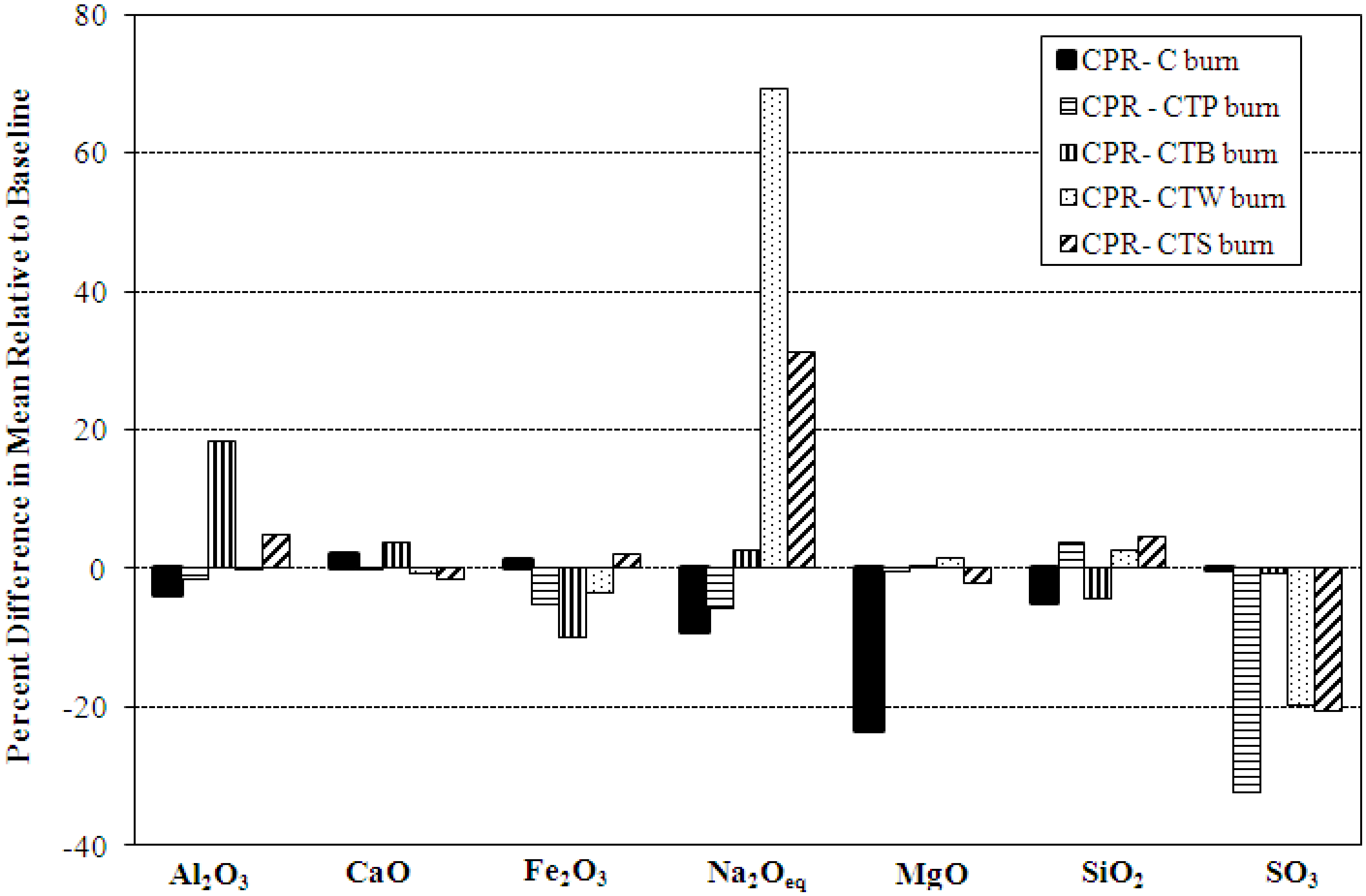


Figure 4.2: CPR-Fuel Burns, Percentage difference in kiln feed composition relative to baseline burns

Table 4.22: ELR- Fuel Burns, Percentage difference in kiln feed composition relative to baseline burns

Parameter	C burn		CTP burn		CTB burn		CTS burn		CTW burn	
	Value (wt %)	% Diff. [1]	Value (wt %)	% Diff. [2]	Value (wt %)	% Diff.[3]	Value (wt %)	% Diff.[3]	Value (wt %)	% Diff.[3]
Al_2O_3	3.05	10.6	4.91	20.1	4.41	-1.2	2.96	-33.6	3.26	-26.9
CaO	44.18	9.8	65.27	1.9	67.86	6.7	41.36	-35.0	42.69	-32.9
Fe_2O_3	2.15	12.1	3.01	-3.3	3.05	0.5	1.83	-39.7	2.00	-34.1
K_2O	0.33	12.5	0.50	8.9	0.57	35.0	0.32	-24.4	0.37	-12.6
MgO	1.90	-8.7	3.35	5.3	3.15	-7.6	2.04	-40.1	2.07	-39.2
Na_2O	0.01	-70.9	0.02	-76.4	0.05	-35.5	0.05	-36.5	0.20	153.9
P_2O_5	0.05	22.4	0.07	52.4	0.05	-26.3	0.02	-71.0	0.05	-27.5
SiO_2	13.38	-21.3	21.87	-9.6	19.97	-16.2	13.26	-44.4	13.95	-41.5
SO_3	0.35	47.6	0.34	28.8	0.37	-30.7	0.21	-60.5	0.33	-37.9
TiO_2	0.17	-17.1	0.24	-9.1	0.24	-9.2	0.15	-43.6	0.14	-47.3
Moisture	0.06	-67.8	0.10	-67.8	0.27	89.6	0.23	61.2	0.18	26.2
LOI	34.44	-2.1	34.67	4.1	32.72	-5.7	37.63	8.4	34.81	0.3
	Value (ppm)	**% Diff. [1]**	**Value (ppm)**	**% Diff. [2]**	**Value (wt %)**	**% Diff.[3]**	**Value (ppm)**	**% Diff.[3]**	**Value (ppm)**	**% Diff.[3]**
As	3	-79.6	18	-21.6	23	0.9	17	-24.9	26	14.8
Ba	192	-25.3	400	100.0	400	33.3	200	-33.3	200	-33.3
Cd	ND	NA	NR	NA	ND	NA	ND	NA	ND	NA
Cl	111	46.1	63	-35.1	84	-20.0	192	82.9	182	73.3
Co	ND	NA	14	1.6	11	16.1	8	-18.8	14	42.2
Cr	51	-14.7	86	-10.8	108	1.5	159	49.5	107	0.6
Cu	43	NA	41	48.8	18	-68.3	ND	NA	ND	NA
Hg	0.02	-80.0	NR	NA	ND	NA	0.30	-43.4	0	-89.4
Mn	664	109.9	1700	-5.6	1700	-15.0	1100	-45.0	1000	-50.0
Mo	ND	NA	16	NA	ND	NA	3	NA	15	NA
Ni	ND	NA	12	161.3	8	-51.6	ND	NA	1640	NA
Pb	24	150.5	ND	NA	4	-77.2	12	-28.3	ND	NA
Sb	33	-62.5	NR	NA	ND	NA	NR	NA	NR	NA
Se	1	NA	NR	NA	ND	NA	ND	NA	ND	NA
Sr	261	13.8	500	0.0	500	0.0	200	-60.0	300	-40.0
V	39	-18.0	73	20.0	70	-2.8	61	-15.1	66	-8.2
Zn	113	6.2	37	79.0	118	-60.7	33	-89.0	34	-88.7

Notes: NA - Not Applicable NR - Not Reported ND - Not Detected CIP-Collection in Progress

[1] Relative to CT1 burn [2] Relative to CT2 burn [3] Relative to CT3 burn

4.3.3 Fuels

Fuels samples were collected by Auburn University and tested at the external laboratory. Coal was the only fuel tested at both the cement plant and the external laboratory. In this section, the chemical composition and properties of the fuels used in the burns will be discussed in detail. Firstly, the composition and properties of coal will be discussed followed by that of scrap tires, waste plastics, broiler litter, woodchips, and switchgrass.

At the specific cement plant where the 3-day trials were conducted, the following specifications were targeted for the as-received alternative fuels:

- energy value ≥ 5,000 BTUs/lb (11.6 MJ/kg),
- chlorine content ≤ 0.2 percent,
- sulfur content ≤ 2.0 percent,
- nitrogen content ≤ 1.4 percent,
- moisture content ≤ 14 percent, and
- ash content ≤ 18 percent.

The average heat values of all the fuels used in the burns are shown in Figure 4.3. These values were determined by combustion analysis and reported by the external laboratory. It must be noted that these values for all the fuels are in the expected range based on the review of literature, presented in Section 2.3.4.

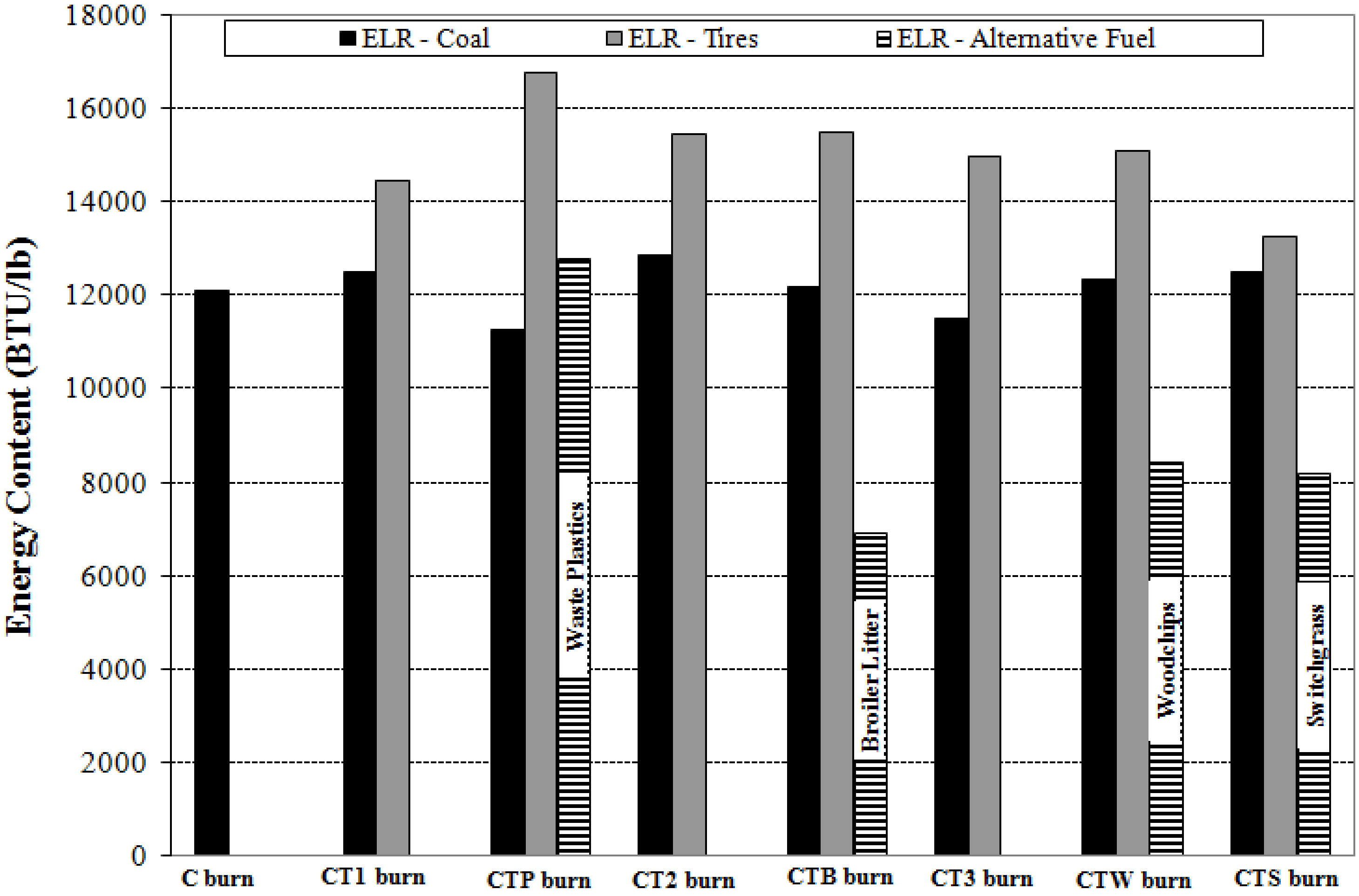


Figure 4.3: ELR: Dry Heat Values of the fuels

4.3.3.1 Coal

Pulverized coal is the primary fuel used to produce clinker from the kiln feed at the cement plant. Proximate, ultimate, and combustion analyses were conducted by the cement plant. These analyses were conducted on a dry basis, which means the tests were done after all moisture had been removed.

Additionally, the standard cement plant parameters were determined. These parameters were determined on the ash from the fuels. This was done because it is the ash from the fuels which is actually incorporated into the clinker. Each of these tests was conducted on a single sample during each burn. The results of these tests, along with the percent differences for all the burns relative to CT1 burn are presented in Table 4.23. Unfortunately, the coal sources have been changed from time to time, during the course of the project. This decision was made with production and economic issues in mind. It is reflected in Table 4.23. The percentage differences of parameters of coal from all the fuel burns relative to CT1 burn have inconsistently wide ranges, making it difficult to group results for any particular baselines burns. For instance, the Fe_2O_3 content in coal from CTP burn was 481 percent higher while the CaO content in coal from CTW burn was 92 percent lower. In addition, the baseline burns have less than 15 percent variation in Fe_2O_3 and less than 10 percent variation in CaO content. Similar observations can be made for different parameters in different burns. This is the reason why the coal compositions from all burn are presented together and compared to that from CT1 burn as a single reference base.

It can be seen that the weight percentage of volatile matter was fairly similar for all burns, with less than 14 percent difference which is also reflected in the heat values, which is, in fact, helpful in comparison of fuel replacement rates of alternative fuels based on total energy replacement.

Similar trends can be found in the coal data from the external laboratory based on composite samples of coal. These data are presented in Tables 4.24 and 4.25. The results from the proximate and ultimate analyses are shown in Table 4.24. The standard parameters in chemical composition of coal are shown in Table 4.25.

4.3.3.2 Scrap tires

The scrap tires as fuel in combination with coal have been used at the cement plant for quite some time. The initial investments in setting up the conveying and feeding system for scrap tires and the favorable results found from CT1 burn have encouraged the cement plant to use the fuel combination on a regular basis.

Scrap tires are not tested for their chemical composition by the cement plant. However, they were sampled by Auburn University, and tested by the external laboratory. The samples were collected by randomly removing eight tires from the feed stream, removing a radial section of each tire, reducing each section to one inch squares, and making a single composite specimen from the pieces. One composite sample per burn, prepared in this manner, was tested by the external laboratory. A proximate, ultimate, and combustion analysis were conducted on this sample. Additionally, a XRF scan was used to determine the standard external laboratory parameters.

The results from the proximate, ultimate, and combustion analyses, as conducted by the external laboratory for all burn samples, are shown in Table 4.26. The percent differences relative to CT1 burn are also shown.

Table 4.23: CPR –All Burns, Chemical analysis of coal and percent difference relative to CT1 burn

Test	Parameter	C burn		CT1 burn	CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
		Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Proximate Analysis	**Ash**	18.9	6.1	17.8	23.4	31.5	16.2	-9.3	18.8	5.4	23.3	30.6	18.8	5.4	17.8	-0.2
	Fixed Carbon	50.2	-3.6	52.1	48.4	-7.0	54.9	5.4	53.9	3.5	55.7	7.1	53.5	2.7	54.5	4.7
	Volatile Matter	30.9	2.7	30.1	28.1	-6.6	29.0	-3.9	27.4	-9.2	26.0	-13.7	27.7	-7.9	27.7	-8.0
Ultimate Analysis	**Carbon**	69.1	-3.0	71.2	64.4	-9.5	72.6	2.1	70.3	-1.3	59.9	-15.9	53.5	-24.9	72.5	1.9
	Hydrogen	4.3	-2.1	4.3	4.0	-7.6	4.4	0.9	4.3	-1.2	4.1	-6.5	4.4	1.2	4.4	0.7
	Nitrogen	1.5	4.1	1.5	1.3	-9.7	1.4	-4.1	1.4	-4.8	1.3	-12.4	1.3	-9.7	1.3	-8.3
	Oxygen	5.2	41.5	3.7	3.1	-17.3	3.6	-3.5	3.6	-2.2	3.3	-9.9	3.2	-12.5	2.7	-28.2
	Sulfur	1.1	-30.7	1.5	3.8	147.7	2.7	77.8	2.6	69.9	2.6	67.5	1.4	-7.8	1.4	-11.1
Standard Parameters	Al_2O_3	24.7	5.2	23.5	15.4	-34.2	21.6	-7.9	24.0	2.5	23.3	-0.8	28.9	23.3	22.7	-3.0
	CaO	13.3	4.6	12.7	3.2	-74.6	7.8	-38.5	6.3	-50.5	6.9	-45.5	1.0	-92.5	8.2	-35.9
	Fe_2O_3	5.8	-6.6	6.2	36.2	480.8	15.7	152.2	9.9	58.0	7.7	22.7	7.5	19.9	7.9	27.2
	K_2O	2.0	-8.8	2.2	1.9	-10.2	2.1	-5.1	2.3	7.9	2.8	30.2	3.3	50.9	2.7	23.1
	MgO	1.2	-20.8	1.5	1.0	-30.2	1.0	-30.9	1.1	-26.2	1.1	-24.6	1.2	-19.5	1.1	-28.2
	Na_2O	0.4	25.8	0.3	0.4	16.1	0.2	-51.6	0.2	-45.2	0.1	-55.9	0.4	38.7	0.2	-48.4
	SiO_2	42.9	-7.2	46.2	36.2	-21.7	43.4	-6.2	48.1	4.1	50.3	8.9	55.6	20.2	48.8	5.7
	SO_3	8.4	12.8	7.4	4.4	-40.6	6.8	-8.2	6.5	-12.1	6.4	-13.5	1.0	-86.4	7.0	-5.3
Heat Value [1]		12102	-3.2	12506	11255	-10.0	12864	2.9	12169	-2.7	11481	-8.2	12321	-1.5	12495	-0.1

Notes: [1] **Value is Reported as BTU/lb**

Table 4.24: ELR –All Burns, Proximate and Ultimate analyses of coal and percent difference relative to CT1 burn

Test	Parameter	C burn		CT1 burn	CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
		Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Proximate Analysis	**Ash**	22.45	34.1	16.74	24.54	46.6	14.51	-13.3	17.65	5.4	26.2	56.5	17.59	-21.6	16.45	-1.7
	Fixed Carbon	49.58	-9.5	54.81	47.68	-13.0	30.19	-44.9	53.61	-2.2	47.39	-13.5	53.8	8.5	55.19	0.7
	Volatile Matter	27.97	-1.7	28.45	27.78	-2.4	55.3	94.4	28.73	1.0	26.41	-7.2	28.61	2.3	28.36	-0.3
Ultimate Analysis	**Carbon**	67.61	-7.5	73.09	64.68	-11.5	72.24	-1.2	69.84	-4.4	63.96	-12.5	71.06	5.1	71.33	-2.4
	Hydrogen	3.61	-22.5	4.66	3.93	-15.7	3.71	-20.4	3.59	-23.0	3.57	-23.4	4.16	15.2	3.75	-19.5
	Nitrogen	1.1	-9.8	1.22	1.08	-11.5	0.5	-59.0	0.59	-51.6	1.45	18.9	1.48	34.5	0.96	-21.3
	Oxygen	3.95	25.8	3.14	4.11	30.9	7.49	138.5	6.77	115.6	3.55	13.1	4.57	15.7	6.41	104.1
	Sulfur	1.28	11.3	1.15	1.66	44.3	1.55	34.8	1.55	34.8	1.27	10.4	1.14	-10.9	1.1	-4.3
Heat Value [1]		11698	-7.3	12624	11369	-9.9	12864	1.9	12431	-1.5	11204	-11.2	12445	6.4	12664	0.3

Notes: [1] **Value is Reported as BTU/lb**

Table 4.25: ELR –All burns, Chemical analysis of coal and percent difference relative to CT1 burn

Test	Parameter	C burn		CT1 burn	CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
		Value (wt. %)	**% Diff.**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Standard Parameters	**Al_2O_3**	25.1	-1.8	25.5	21.0	-17.6	22.9	-10.5	24.3	-5.0	25.2	-1.1	24.6	-3.6	23.9	-6.5
	CaO	7.5	-5.6	8.0	8.3	3.5	5.6	-29.3	7.2	-9.5	4.7	-40.5	9.3	16.7	12.8	60.7
	Fe_2O_3	7.6	3.5	7.4	15.2	106.2	18.7	153.8	9.0	22.9	6.6	-10.8	7.5	1.6	7.8	5.7
	K_2O	2.6	-3.5	2.7	2.5	-6.7	1.8	-33.3	2.4	-10.1	3.3	21.8	2.2	-15.9	2.6	-4.0
	MgO	1.4	0.6	1.3	1.3	-7.0	1.0	-24.7	1.1	-19.9	1.3	-0.4	1.1	-19.9	1.3	-2.5
	Na_2O	0.2	-48.6	0.4	0.4	-15.8	0.2	-42.5	0.2	-61.1	0.2	-59.2	0.2	-53.4	0.6	33.3
	P_2O_5	0.2	-11.6	0.2	0.2	12.9	0.4	73.8	0.2	-13.5	0.1	-33.3	0.2	-16.8	0.1	-41.1
	SiO_2	47.4	3.0	46.0	43.4	-5.6	42.4	-7.9	47.2	2.6	53.4	16.0	47.2	2.5	49.4	7.4
	SO_3	7.0	-5.2	7.3	6.5	-11.3	5.5	-24.4	7.2	-1.7	4.0	-45.9	6.4	-12.8	0.3	-95.5
	TiO_2	1.1	-2.3	1.2	1.0	-16.6	1.0	-11.1	1.0	-10.7	4.0	244.9	1.2	0.5	1.0	-9.6
		Value (ppm)	**% Diff.**	**Value (ppm)**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**
	As	325	304	80	316	292	200	148.3	94	16.8	72	-10.5	86	6.9	114	41.7
	Ba	1274	18	1083	1300	20	1500	38.5	1200	10.8	1100	1.5	1096	1.2	1100	1.5
	Cd	ND	NA	ND	5 [1]	NA	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
	Cl	125 [1]	-31	182	134 [1]	-26	94	-48.4	101	-44.5	89	-51.1	105	-42.3	236	29.7
	Co	ND	NA	30	44	49	61	105.6	41	39.3	29	-1.8	54	82.9	43	45.6
	Cr	109	-14	127	117	-8	107	-16.2	114	-10.8	109	-14.4	190	49.3	132	3.7
	Cu	150	29	116	103	-11	116	-0.5	114	-2.2	81	-30.2	70	-39.7	103	-11.3
	Hg	0.23 [1]	NA	ND	0.022 [1]	NA	0	NA	0	NA	0	NA	0.2	NA	0.08	NA
	Mn	221	-38	355	1500	322	2900	716	300	-15.6	300	-15.6	498	40.1	500	40.7
	Mo	ND	NA	9	39	326	37	306.0	35	284.6	24	161.9	31	238.3	29	216.5
	Ni	81	-19	100	92	-8	107	6.9	86	-13.7	68	-31.9	79	-20.8	78	-21.8
	Pb	42	-13	48	45	-6	39	-18.2	49	2.3	43	-10.1	47	-1.8	ND	NA
	Sb	ND	NA	ND	NR	NA	NR	NA	NR	NA	NR	NA	NR	NA	NR	NA
	Se	ND	NA	8	1 [1]	-88	7	-14.1	5	-38.6	7	-14.1	6	-26.3	7	-14.1
	Sr	487	-17	591	500	-15	900	52.4	700	18.5	500	-15.3	598	1.3	400	-32.3
	V	226	0	225	214	-5	210	-6.9	213	-5.2	226	0.4	214	-4.9	228	1.3
	Zn	68	-49	133	197	48	179	34.3	73	-45.0	81	-39.3	63	-52.8	9	-93.3

Notes: [1] **Dry Basis** **ND - Not Detected** **NR - Not Reported** **NA - Not Applicable** **CIP - Collection in Progress**

Overall, there are relatively large differences in many of the parameters. Some of the oxygen, moisture, and volatile matter values showed the greatest decreases, while some nitrogen and sulfur values showed the greatest increases. These changes are most likely due to the variable nature of the tires being used in the fuel feed stream. Many different tire types and sources are used, and these differences in results may simply be an indication of the actual variability in the stream. Similar trends can be observed in the standard external laboratory parameters for the tires presented in Table 4.27. The high content of Fe_2O_3 is due to the steel belts used in the tires, which act as an iron source for portland cement production.

The final aspect of the tires that is pertinent to this study is the rate of substitution of tires relative to the total fuel consumption rate. The ranges of fuel replacement rates for tires for each burn are listed in Table 4.1. This percentage was calculated using the average heat value of the fuels (reported from each burn) as determined by the external laboratory. The heat values used in this calculation were 11,897 BTU/lb for the coal, and 14,577 BTU/lb for the tires. The feed rate data (in tons per hour) were collected at the cement plant every five minutes. A 30-minute rolling average, reported over each of the 72-hour burns in which tires were used, was calculated to report the feed rates. The average tire-to-fuel replacement rates in percentages for CT1, CTP, CT2, CTB, CT3, CTW, and CTS burns are 6.5 %, 4.8 %, 1.7 %, 1.7 %, 1.0 %, 5.7 % and 16.3 % respectively. The value for the CTS burn was unusually high, which is considered an anomaly that may have arisen due to malfunctioning of the weighing scale, as reported by the cement plant personnel.

Table 4.26: ELR –All Burns, Proximate, Ultimate, and Combustion Analyses for tires, and percent difference relative to CT1burn

Test	Parameter	CT1 burn	CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
		Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Proximate Analysis	**Ash**	13.7	14.6	6.1	14.5	6.0	12.2	-11.0	18.9	37.7	15.0	9.3	24.4	77.8
	Fixed Carbon	24.6	26.4	7.2	46.9	90.7	49.4	100.9	41.9	70.3	23.6	-4.2	19.8	-19.4
	Moisture [1]	0.14	0.07	-50.0	0.09	-33.7	0.09	-33.7	0.07	-49.8	0.4	157.1	1.0	610.9
	Volatile Matter	61.7	59.1	-4.2	38.5	-37.7	38.3	-37.9	39.2	-36.5	61.5	-0.4	55.8	-9.6
Ultimate Analysis	**Carbon**	72.3	75.9	5.0	77.9	7.6	79.0	9.2	69.5	-3.9	77.6	7.3	72.6	0.4
	Hydrogen	7.1	6.5	-7.4	5.6	-21.0	5.4	-22.9	5.0	-29.6	5.9	-16.3	0.2	-96.8
	Nitrogen	0.36	0.5	44.4	0.07	-79.4	0.06	-84.5	1.74	383.2	0.1	-72.2	0.4	9.1
	Oxygen	5.0	0.5	-90.8	0.7	-86.9	1.8	-63.0	1.8	-64.5	0.3	-93.8	1.1	-78.8
	Sulfur	1.54	2.00	29.9	1.31	-15.0	1.47	-4.8	3.15	104.3	1.1	-28.6	1.3	-16.1
Heat Value [2]		14467	16754	15.8	15456	6.8	15501	7.1	14972	3.5	15098	4.4	13239	-8.5

Notes: [1] **As Received** [2] **Values Reported as BTU/lb** **CIP- Collection in Progress** **NA- Not Applicable**

Table 4.27: ELR –All Burns, Chemical analysis for tires and percent difference relative CT1 burn

Test	Parameter	CT1 burn	CTP burn		CT2 burn		CTB burn		CT3 burn		CTW burn		CTS burn	
		Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Standard Parameters	**Al_2O_3**	1.2	1.2	-2.5	0.8	-33.7	6.2	423.0	0.2	-86.1	4.4	274.2	0.5	-54.9
	CaO	2.4	1.7	-28.8	3.8	62.0	3.2	34.2	1.6	-31.6	3.0	27.2	2.9	24.7
	Fe_2O_3	68.6	84.7	23.4	57.4	-16.3	46.8	-31.8	85.9	25.1	57.7	-15.9	77.1	12.3
	K_2O	0.3	0.2	-48.5	0.3	-12.0	0.3	-13.3	0.2	-43.6	0.5	44.8	0.3	-23.0
	MgO	0.4	0.3	-5.7	0.0	-87.2	0.0	-91.6	0.1	-78.2	0.4	2.7	0.2	-41.7
	Na_2O	0.3	0.2	-38.7	0.5	51.3	0.6	104.5	0.2	-31.9	1.5	380.6	0.1	-58.7
	P_2O_5	0.2	0.1	-42.9	0.2	3.7	0.2	0.1	0.1	-68.2	0.4	106.3	0.2	-6.7
	SiO_2	16.9	4.9	-70.9	25.1	48.9	27.1	60.6	2.8	-83.6	12.9	-23.6	5.4	-68.1
	SO_3	2.6	0.5	-80.7	0.8	-67.8	0.5	-81.9	0.3	-88.5	4.2	57.4	2.3	-14.7
	TiO_2	0.2	0.0	-95.0	0.4	98.1	6.8	3309.5	0.3	69.9	3.7	1772.0	0.1	-50.0
		Value (ppm)	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**
	As (ppm)	NR	NR	NA	ND	NA	ND	NA	4	NA	ND	NA	ND	NA
	Ba (ppm)	300	300	0.0	1135	278.3	1134	278.0	0	-100.0	ND	NA	0	-100.0
	Cd (ppm) ^{1}	6	3	-50.0	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
	Cl (ppm) ^{1}	405	NR	NA	1174	189.9	568	40.2	946	133.6	515	27.2	1696	318.8
	Co (ppm)	616	536	-13.0	852	38.3	759	23.2	1191	93.3	642	4.2	724	17.5
	Cr (ppm)	118	178	50.8	94	-20.6	56	-52.6	260	120.4	133	13.0	129	9.5
	Cu (ppm)	1398	900	-35.6	546	-61.0	408	-70.8	1068	-23.6	3762	169.1	0	-100.0
	Hg (ppm) ^{1}	0.38	ND	NA	0.16	-58.2	0.21	-45.2	ND	NA	0.1	-73.9	NR	NA
	Mn (ppm)	4100	5200	26.8	3600	-12.2	2900	-29.3	3900	-4.9	3754	-8.4	4300	4.9
	Mo (ppm)	28	23	-17.9	31	9.8	11	-60.3	21	-25.6	8	-71.3	11	-59.3
	Ni (ppm)	367	239	-34.9	91	-75.3	70	-80.8	215	-41.5	8	-97.8	332	-9.5
	Pb (ppm)	11	13	18.2	17	58.3	ND	NA	10	-5.6	30	168.9	8	-27.3
	Sb (ppm)	NR	NR	NA	NR	NA	NR	NA	NR	NA	NR	NA	NR	NA
	Se (ppm) ^{1}	ND	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA	ND	NA
	Sr (ppm)	200	100	-50.0	0	-100.0	0	-100.0	0	-100.0	36	-82.0	20	-90.0
	V (ppm)	37	50	35.1	50	34.4	214	477.5	20	-47.1	117	216.8	10	-74.1
	Zn (ppm)	0.05	0.10	85.2	0.07	33.3	0.06	16.1	0.07	20.9	0.09	69.1	0.07	35.6

Notes: ^{1} **Dry Basis** **NR - Not Reported** **NA - Not Applicable** **ND - Not Detected** **CIP - Collection in Progress**

4.3.3.2 Waste Plastics

The waste plastics used in CTP burn were derived from automotive trim scrap material, i.e. the discarded interior carpet and lining of cars. The material was not tested for any chemical parameters by the cement plant. However, samples of the plastics were collected by Auburn University and tested by the external laboratory. Discrete samples were collected every three hours, and each of them was tested. In addition, every fourth sample was tested in duplicate. The tests conducted on each of these specimens were the same as for each of the other fuels. The complete set of summary statistics for the proximate, ultimate, and combustion analyses is shown in Table 4.28. The summary statistics applicable to the standard external laboratory parameters for the plastics are shown in Table 4.29. Perhaps the most interesting result was the extremely high concentration of CaO in the plastics, which composed 92 percent of the total weight.

The plastics were substituted at an average rate of 16.9 percent, which was significantly higher than the replacement rate of the tires. This percentage was based on an average energy content of 12,754 BTU/lb for the plastics, 16754 BTU/lb for tires and 11,369 BTU/lb for the coal, as determined by the external laboratory. The fuel feed rates (in tons per hour) was supplied by the cement plant.

One final property of the plastics which is pertinent to this study is the material's density. The density of each of the 24 samples of plastics collected at the cement plant was determined by researchers at Auburn University. Each of the 24 results can be found in Appendix B.3. The average of these values was 5.26 lb/ft^3 which is very low compared to other fuels. The low density material created feed problems during the cement production and hence affected the fuel feed rates.

Table 4.30 shows the proximate and ultimate analysis of all the fuels used in CTP burn and Table 4.31 shows the chemical composition the fuels used in CTP burn, as reported by the external laboratory. Although the data presented have been shown previously, presentation in this manner allows the reader to easily see the differences in composition of each of the fuels relative to one another. This table will serve as the basis for determining if the changes in chemical composition of the output materials can be attributed in any way to the fuels. Additionally, Table 4.30 shows the heat value for each of the fuels. The plastics had a higher heat value than any of the coal samples tested for any of the burns, which is very encouraging.

Table 4.28: ELR – Proximate, Ultimate, and Combustions Analysis of Plastics from CTP burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Proximate Analysis	**Ash (wt. %)**	0.32	40.5 [1]	0.026
	Fixed Carbon (wt. %)	8.75	40.8 [1]	0.013
	Moisture (wt. %) [3]	88.30	2.7 [1]	<0.005
	Volatile Matter (wt. %)	2.95	43.9 [1]	0.026
Ultimate Analysis	**Carbon (wt. %)**	8.06	18.4 [1]	<0.005
	Hydrogen (wt. %)	64.23	13.1 [1]	<0.005
	Nitrogen (wt. %)	1.27	31.6	0.888
	Oxygen (wt. %)	0.22	185.6 [1]	<0.005
	Sulfur (wt. %)	17.46	49.3 [1]	<0.005
Heat Value (BTU/lb)		12754	7.9	0.313

Notes: [1] Not Normally Distributed [3] As Received

[2] Based on Anderson-Darling Statistics

Table 4.29: ELR - Standard Parameters of Plastics from CTP burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Standard Parameters	Al_2O_3 (wt. %)	0.48	59.8 [1]	<0.005
	CaO (wt. %)	92.00	2.0 [1]	0.034
	Fe_2O_3 (wt. %)	0.54	25.8 [1]	0.041
	K_2O (wt. %)	0.13	40.4 [1]	<0.005
	MgO (wt. %)	1.75	4.2	0.727
	Na_2O (wt. %)	0.17	91.9 [1]	<0.005
	P_2O_5 (wt. %)	0.14	41.3	0.429
	SiO_2 (wt. %)	2.12	34.6 [1]	<0.005
	SO_3 (wt. %)	0.41	30.5	0.116
	TiO_2 (wt. %)	1.77	46.8	0.177
	As (ppm)	62	62.7 [1]	0.067
	Ba (ppm)	4100	47.1	0.518
	Cd (ppm) [3]	7	9.3 [1]	<0.005
	Cl (ppm) [3]	54	25.8 [1]	<0.005
	Co (ppm)	142	27.8	0.113
	Cr (ppm)	356	33.0	0.504
	Cu (ppm)	369	28.4	0.279
	Hg (ppm) [3]	ND	NA	NA
	Mn (ppm)	300	20.9 [1]	<0.005
	Mo (ppm)	6	172.3	0.144
	Ni (ppm)	50	165.2 [1]	<0.005
	Pb (ppm)	628	59.6 [1]	0.009
	Sb (ppm)	NR	NA	NA
	Se (ppm) [3]	ND	NA	NA
	Sr (ppm)	600	8.8 [1]	<0.005
	V (ppm)	66	83.8 [1]	<0.005
	Zn (ppm)	283	50.0	0.275

Notes:

NR - Not Reported

NA - Not Applicable

ND- Not Detected

[1] Not Normally Distributed

[2] Based on Anderson-Darling Statistics

[3] Dry Basis

Many differences between the fuels are shown in Table 4.31. The tires and the plastics contained very little Al_2O_3, but each of the coal samples was approximately 21 percent Al_2O_3. The plastics were over 90 percent CaO, whereas the coal and tires contained less than two percent. The Fe_2O_3 was much higher in the tires than in the coal or plastics. This can be attributed to the steel belts present in the tires. The final primary parameter that showed a large difference was the SiO_2. Each coal sample was made up of approximately 40 percent SiO_2, while the tires and the plastics contained much less. A number of the less prominent parameters showed pronounced differences. Ba, V, and Zn levels were reasonably lower in the tires than the other fuels. Co, Cu, Mn, and Ni all showed appreciably higher concentrations in tires than the other fuels. The plastics showed higher concentrations of Ba, Cr, Pb, and Zn than the other fuels. Cl and Ni were lower in the plastics than in the other fuels.

Table 4.30: ELR – Proximate and Ultimate analyses of all fuels from CTP burn

Test	**Parameter**	**CTP burn**		
		Coal	**Tires**	**Plastics**
Proximate Analysis	**Ash (wt. %)**	24.54	14.56	0.32
	Fixed Carbon (wt. %)	47.68	26.38	8.75
	Volatile Matter (wt. %	27.78	59.06	2.95
Ultimate Analysis	**Carbon (wt. %)**	64.68	75.94	8.06
	Hydrogen (wt. %)	3.93	6.53	64.23
	Nitrogen (wt. %)	1.08	0.52	1.27
	Oxygen (wt. %)	4.11	0.46	0.22
	Sulfur (wt. %)	1.66	2.00	17.46
Heat Value (BTU/lb)		11369	16754	12754

Table 4.31: ELR – Chemical composition of all fuels from CTP burn

Test	Parameter	CTP burn		
		Coal	Tires	Plastics
Standard Parameters	Al_2O_3 (wt. %)	21.04	1.15	0.48
	CaO (wt. %)	8.25	1.68	92.00
	Fe_2O_3 (wt. %)	15.16	84.72	0.54
	K_2O (wt. %)	2.49	0.17	0.13
	MgO (wt. %)	1.25	0.33	1.75
	Na_2O (wt. %)	0.36	0.19	0.17
	P_2O_5 (wt. %)	0.23	0.12	0.14
	SiO_2 (wt. %)	43.44	4.91	2.12
	SO_3 (wt. %)	6.5	0.51	0.41
	TiO_2 (wt. %)	0.96	0.01	1.77
	As (ppm)	316	NR	62
	Ba (ppm)	1300	300	4100
	Cd (ppm) [1]	5	3	7
	Cl (ppm) [1]	134	NR	54
	Co (ppm)	44	536	142
	Cr (ppm)	117	178	356
	Cu (ppm)	103	900	369
	Hg (ppm) [1]	0.02	0	0
	Mn (ppm)	1500	5200	300
	Mo (ppm)	39	23	6
	Ni (ppm)	92	239	50
	Pb (ppm)	45	13	628
	Sb (ppm)	NR	NR	NR
	Se (ppm) [1]	1	ND	ND
	Sr (ppm)	500	100	600
	V (ppm)	214	50	66
	Zn (ppm)	197	0	283

Notes: ND - Not Detected NR - Not Reported

[1] Dry Basis

4.3.3.3 Broiler Litter

Broiler litter used in CTB burn was obtained from a local broiler producer. The material was not tested for any chemical parameters by the cement plant. However, samples of the broiler litter were collected by Auburn University staff and tested by the external laboratory. Discrete samples were collected every three hours, and each of them was tested. In addition, every fourth sample was tested in duplicate. The tests conducted on each of these specimens were the same as for each of the other fuels. The complete set of summary statistics for the proximate, ultimate, and combustion analyses is shown in Table 4.32. The summary statistics applicable to the standard external laboratory parameters for the broiler litter are shown in Table 4.33.

Table 4.32: ELR – Proximate, Ultimate and Combustion analyses of Broiler litter from CTB burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Proximate Analysis	**Ash (wt. %)**	20.61	8.5 [1]	0.045
	Fixed Carbon (wt. %)	33.75	11.5 [1]	0.023
	Moisture (wt. %) [3]	29.06	7.6 [1]	<0.005
	Volatile Matter (wt. %)	45.64	5.7 [1]	<0.005
Ultimate Analysis	**Carbon (wt. %)**	40.89	6.1 [1]	<0.005
	Hydrogen (wt. %)	4.86	7.5 [1]	<0.005
	Nitrogen (wt. %)	4.30	8.6	0.188
	Oxygen (wt. %)	28.66	10.2 [1]	<0.005
	Sulfur (wt. %)	0.68	16.6 [1]	<0.005
Heat Value (BTU/lb)		6875	2.9	0.113

Notes: [1] Not Normally Distributed [3] As Received

[2] Based on Anderson-Darling Statistics

Table 4.33: ELR - Standard Parameters of Broiler Litter from CTB burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Standard Parameters	**Al_2O_3 (wt. %)**	0.84	28.6 [1]	<0.005
	CaO (wt. %)	23.52	8.0 [1]	0.024
	Fe_2O_3 (wt. %)	0.85	25.4 [1]	<0.005
	K_2O (wt. %)	20.44	7.2 [1]	<0.005
	MgO (wt. %)	7.73	5.5	0.727
	Na_2O (wt. %)	7.02	6.42 [1]	<0.005
	P_2O_5 (wt. %)	24.54	7.2	0.429
	SiO_2 (wt. %)	7.44	43.1 [1]	<0.005
	SO_3 (wt. %)	6.58	4.0	0.116
	TiO_2 (wt. %)	0.07	41.0	0.177
	As (ppm)	13	49.3 [1]	0.067
	Ba (ppm)	468	19.7	0.518
	Cd (ppm) [3]	ND	NA	NA
	Cl (ppm) [3]	5843	5.4 [1]	<0.005
	Co (ppm)	3	36.4	0.113
	Cr (ppm)	29	52.0	0.504
	Cu (ppm)	2505	3.9	0.279
	Hg (ppm) [3]	0.2	NA	NA
	Mn (ppm)	8870	8.1 [1]	<0.005
	Mo (ppm)	43	8.3	0.144
	Ni (ppm)	44	20.5 [1]	<0.005
	Pb (ppm)	32	91.6 [1]	0.010
	Sb (ppm)	NA	NA	NA
	Se (ppm) [3]	ND	NA	NA
	Sr (ppm)	379	13.8 [1]	<0.005
	V (ppm)	18	18.3 [1]	<0.005
	Zn (ppm)	2685	4.5	0.275

Notes: NR - Not Reported
NA - Not Applicable

[1] Not Normally Distributed
[2] Based on Anderson-Darling Statistics
[3] Dry Basis

Broiler Litter was found to be high in CaO, K_2O and P_2O_5. It is interesting to note that the nitrogen content in broiler litter exceeds the plant target of 1.4, mentioned in Section 4.3.3. It also had high volatile matter content. Its average heat value as determined at the external laboratory was about 6875 BTU/lb which is lower than that of coal. The broiler litter was substituted at an average rate of 6.5 percent, which was higher than the replacement rate of the tires. This percentage was based on an average as-received energy content of 6875 BTU/lb for the broiler litter, 15501 BTU/lb for scrap tires and 12,481BTU/lb for the coal. The fuel feed rates (in tons per hour) was supplied by the cement plant.

The average density of Broiler Litter was measured to be 41.7 lb/ft^3. Though it has low energy value, it did not cause any feeding problems and handled easily. The odor of the litter was noticeable but the plant personnel were informed of it in advance.

The proximate and ultimate analyses of all the fuels used in CTB burn are shown in Table 4.34. The chemical compositions of all the fuels used in CTB burn are presented in Table 4.35. These tables provide a basis to draw comparisons between all the fuels from CTB burn.

The high content of CaO, K_2O and P_2O_5 makes broiler litter completely unique and different from coal and scrap tires which mostly contain SiO_2 and Fe_2O_3, respectively. The lower sulfur and higher oxygen content than coal and tires may be reflected in lower sulfur emissions which will be discussed in Section 4.3.8. The higher alkali content (K_2O and Na_2O) of broiler litter than that of coal or tires may affect the kiln condition. Broiler litter has very little Al_2O_3 and Fe_2O_3 compared to coal or tires. This may take away the advantage of fuels contributing as raw materials.

Broiler litter is rich in manganese and copper, but has lower content of toxic elements such as arsenic and lead than coal. It has very high chlorine content compared to coal or tires and is also rich in zinc.

Table 4.34: ELR – Proximate and Ultimate analyses of all fuels from CTB burn

Test	Parameter	CTB burn		
		Coal	Tires	Broiler Litter
Proximate Analysis	Ash (wt. %)	17.65	12.21	20.61
	Fixed Carbon (wt. %)	53.61	49.41	33.75
	Volatile Matter (wt. %)	28.73	38.28	29.06
Ultimate Analysis	Carbon (wt. %)	69.84	78.98	40.89
	Hydrogen (wt. %)	3.59	5.44	4.86
	Nitrogen (wt. %)	0.59	0.06	4.30
	Oxygen (wt. %)	6.77	1.84	28.66
	Sulfur (wt. %)	1.55	1.47	0.68
Heat Value (BTU/lb)		12431	15501	6875

Table 4.35: ELR – Standard parameters of all fuels from CTB burn

Test	Parameter	CTB burn		
		Coal	Tires	Broiler Litter
Standard Parameters	Al_2O_3 (wt. %)	24.27	6.17	0.84
	CaO (wt. %)	7.22	3.17	23.52
	Fe_2O_3 (wt. %)	9.04	46.84	0.85
	K_2O (wt. %)	2.40	0.29	20.44
	MgO (wt. %)	1.08	0.03	7.73
	Na_2O (wt. %)	0.17	0.63	7.02
	P_2O_5 (wt. %)	0.18	0.21	24.54
	SiO_2 (wt. %)	47.21	27.09	7.44
	SO_3 (wt. %)	7.21	0.48	6.58
	TiO_2 (wt. %)	1.03	6.82	0.07
	As (ppm)	94	ND	13
	Ba (ppm)	1200	1134	468
	Cd (ppm) [1]	ND	ND	ND
	Cl (ppm) [1]	101	568	5843
	Co (ppm)	41	759	3
	Cr (ppm)	114	56	29
	Cu (ppm)	114	408	2505
	Hg (ppm) [1]	0.17	0.21	0.18
	Mn (ppm)	300	2900	8870
	Mo (ppm)	35	11	43
	Ni (ppm)	86	70	44
	Pb (ppm)	49	ND	32
	Sb (ppm)	NR	NR	NA
	Se (ppm) [1]	5	ND	ND
	Sr (ppm)	700	0	379
	V (ppm)	213	214	18
	Zn (ppm)	73	0	2685

Notes: ND - Not Detected NR - Not Reported

[1] Dry Basis

4.3.3.3 Woodchips

Woodchips were obtained from a local timber company near the cement plant. Like other alternative fuels, they were not tested for composition or properties at the cement plant. Woodchips samples were collected by Auburn University and tested for fuel characteristics and composition at the external laboratory. Discrete samples were collected every three hours, and each sample was tested individually. In addition, every fourth sample was tested in duplicate. The tests conducted on each of these specimens were the same as for each of the other fuels. The complete set of summary statistics for the proximate, ultimate, and combustion analyses is shown in Table 4.36. The summary statistics applicable to the standard external laboratory parameters for the woodchips are shown in Table 4.37.

In Tables 4.36 and 4.37, it is observed that the coefficient of variation (C.V. %) values are unusually high for some of the data. It suggests that there is a lot of variation in the data obtained from testing of the discrete samples, which indicates that the woodchips samples are not uniform and consistent in composition. This could be a result of the woodchips coming from different kinds of wood used at the timber company. Woodchips are discussed in detail in Section 2.3.4.4.

From Table 4.36, it is observed that the volatile matter content of woodchips is very high and in turn, the ash content is very low which is an excellent property for any fuel. However the moisture content of woodchips is on the higher side for a fuel (> 14 percent), which can directly affect the heating value. More information about woodchips can be found in Section 2.3.4.4. The nitrogen and sulfur content of the woodchips is found to be low and it can directly lower the emissions, as will be discussed in Section

4.3.8. From the averages listed in Table 4.37, it can be inferred that woodchips are very high in CaO, K_2O and MgO. They have a low content of the heavy metals, except for barium, manganese and strontium.

Woodchips were substituted for coal at an average woodchips-to-fuel replacement rate of 6.9 percent on an energy replacement basis, determined by using an average as-received heating value of 8388 BTU/lb for woodchips, 15098 BTU/lb for scrap tires and 12,445 BTU/lb for the coal. The fuel feed rates (tons per hour) were provided by the cement plant.

The average density of the woodchips samples was measured by Auburn University staff and was determined to 16.40 lb/ft^3. Woodchips, like broiler litter, did not cause any feed problems. The CTW burn was conducted for three days without any interruptions.

Table 4.36: ELR – Proximate, Ultimate and Combustion analyses of woodchips from CTW burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Proximate Analysis	**Ash (wt. %)**	0.82	33.5 [1]	<0.005
	Fixed Carbon (wt. %)	16.94	8.0	0.126
	Moisture (wt. %) [3]	36.46	4.3	0.206
	Volatile Matter (wt. %)	82.24	1.7	0.105
Ultimate Analysis	**Carbon (wt. %)**	52.64	0.6 [1]	<0.005
	Hydrogen (wt. %)	5.83	4.7 [1]	<0.005
	Nitrogen (wt. %)	0.15	63.3 [1]	<0.005
	Oxygen (wt. %)	40.53	1.3	0.13
	Sulfur (wt. %)	0.02	41.2 [1]	<0.005
Heat Value (BTU/lb)		8388	1.2	0.305

Notes: [1] Not Normally Distributed [3] As Received

[2] Based on Anderson-Darling Statistics

Table 4.37: ELR - Standard Parameters of woodchips from CTW burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Standard Parameters	**Al_2O_3 (wt. %)**	0.93	33.3 [1]	<0.005
	CaO (wt. %)	54.61	16.1 [1]	0.042
	Fe_2O_3 (wt. %)	1.79	59.7 [1]	<0.005
	K_2O (wt. %)	17.28	32.1 [1]	<0.005
	MgO (wt. %)	9.83	18.0 [1]	<0.005
	Na_2O (wt. %)	0.38	56.6 [1]	<0.005
	P_2O_5 (wt. %)	2.80	29.1 [1]	<0.005
	SiO_2 (wt. %)	3.27	51.1 [1]	<0.005
	SO_3 (wt. %)	3.33	80.2 [1]	<0.005
	TiO_2 (wt. %)	0.02	139.1 [1]	<0.005
	As (ppm)	12	53.9 [1]	<0.005
	Ba (ppm)	9692	21.7 [1]	<0.005
	Cd (ppm) [3]	ND	NA	NA
	Cl (ppm) [3]	425	96.0 [1]	<0.005
	Co (ppm)	64	192.4 [1]	<0.005
	Cr (ppm)	16	117.87 [1]	<0.005
	Cu (ppm)	126	25.4 [1]	<0.005
	Hg (ppm) [3]	0.1	51.4 [1]	<0.005
	Mn (ppm)	43581	45.6 [1]	<0.005
	Mo (ppm)	65	181.8 [1]	<0.005
	Ni (ppm)	169	117.0 [1]	<0.005
	Pb (ppm)	60	150.7 [1]	<0.005
	Sb (ppm)	NR	NA	NA
	Se (ppm) [3]	ND	NA	NA
	Sr (ppm)	4230	27.9 [1]	<0.005
	V (ppm)	172	123.7 [1]	<0.005
	Zn (ppm)	959	39.9 [1]	<0.005

Notes:

NR - Not Reported

NA - Not Applicable

ND - Not Detected

[1] Not Normally Distributed

[2] Based on Anderson-Darling Statistics

[3] Dry Basis

The proximate and ultimate analyses of all the fuels used in CTW burn are shown in Table 4.38. The chemical compositions of all the fuels used in CTW burn are presented in Table 4.39. From these tables, composition and properties of woodchips can be compared to those of coal and tires.

It is observed that the ash content is much lower and volatile matter is much higher in woodchips than in both coal and tires. Sulfur content is also very low compared to both coal and tires. Woodchips are rich in CaO and K_2O, unlike both coal and tires, and have low contents of SiO_2, Al_2O_3 and Fe_2O_3, which in contrast are the major parameters of coal and tires. Woodchips are found to have an average of 4.35 percent by weight of MnO_2 (43581 ppm of Mn in Table 4.37) which is much higher than the value for both coal and tires. The heating value is also low compared to both coal and tires. The arsenic content is lower than the value for coal but the lead content is found to be higher than the value for coal.

Table 4.38: ELR – Proximate and Ultimate analyses of all fuels from CTW burn

Test	Parameter	CTW burn		
		Coal	Tires	Woodchips
Proximate Analysis	Ash (wt. %)	17.59	14.99	0.82
	Fixed Carbon (wt. %)	53.80	23.56	16.94
	Volatile Matter (wt. %)	28.61	61.45	82.24
Ultimate Analysis	Carbon (wt. %)	71.06	77.60	52.64
	Hydrogen (wt. %)	4.16	5.90	5.83
	Nitrogen (wt. %)	1.48	0.10	0.15
	Oxygen (wt. %)	4.57	0.31	40.53
	Sulfur (wt. %)	1.14	1.1	0.02
Heat Value (BTU/lb)		12445	15098	8388

Table 4.39: ELR – Standard parameters of all fuels from CTW burn

Test	Parameter	CTW burn		
		Coal	Tires	Woodchips
Standard Parameters	Al_2O_3 (wt. %)	24.62	4.42	0.93
	CaO (wt. %)	9.30	3.00	54.61
	Fe_2O_3 (wt. %)	7.47	57.72	1.79
	K_2O (wt. %)	2.24	0.48	17.28
	MgO (wt. %)	1.08	0.36	9.83
	Na_2O (wt. %)	0.20	1.49	0.38
	P_2O_5 (wt. %)	0.17	0.43	2.80
	SiO_2 (wt. %)	47.18	12.89	3.27
	SO_3 (wt. %)	6.39	4.15	3.33
	TiO_2 (wt. %)	1.16	3.74	0.02
	As (ppm)	86	ND	12
	Ba (ppm)	1096	ND	9692
	Cd (ppm) [1]	ND	ND	ND
	Cl (ppm) [1]	105	515	425
	Co (ppm)	54	642	64
	Cr (ppm)	190	133	16
	Cu (ppm)	70	3762	126
	Hg (ppm) [1]	0.2	0	0
	Mn (ppm)	498	3754	43581
	Mo (ppm)	31	8	65
	Ni (ppm)	79	8	169
	Pb (ppm)	47	30	60
	Sb (ppm)	NR	NR	NR
	Se (ppm) [1]	6	ND	ND
	Sr (ppm)	598	36	4230
	V (ppm)	214	117	172
	Zn (ppm)	63	0	959

Notes: ND - Not Detected NR - Not Reported

[1] Dry Basis

4.3.3.4 Switchgrass

Switchgrass was obtained from a local farm and was delivered to the cement plant in form of bales. However, because of the severe drought experienced in Alabama during 2007, there was a shortage of supply and the stockpiled switchgrass lasted for two days only. Accordingly, the CTS burn was conducted for two days only. The bales of the switchgrass had to be shredded before this fuel could be fed into the system for easy flow of the stream. Discrete samples of these shreds were collected every three hours for two days by Auburn University.

The cement plant did not test the switchgrass properties and composition of the switchgrass. Auburn University staff sent the collected samples to the external laboratory to be analyzed. Discrete samples were collected every three hours, and each of them was tested. In addition, every fourth sample was tested in duplicate. The tests conducted on each of these specimens were the same as for each of the other fuels. The complete set of summary statistics for the proximate, ultimate, and combustion analyses is shown in Table 4.40. The summary statistics applicable to the standard external laboratory parameters for the switchgrass are shown in Table 4.41.

From Tables 4.40 and 4.41, it is observed that the coefficients of variation values are high for some parameters, suggesting high variation in the chemical composition of the switchgrass samples. However, the average values indicate that switchgrass is low in ash content and high in volatile matter. The sulfur content in the switchgrass is also found to be low. The average heat value is determined to be 8,162 BTU/lb, with a low coefficient of variation suggesting a uniform heat value among the switchgrass samples.

From Table 4.41, it can be concluded that switchgrass mainly consists of SiO_2, K_2O, CaO, MgO and P_2O_5. Switchgrass also has high manganese and zinc contents.

Table 4.40: ELR – Proximate, Ultimate and Combustion analyses of switchgrass from CTS burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Proximate Analysis	**Ash (wt. %)**	5.27	28.3 [1]	<0.005
	Fixed Carbon (wt. %)	17.02	10.1 [1]	<0.005
	Moisture (wt. %) [3]	9.87	23.3 [1]	<0.005
	Volatile Matter (wt. %)	77.72	1.7	0.2
Ultimate Analysis	**Carbon (wt. %)**	50.25	1.4	0.13
	Hydrogen (wt. %)	5.70	4.1	0.215
	Nitrogen (wt. %)	1.22	20.4 [1]	<0.005
	Oxygen (wt. %)	37.37	2.6	0.15
	Sulfur (wt. %)	0.19	7.3 [1]	<0.005
Heat Value (BTU/lb)		8162	1.8	0.323

Notes: [1] Not Normally Distributed [3] As Received

[2] Based on Anderson-Darling Statistics

Switchgrass was substituted for coal at an average switchgrass-to-fuel replacement rate of 6.8 percent on an energy replacement basis, determined by using an average as-received heating value of 8162 BTU/lb for switchgrass, 13,239 BTU/lb for scrap tires and 12,664 BTU/lb for the coal. The fuel feed rates (tons per hour) were provided by the cement plant. The average density of the switchgrass shreds samples was measured by Auburn University staff and was determined to 4.57 lb/ft^3. The shredding system installed for switchgrass at the cement plant was not efficient enough and hence, the shredding of switchgrass bales into manageable sizes involved a great deal of labor from cement plant personnel. But, once shredded, the switchgrass was easily conveyed into the system, though feed rates were low because of its low density.

Table 4.41: ELR - Standard parameters of switchgrass from CTS burn

Test	Parameter	Average	C.V. (%)	P-Value [2]
Standard Parameters	Al_2O_3 (wt. %)	1.57	58.1	<0.005
	CaO (wt. %)	13.99	11.0 [1]	<0.005
	Fe_2O_3 (wt. %)	1.06	84.7 [1]	<0.005
	K_2O (wt. %)	24.72	21.8 [1]	<0.005
	MgO (wt. %)	9.02	14.7 [1]	<0.005
	Na_2O (wt. %)	0.96	77.4 [1]	<0.005
	P_2O_5 (wt. %)	8.49	17.9 [1]	<0.005
	SiO_2 (wt. %)	34.86	13.1 [1]	<0.005
	SO_3 (wt. %)	4.53	47.7 [1]	<0.005
	TiO_2 (wt. %)	0.14	84.9 [1]	<0.005
	As (ppm)	11.00	58.6 [1]	<0.005
	Ba (ppm)	739	16.2 [1]	<0.005
	Cd (ppm) [3]	ND	NA	NA
	Cl (ppm) [3]	819	20.2 [1]	<0.005
	Co (ppm)	6	69.4 [1]	<0.005
	Cr (ppm)	22	68.1 [1]	<0.005
	Cu (ppm)	56	70.9 [1]	<0.005
	Hg (ppm) [3]	0.1	56.9 [1]	<0.005
	Mn (ppm)	5511	35.2 [1]	<0.005
	Mo (ppm)	146	121.6 [1]	<0.005
	Ni (ppm)	145	96.9 [1]	<0.005
	Pb (ppm)	47	67.9 [1]	<0.005
	Sb (ppm)	NR	NA	NA
	Se (ppm) [3]	ND	NA	NA
	Sr (ppm)	267	34.0 [1]	<0.005
	V (ppm)	82	132.8 [1]	<0.005
	Zn (ppm)	1118	77.6 [1]	<0.005

Notes: NR - Not Reported

NA - Not Applicable

ND - Not Detected

[1] Not Normally Distributed

[2] Based on Anderson-Darling Statistics

[3] Dry Basis

The proximate and ultimate analyses of all the fuels used in CTS burn are shown in Table 4.42. The chemical compositions of all the fuels used in CTS burn are shown in Table 4.43. From these tables, composition and properties of switchgrass can be compared to those of coal and tires.

It is observed that the ash content is much lower and volatile matter is much higher in switchgrass than in both coal and tires. Sulfur content is also very low compared to both coal and tires. Switchgrass, like coal, is rich in SiO_2 and CaO but has lower Al_2O_3 and Fe_2O_3 contents than both coal and tires. The P_2O_5 and MgO contents of switchgrass are higher than that of both coal and tires. Switchgrass has a low heating value as compared to both coal and tires. The arsenic content is lower than the value for coal but the lead content is higher than that of tires.

Table 4.42: ELR – Proximate and Ultimate analyses of all fuels from CTS burn

Test	Parameter	CTS burn		
		Coal	Tires	Switchgrass
Proximate Analysis	**Ash (wt. %)**	16.5	24.4	5.3
	Fixed Carbon (wt. %)	55.2	19.8	17.0
	Volatile Matter (wt. %)	28.4	55.8	77.7
Ultimate Analysis	**Carbon (wt. %)**	71.3	72.6	50.2
	Hydrogen (wt. %)	3.8	0.2	5.7
	Nitrogen (wt. %)	1.0	0.4	1.2
	Oxygen (wt. %)	6.4	1.1	37.4
	Sulfur (wt. %)	1.1	1.3	0.2
Heat Value (BTU/lb)		12664	13239	8162

Table 4.43: ELR – Standard parameters of all fuels from CTS burn

Test	Parameter	CTS burn		
		Coal	Tires	Switchgrass
Standard Parameters	**Al_2O_3 (wt. %)**	23.87	0.53	1.57
	CaO (wt. %)	12.81	2.94	13.99
	Fe_2O_3 (wt. %)	7.77	77.06	1.06
	K_2O (wt. %)	2.56	0.25	24.72
	MgO (wt. %)	1.31	0.20	9.02
	Na_2O (wt. %)	0.57	0.13	0.96
	P_2O_5 (wt. %)	0.12	0.20	8.49
	SiO_2 (wt. %)	49.44	5.38	34.86
	SO_3 (wt. %)	0.33	2.25	4.53
	TiO_2 (wt. %)	1.04	0.10	0.14
	As (ppm)	114	ND	11
	Ba (ppm)	1100	0	739
	Cd (ppm) ^{1}	ND	ND	ND
	Cl (ppm) ^{1}	236	1696	819
	Co (ppm)	43	724	6
	Cr (ppm)	132	129	22
	Cu (ppm)	103	0	56
	Hg (ppm) ^{1}	0.076	NR	0
	Mn (ppm)	500	4300	5511
	Mo (ppm)	29	11	146
	Ni (ppm)	78	332	145
	Pb (ppm)	ND	8	47
	Sb (ppm)	NR	NR	NR
	Se (ppm) ^{1}	7	ND	ND
	Sr (ppm)	400	20	267
	V (ppm)	228	10	82
	Zn (ppm)	9	0	1118

Notes: ND - Not Detected NR - Not Reported

^{1} Dry Basis

4.3.4 Chemical Composition of Cement Kiln Dust (CKD)

The cement plant collected two cement kiln dust samples every day during each of the burns. Each of these samples was tested once for the standard cement plant parameters, except for moisture and loss on ignition. Since only six data points of results of CKD were available for each burn, complete summary statistics are not presented.

CKD, like emissions, can be sensitive to changes in the raw materials' composition and it was decided to analyze the data using different baselines for different fuel burns, as discussed in Section 4.3. Table 4.44 shows the results of the tests for the baseline burns, along with the percent differences relative to CT1 burn.

Table 4.44: CPR –Baseline burns, Chemical analysis and percent difference for cement kiln dust

Test	Parameter	Burn CT1	Burn CT2		Burn CT3	
		Value (wt. %)	Value (wt. %)	% Diff.	Value(wt. %)	% Diff.
Standard Parameters	**Al_2O_3**	4.00	3.71	-7.1	3.77	-5.6
	CaO	44.69	45.06	0.8	45.49	1.8
	Fe_2O_3	2.01	1.96	-2.9	1.89	-6.4
	K_2O	0.42	0.44	5.1	0.38	-8.9
	MgO	1.65	1.30	-21.6	1.29	-22.2
	Na_2O	0.09	0.04	-58.3	0.07	-19.8
	SiO_2	12.05	11.99	-0.5	11.06	-8.2
	SO_3	0.95	0.17	-82.1	0.29	-69.1

It is observed that there is less than 2 percent variation in CaO content and less than 9 percent variation in SiO_2, the major constituents of CKD, as reported by the cement plant. This result is consistent with the chemical compositions of kiln feed reported in Section 4.3.2 and Table 4.19. However, as found in case of kiln feed, some of the results for CKD, reported by the external laboratory in Table 4.45, are quite different from those reported by the cement plant.

Table 4.45: ELR –Baseline burns, Chemical composition of cement kiln dust

Parameter	CT1 burn	CT2 burn		CT3 burn	
	Value	Value	% Diff.	Value	% Diff.
Al_2O_3 (wt. %)	3.72	5.46	46.9	5.75	54.6
CaO (wt. %)	46.78	69.91	49.4	69.46	48.5
Fe_2O_3 (wt. %)	2.10	2.99	42.3	2.85	35.8
K_2O (wt. %)	0.57	0.65	15.1	0.55	-3.6
MgO (wt. %)	1.53	2.16	40.9	2.20	43.8
Na_2O (wt. %)	0.02	0.07	251.2	0.08	313.8
P_2O_5 (wt. %)	0.05	0.06	28.2	0.09	85.5
SiO_2 (wt. %)	11.08	17.87	61.3	17.61	59.0
SO_3 (wt. %)	1.26	0.32	-74.3	0.89	-29.4
TiO_2 (wt. %)	0.22	0.34	55.6	0.33	52.4
Moisture (wt. %)	0.22	0.28	27.5	0.17	-23.0
LOI (wt. %)	32.55	35.60	9.4	36.06	10.8
As (ppm)	18	28	53.9	27	51.4
Ba (ppm)	309	452	46.1	394	27.5
Cd (ppm)	ND	ND	NA	ND	NA
Cl (ppm)	60	205	245.1	155	159.9
Co (ppm)	17	13	-24.5	10	-39.6
Cr (ppm)	45	57	28.3	66	47.9
Cu (ppm)	15	21	40.7	31	107.8
Hg (ppm)	ND	0.46	NA	ND	NA
Mn (ppm)	168	697	314	1000	494.2
Mo (ppm)	ND	3	NA	NA	NA
Ni (ppm)	15	10	-31.3	14	-7.6
Pb (ppm)	18	14	-25.6	17	-6.2
Sb (ppm)	58	NA	NA	NA	NA
Se (ppm)	2	NA	NA	NA	NA
Sr (ppm)	293	493	68.2	591	101.4
V (ppm)	50	73	45.8	75	50.3
Zn (ppm)	101	28	-72.3	215	113.5

Notes: ND - Not Detected NA - Not Applicable

The high percentage differences of CaO and SiO_2 in CKD over the three baseline burns, as reported by the external laboratory, show exactly the same trend as in the case of kiln feed, observed in Table 4.20. Similarly, the trend of increase in chlorine and manganese content in CKD over the baseline burns in Table 4.45 can be correlated to the increase of the same in kiln feed, as observed in Table 4.19. This again validates the data and confirms that the chemical composition of the process inputs was indeed different for different baselines.

The differences in the chemical composition of CKD between the fuel burns relative to their respective baseline burns as reported by the cement plant are presented in Table 4.46. It can be seen that there is less than 7 percent difference in CaO content and about 10 percent difference in SiO_2 content, the major constituents of CKD based on the cement plant results. The average values of other parameters are small and hence even a slight and practically insignificant change appears as a large percentage difference. The percentage difference values for all the parameters of CKD determined by the cement plant are plotted in Figure 4.4.

Table 4.47 presents the variation in chemical composition of CKD between the fuel burns relative to their respective baseline burn based on the results from the external laboratory. The trends from the external laboratory for CKD compositions are similar to those from the cement plant except for the CTW and CTS burns. The percentage differences in major parameters are much higher for the CTW and CTS burns for results from the external laboratory as compared to the results from the cement plant.

Table 4.46: CPR –Fuel Burns, Chemical composition of cement kiln dust relative to baseline burns

Test	Parameter	Burn C		Burn CTP		Burn CTB		Burn CTW		Burn CTS	
		Value (wt. %)	% Diff. [1]	Value (wt. %)	% Diff. [2]	Value (wt. %)	% Diff. [3]	Value (wt. %)	% Diff. [3]	Value (wt. %)	% Diff. [3]
Standard Parameters	**Al_2O_3**	3.69	-7.6	3.65	-1.6	3.85	2.0	4.12	9.3	3.97	5.1
	CaO	47.55	6.4	47.63	5.7	44.78	-1.6	44.59	-2.0	44.35	-2.5
	Fe_2O_3	1.82	-9.7	1.74	-11.2	1.88	-0.1	2.07	9.6	2.00	5.9
	K_2O	0.48	14.7	0.38	-12.9	0.51	33.3	0.53	38.2	0.58	51.6
	MgO	1.66	0.2	1.81	39.4	1.39	8.0	1.34	3.8	1.33	3.4
	Na_2O	0.07	-18.3	0.05	44.0	0.05	-27.3	0.04	-48.1	0.05	-27.3
	SiO_2	11.68	-3.0	11.57	-3.5	11.50	4.0	12.17	10.0	12.15	9.9
	SO_3	1.13	18.9	0.85	397.5	0.27	-6.6	0.26	-10.5	0.20	-31.1

Notes: NA - Not Applicable [2] Relative to Burn CT2
[1] Relative to Burn CT1 [3] Relative to Burn CT3

4.3.5 Chemical Composition of Clinker

Clinker is the primary output of the kiln process. For that reason, more clinker samples were collected for chemical analysis than any other material. Twelve samples of clinker were collected per day by the cement plant. Each of these samples was tested to determine chemical composition. The results shown in Tables 4.48 and 4.49 are the summary statistics from at least 36 discrete samples collected for each burn at the cement plant. The coefficient of variation (C.V. %) represents the measure of deviation from the mean of the data. From Tables 4.48 and 4.49, it can be observed that most of the data for clinker provided by the cement plant have low C.V. values, indicating that the sample mean (given average) is close to the true value (idealistic mean of an infinite number of data points) .Whenever the P-value is less than 0.1, the data is not normally distributed.

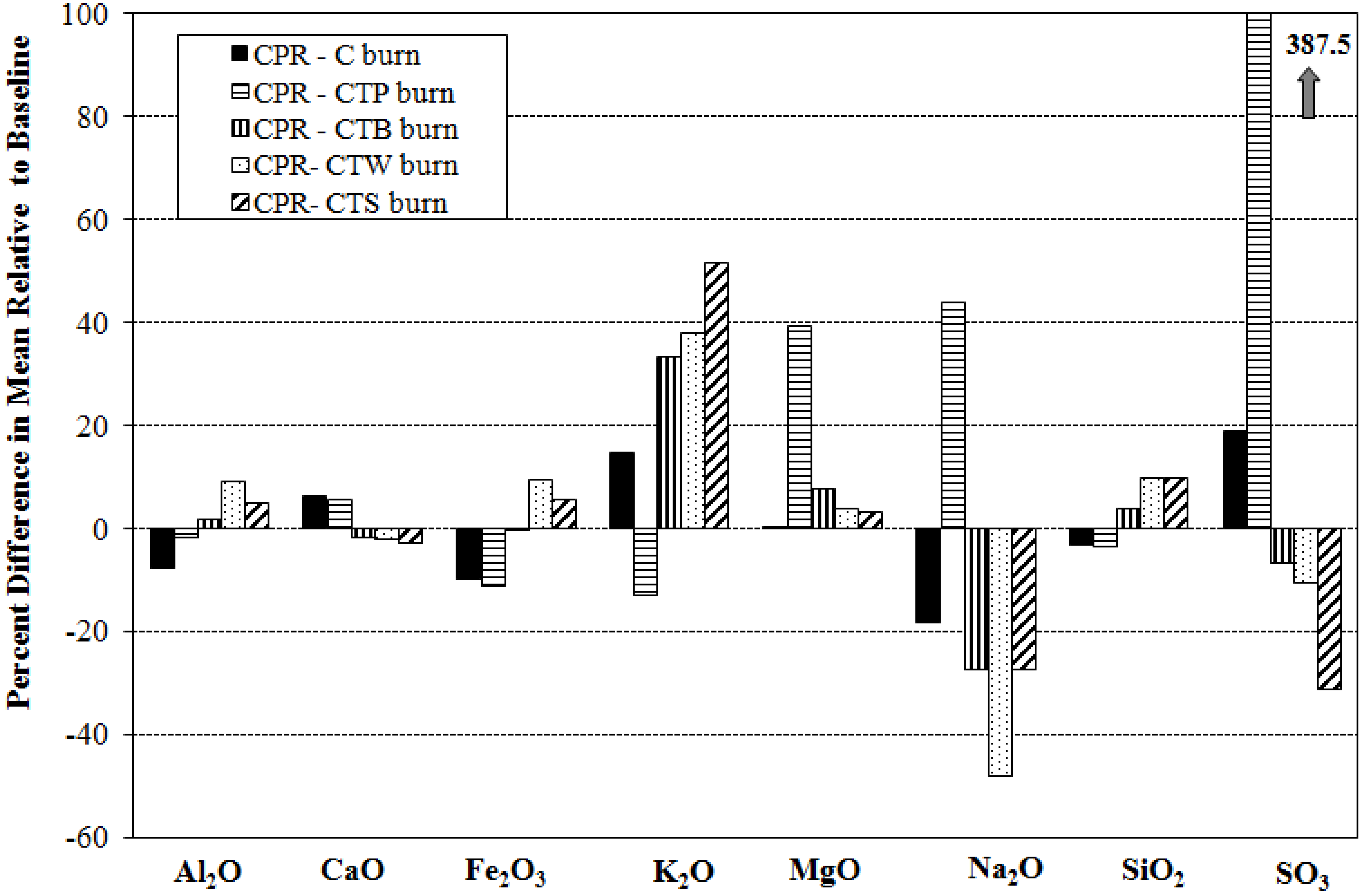


Figure 4.4: CPR-Fuel Burns, Percentage difference in CKD composition relative to baseline burns

Table 4.47: ELR –Fuel Burns, Chemical composition of cement kiln dust relative to baseline burns

Parameter	C burn		CTP burn		CTB burn		CTW burn		CTS burn	
	Value	% Diff.^{1}	Value	% Diff.^{2}	Value	% Diff.^{3}	Value	% Diff.^{3}	Value	% Diff.^{3}
Al_2O_3 (wt. %)	3.77	1.3	5.12	-6.3	6.00	4.4	3.86	-32.9	3.89	-32.3
CaO (wt. %)	56.33	20.4	72.01	3.0	69.60	0.2	43.64	-37.2	44.02	-36.6
Fe_2O_3 (wt. %)	2.01	-4.3	2.58	-13.8	2.99	5.0	1.99	-30.1	2.00	-29.8
K_2O (wt. %)	0.43	-24.5	0.47	-28.6	0.84	53.4	0.42	-23.9	0.58	6.0
MgO (wt. %)	1.90	23.9	2.54	18.0	2.16	-2.0	1.32	-40.2	1.37	-37.9
Na_2O (wt. %)	0.01	-49.5	0.08	14.7	0.08	2.7	0.06	-33.1	0.09	9.5
P_2O_5 (wt. %)	0.06	20.2	0.07	2.2	0.09	-4.3	0.04	-62.0	0.07	-26.7
SiO_2 (wt. %)	11.32	2.2	15.71	-12.1	17.19	-2.4	11.95	-32.1	11.58	-34.3
SO_3 (wt. %)	1.43	14.0	1.01	213.0	0.56	-36.8	0.25	-71.7	0.29	-67.4
TiO_2 (wt. %)	0.22	0.3	0.25	-25.4	0.31	-7.6	0.20	-40.5	0.17	-50.1
Moisture (wt. %)	0.07	-70.1	0.14	-51.9	0.24	41.9	3.17	NA	0.24	37.0
LOI (wt. %)	22.54	-30.7	33.25	-6.6	35.42	-1.8	36.19	0.4	35.85	-0.6
As (ppm)	4	-79.4	29	5.8	33	21.5	16	-42.6	22	-21.2
Ba (ppm)	278	-9.9	333	-26.3	500	26.9	217	-45.0	250	-36.5
Cd (ppm)	ND	NA	NR	NA	ND	NA	ND	NA	ND	NA
Cl (ppm)	483	711	131	-36.2	734	375	538	248	303	95.9
Co (ppm)	15	-9.6	13	3.8	15	47.3	10	-1.9	16	59.6
Cr (ppm)	33	-26.4	54	-6.0	59	-11.4	114	71.8	70	4.9
Cu (ppm)	49	229	47	122	35	12.7	12	-63.2	19	-39.1
Hg (ppm)	0	NA	NR	NA	2	NA	1	NA	0	NA
Mn (ppm)	315	87.2	883	26.6	NA	NA	517	-48.3	550	-45.0
Mo (ppm)	ND	NA	16	381.4	3	NA	7	NA	11	NA
Ni (ppm)	11	-25.5	14	38.1	15	9.4	11	-19.4	586	4193
Pb (ppm)	20	10.9	22	60.7	18	2.9	22	26.4	17	-3.4
Sb (ppm)	55	-5.2	NR	NA	NA	NA	NR	NA	NR	NA
Se (ppm)	1	-41.8	NR	NA	NA	NA	ND	NA	ND	NA
Sr (ppm)	321	9.3	533	8.0	NA	NA	300	-49.2	300	-49.2
V (ppm)	55	10.0	64	-12.0	75	0.6	66	-11.9	67	-11.3
Zn (ppm)	91	-9.2	38	36.1	66	-69.1	38	-82.3	34	-84.3

Notes: ND - Not Detected NR- Not Reported NA- Not Applicable CIP- Collection in Progess

[1] Relative to Burn CT1 [2] Relative to Burn CT2 [3] Relative to Burn CT3

Table 4.48 CPR - Summary statistics of chemical composition of clinker for C, CT1, CTP and CT2 burns

Parameter	C burn			CT1 burn			CTP burn			CT2 burn		
	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value
Al_2O_3	5.30	3.2 [1]	0.033	5.08	2.0	0.840	5.15	2.0 [1]	<0.005	5.08	2.13 [1]	<0.005
CaO	64.97	0.4	0.116	64.49	0.2	0.908	64.56	0.6 [1]	0.039	64.62	0.75 [1]	0.022
Fe_2O_3	3.41	6.6 [1]	0.012	3.36	4.7	0.289	3.57	6.1 [1]	<0.005	3.41	3.4	0.204
K_2O	0.56	4.1 [1]	0.022	0.48	3.8	0.118	0.47	4.6 [1]	0.077	0.50	8.2 [1]	0.011
MgO	2.93	2.3	0.453	3.48	5.4 [1]	<0.005	3.25	3.3	0.589	3.38	4.7	0.345
Na_2O	0.07	6.8 [1]	<0.005	0.10	9.6 [1]	<0.005	0.07	5.8 [1]	<0.005	0.06	4.6 [1]	<0.005
Na_2O_{eq}	0.44	3.7 [1]	0.022	0.42	3.7 [1]	0.069	0.38	4.4 [1]	0.053	0.39	7.6 [1]	<0.005
SiO_2	21.38	0.9	0.391	21.23	0.9	0.869	21.31	1.2 [1]	<0.005	21.52	1.4 [1]	<0.005
SO_3	0.85	12.1	0.323	0.67	12.1	0.117	0.92	21.1 [1]	<0.005	0.70	14.2 [1]	<0.005
Free CaO	1.10	37.1	0.605	1.06	38.8 [1]	<0.005	1.24	41.0	0.374	0.78	49.6 [1]	0.084
C_3A	8.28	6.8 [1]	0.043	7.78	4.9	0.416	7.62	5.4 [1]	0.021	7.70	2.9 [1]	0.021
C_4AF	10.38	6.7 [1]	0.009	10.22	4.7	0.206	10.86	6.2 [1]	<0.005	10.39	3.4 [1]	<0.005
C_3S	61.49	4.4	0.362	62.24	2.8	0.544	61.15	3.9 [1]	0.033	60.47	2.0 [1]	0.055
C_2S	14.91	16.6	0.742	13.92	13.2	0.602	14.97	16.4 [1]	0.007	16.08	10.1 [1]	0.001

Notes: [1] Data Not Normally Distributed

Table 4.49 CPR - Summary statistics of chemical composition of clinker for CTB, CT3, CTW and CTS burns

Parameter	CTB burn			CT3 burn			CTW burn			CTS burn		
	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value
Al_2O_3	5.27	1.9	0.416	5.29	2.2[1]	<0.005	5.04	2.1[1]	0.032	5.09	2.4[1]	<0.005
CaO	64.32	0.6[1]	<0.005	64.49	0.5	0.303	64.76	0.4	0.311	64.74	0.2[1]	0.093
Fe_2O_3	3.13	2.6	0.542	3.39	4.9	0.121	3.21	4.1[1]	<0.005	3.39	1.8	0.177
K_2O	0.63	5.4[1]	0.077	0.52	4.9[1]	0.011	0.57	14.7	0.177	0.64	7.1	0.412
MgO	3.18	3.7	0.612	3.31	3.4	0.685	3.26	2.0	0.572	3.15	2.1	0.625
Na_2O	0.08	11.8[1]	<0.005	0.08	13.8[1]	<0.005	0.06	17.8[1]	<0.005	0.09	5.3	0.179
Na_2O_{eq}	0.49	5.3	0.413	0.42	4.3[1]	0.035	0.43	11.6	0.253	0.51	6.4[1]	<0.005
SiO_2	21.45	1.3	0.323	21.34	0.8[1]	<0.005	21.51	0.7	0.304	21.48	0.4	0.226
SO_3	0.79	5.4	0.202	0.79	9.8[1]	0.080	0.84	42.5[1]	<0.005	0.64	18.3[1]	<0.005
Free CaO	0.98	34.2	0.374	1.08	34.3	0.374	1.20	40.5	0.374	1.01	58.3[1]	<0.005
C_3A	8.67	2.3	0.721	8.29	3.5[1]	0.012	7.91	2.8[1]	0.031	7.77	3.6[1]	0.021
C_4AF	9.52	2.6[1]	<0.005	10.31	4.9[1]	<0.005	9.76	4.1	0.102	10.30	1.9[1]	<0.005
C_3S	58.94	3.3[1]	0.033	59.97	2.7	0.213	61.76	2.7	<0.005	61.26	2.6	0.143
C_2S	17.03	12.7	0.807	15.96	9.9[1]	<0.005	15.09	9.3	0.007	15.36	8.9	0.107

Notes: [1] Data Not Normally Distributed

Table 4.50 shows the percent difference of the means for Baseline Burns CT2 and CT3 relative to the mean of CT1 burn. This table also shows whether or not the difference in each mean is statistically significant, along with the P-value, which is the indicator of significance.

Table 4.50 CPR –Baseline Burns, Percent difference and statistical significance for clinker relative to CT1 burn

Parameter	Burn CT2			Burn CT3		
	Percent Difference	P-Value	Significant	Percent Difference	P-Value	Significant
Al_2O_3	0.06	0.350	No	4.13	0.005	Yes
CaO	0.21	0.250	No	0.01	0.300	No
Fe_2O_3	1.66	0.411	No	0.97	0.000	Yes
K_2O	4.39	0.000	Yes	6.96	0.000	Yes
MgO	-2.79	0.000	Yes	-5.06	0.105	No
Na_2O	-39.82	0.000	Yes	-17.48	0.000	Yes
Na_2O_{eq}	-6.49	0.000	Yes	1.11	0.000	Yes
SiO_2	1.37	0.105	No	0.52	0.130	No
SO_3	4.94	0.000	Yes	17.42	0.000	Yes
Free CaO	-26.20	0.000	Yes	1.65	0.000	Yes
C_3A	-1.10	0.000	Yes	6.51	0.086	Yes
C_4AF	1.69	0.000	Yes	0.91	0.200	No
C_3S	-2.85	0.000	Yes	-3.66	0.031	Yes
C_2S	15.49	0.055	Yes	14.67	0.042	Yes

In most of the parameters, there was a statistically significant difference between the means of the baseline burns. However, this does not mean that the difference is of practical significance. The major parameters, CaO and SiO_2, showed little percentage difference in means and they are not statistically different either. However, the Bogue compounds showed statistically significant differences. The percentage difference for fuel burns relative to the respective baseline burns based on the cement plant results are shown in Table 4.51. Also, whether or not the difference in each mean is statistically significant, along with the P-value, which is the indicator of significance are shown.

Most of the parameters from the fuel burns showed statistically significant differences in means relative to their respective baseline burns. However, the actual percentage differences in CaO and SiO_2, the major parameters, are small and not of practical significance. The percentage differences in standard parameters based on cement plant results are graphically presented in Figure 4.5.

The major differences were found in SO_3 content at 27 percent in Burn C and 31 percent in CTP burn. However, the total SO_3 content of the cement is regulated by the controlled addition of gypsum prior to grinding. The Free CaO content was increased for CTP burn, which perhaps can be correlated to the high content of CaO in waste plastics in Table 4.29. It is interesting to note that the content of Bogue compounds was not altered much by introduction of alternative fuels with less than 8 percent change at its worst. K_2O and Na_2O contents were altered by considerable percentages; their impact on cement performance can best be evaluated by looking at the equivalent alkali content, Na_2O_{eq} ($Na_2O + 0.658 \times K_2O$). Most of the other parameters for fuel burns saw less than 5 percent change relative to the respective baseline burn.

The external laboratory results of chemical analysis on composite samples are presented in Table 4.52. The major parameters followed the same trend as found in the cement plant results. The arsenic content was found to be increased by about 73 percent for CTP burn and 30 percent for CTB burn but was much lower for C burn. The lead content was lowered whenever alternative fuels were used. The zinc content was increased for the CTP burn but was lowered for all other trial burns.

Table 4.51 CPR – Percent differences and statistical significance for clinker

Parameter	**C burn**			**CTP burn**			**CTB burn**			**CTW burn**			**CTS burn**		
	% Diff.[1]	**P-Value**	**Significant**	**% Diff.**[2]	**P-Value**	**Significant**	**% Diff.**[3]	**P-Value**	**Significant**	**% Diff.**[3]	**P-Value**	**Significant**	**% Diff.**[3]	**P-Value**	**Significant**
Al_2O_3	4.40	0.000	Yes	1.31	0.005	Yes	-0.34	0.000	Yes	-4.81	0.000	Yes	-3.71	0.001	Yes
CaO	0.74	0.000	Yes	-0.10	0.310	No	-0.27	0.000	Yes	0.41	0.125	No	0.38	0.000	Yes
Fe_2O_3	1.60	0.241	No	4.49	0.000	Yes	-7.74	0.100	No	-5.42	0.000	Yes	-0.14	0.037	Yes
K_2O	16.00	0.000	Yes	-7.77	0.000	Yes	21.95	0.000	Yes	9.37	0.201	No	23.37	0.000	Yes
MgO	-15.81	0.000	Yes	-3.83	0.000	Yes	-3.80	0.000	Yes	-1.22	0.005	Yes	-4.76	0.102	No
Na_2O	-26.47	0.000	Yes	15.98	0.000	Yes	-6.04	0.000	Yes	-33.07	0.000	Yes	12.51	0.000	Yes
Na_2O_{eq}	5.92	0.000	Yes	-4.03	0.000	Yes	15.97	0.000	Yes	0.86	0.000	Yes	20.72	0.000	Yes
SiO_2	0.70	0.001	Yes	-0.99	0.135	No	0.49	0.001	Yes	0.77	0.000	Yes	0.64	0.120	No
SO_3	27.00	0.000	Yes	30.88	0.000	Yes	0.90	0.000	Yes	6.57	0.189	No	-18.48	0.000	Yes
Free CaO	3.80	0.647	No	58.45	0.000	Yes	-9.06	0.000	Yes	11.43	0.000	Yes	-6.48	0.000	Yes
C_3A	6.43	0.000	Yes	-0.99	0.086	Yes	4.65	0.000	Yes	-4.51	0.071	Yes	-6.23	0.212	No
C_4AF	1.56	0.253	No	4.54	0.000	Yes	-7.64	0.090	Yes	-5.35	0.212	No	-0.11	0.000	Yes
C_3S	-1.20	0.166	No	1.13	0.031	Yes	-1.71	0.000	Yes	2.99	0.035	Yes	2.16	0.010	Yes
C_2S	7.10	0.055	Yes	-6.88	0.042	Yes	6.68	0.005	Yes	-5.47	0.043	Yes	-3.74	0.024	Yes

Notes: [1] Relative to Burn CT1 [2] Relative to Burn CT2 [3] Relative to Burn CT3

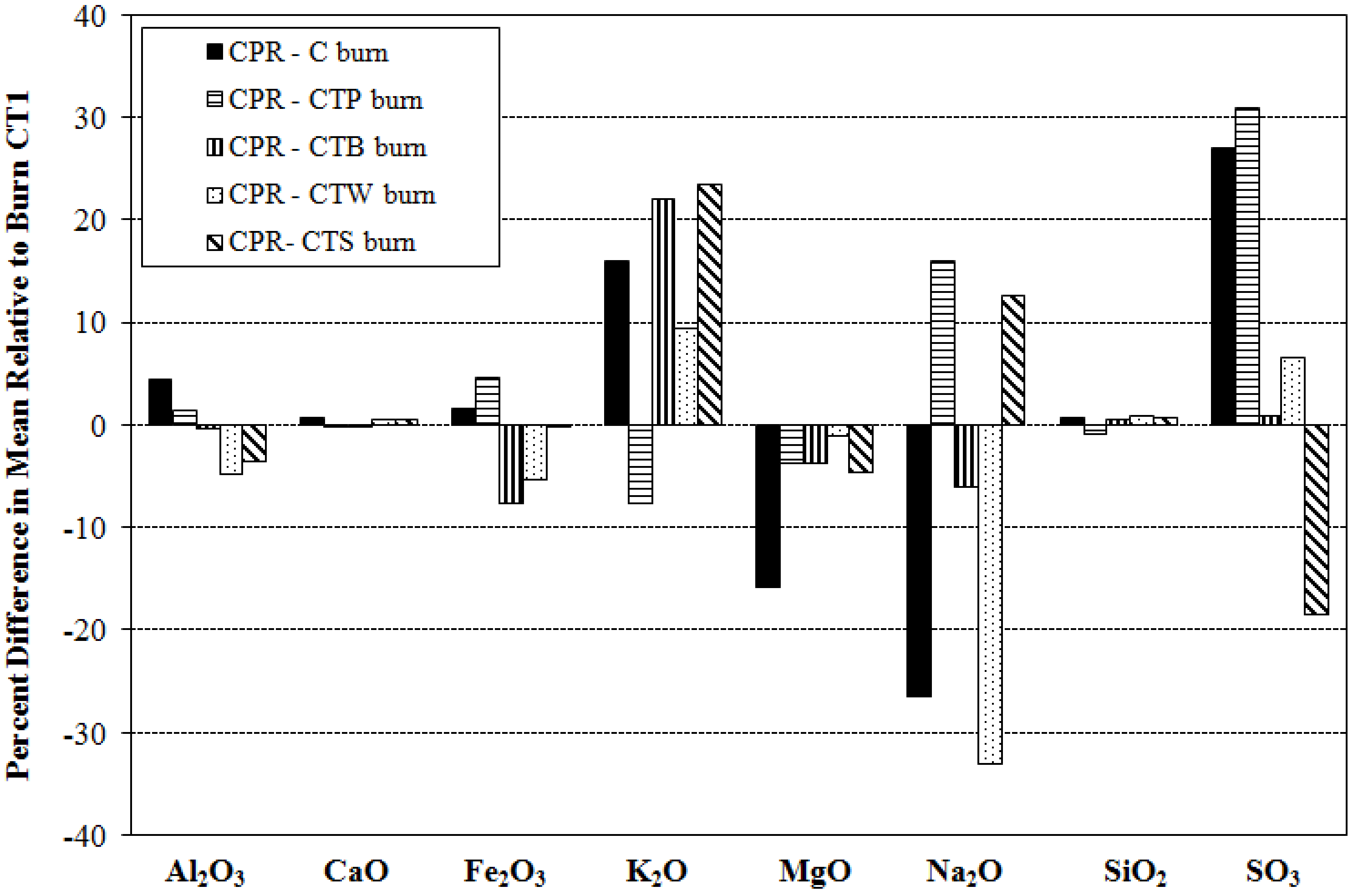


Figure 4.5: CPR- Fuel Burns, Percentage difference in clinker composition relative to baseline burns

The most important results from Tables 4.51 and 4.52 and Figure 4.5 are the percent changes in Al_2O_3, CaO, Fe_2O_3, and SiO_2. Each showed very little change between the burns from both the cement plant and the external laboratory results. These results are significant because these four parameters are the primary compounds in the clinker, and are the ones that have the most effect on cement and concrete properties. Based on these results, it can be concluded that the cement plant is capable of maintaining consistent concentrations of the primary parameters in the clinker, regardless of the fuels that are used.

The final result concerning the chemical composition of clinker is from Rietveld analysis conducted at cement plant's specialty laboratory. This test determines the principal cement compounds in the clinker more accurately than the Bogue formulae used in ASTM C 150. These results, along with the percent difference of baseline burns relative to CT1 burn, are shown in Table 4.53. The results for the fuel burns relative to the respective baseline burn are presented in Table 4.54.

From Table 4.54, it can be observed that the percentage differences for Bogue compounds from all the alternative fuel burns were small except for C_3A (aluminate) in CTP , CTB and CTS burns, and C_2S (belite) in CTW and CTS burns.

Table 4.52: ELR –Fuel Burns, Percent differences for clinker relative to baseline burn

Parameter	C burn		CTP burn		CTB burn		CTS burn		CTW burn	
	Value (wt %)	% Diff.[1]	Value (wt %)	% Diff.[2]	Value (wt %)	% Diff.[3]	Value (wt %)	% Diff.[3]	Value (wt %)	% Diff.[3]
Al_2O_3	5.27	4.60	4.96	0.5	5.06	-5.8	5.1	-5.9	4.83	-10.3
CaO	65.15	1.36	64.71	-0.1	64.73	0.8	64.4	0.4	65.34	1.8
Fe_2O_3	3.34	2.38	3.33	2.7	2.93	-10.2	3.1	-6.0	3.34	2.3
K_2O	0.60	16.49	0.42	-21.8	0.66	44.8	0.5	18.6	0.59	29.8
MgO	2.88	-18.43	3.40	-2.3	3.34	-1.5	3.3	-1.3	3.35	-1.4
Na_2O	0.01	-69.86	0.10	63.2	0.08	-5.2	0.1	-13.8	0.12	41.4
P_2O_5	0.08	19.33	0.07	27.8	0.10	49.7	0.1	-28.7	0.07	3.4
SiO_2	21.24	-2.92	21.51	-0.4	21.80	-0.3	22.1	1.2	21.03	-3.9
SO_3	0.97	37.34	0.98	27.7	0.81	8.3	0.6	-14.9	0.71	-5.8
TiO_2	0.30	14.07	0.26	-2.1	0.24	-11.9	0.3	-8.1	0.22	-21.5
Moisture	0.01	-59.87	0.00	-100.0	0.06	-65.0	0.0	-81.8	0.00	-100.0
LOI	0.15	-60.31	0.13	-41.9	0.33	42.1	0.1	-40.3	0.21	-12.6
	Value (ppm)	% Diff.	Value (ppm)	% Diff.[2]	Value (ppm)	% Diff.	Value (ppm)	% Diff.[3]	Value (ppm)	% Diff.[3]
As	9	-59.25	36	72.9	23	29.5	18	2.6	26	44.8
Ba	366	79.84	367	-18.7	453	15.8	317	-19.1	325	-16.9
Cd	ND	NA	NR	NA	NA	NA	NA	NA	ND	NA
Cl	239	-43.75	177	22.6	303	98.3	292	90.5	399	160.6
Co	15	NA	12	21.9	10	2.5	9	-7.5	16	60.8
Cr	72	-7.58	90	4.2	93	-21.9	98	-17.6	104	-12.1
Cu	65	154.43	28	61.8	29	18.0	15	-39.5	67	171.6
Hg	0.02	-41.67	NR	NA	0	-81.3	0	-47.7	0	-74.7
Mn	959	81.75	1683	141.3	781	-58.0	2100	13.0	1525	-18.0
Mo	12	NA	19	303.1	4	28.7	5	34.6	18	417.1
Ni	43	142.23	15	63.4	13	12.7	8	-32.8	137	1116
Pb	36	6.55	12	-40.8	15	-25.8	17	-16.0	18	-11.3
Sb	57	15.79	NR	NA	NA	NA	NA	NA	NR	NA
Se	1	-50.24	NR	NA	3	50.0	NA	NA	ND	NA
Sr	402	1.43	500	1.3	513	4.8	400	-18.2	400	-18.2
V	64	-1.52	66	4.0	67	-3.1	66	-4.2	71	3.0
Zn	135	-28.01	68	82.7	99	-69.0	75	-76.7	81	-74.8

Notes: ND- Not Detected NR- Not reported NA-Not Applicable CIP- Collection in progress

[1] Relative to Burn CT1 [2] Relative to Burn CT2 [3] Relative to Burn CT3

Table 4.53: SLR –Baseline Burns, Rietveld analysis of clinker relative to CT1 burn

Parameter	CT1 burn	CT2 Burn		CT3 Burn	
	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Alite (C_3S)	62.52	55.69	-10.93	59.33	-5.11
Belite (C_2S)	18.54	22.10	19.20	21.11	13.86
Ferrite (C_4AF)	10.63	10.78	1.44	11.36	6.90
Aluminate (C_3A)	4.28	3.14	-26.71	3.63	-15.26

Table 4.54: SLR –Fuel Burns, Rietveld analysis of clinker relative to the baseline burns

Parameter	C burn		CTP burn		CTB burn		CTW burn		CTS burn	
	Value (wt. %)	Diff.[1]	Value (wt. %)	% Diff.[2]	(wt. %)	% Diff.[3]	(wt. %)	% Diff.[3]	(wt. %)	% Diff.[3]
Alite (C_3S)	65.11	4.1	56.67	1.75	60.00	1.13	66.16	11.51	64.40	8.55
Belite (C_2S)	17.12	-7.7	23.91	8.17	20.99	-0.57	15.38	-27.13	16.35	-22.57
Ferrite (C_4AF)	6.36	-40.2	11.47	6.40	10.06	-11.44	10.87	-4.34	11.31	-0.44
Aluminate (C_3A)	5.67	32.5	2.94	-6.16	5.23	44.30	3.62	-0.28	3.40	-6.39

Notes: [1] Relative to Burn CT1 [2] Relative to Burn CT2 [3] Relative to Burn CT3

4.3.6 Portland Cement

Portland cement is the primary output from the overall production process. Because of this, it was sampled very frequently at the cement plant. The samples that were collected were tested for their chemical composition by both the cement plant and the external laboratory. Discrete samples were tested at the cement plant and one-day composite samples were sent to the external laboratory for testing. As discussed earlier in Section 4.1, CT1 burn will be considered as the baseline reference for the fuel burns.

4.3.6.1 Chemical Composition of Cement

The tests at the cement plant were conducted on eight discrete specimens each day during all the burns. The complete set of summary statistics, based on the results collected by the cement plant, is shown in Table 4.55. All parameters are presented as percentage weights except for the Blaine specific surface area (SSA) which is given in m^2/kg.

Table 4.56 shows the percent difference relative to CT1 burn between all the parameters tested at cement plant. Almost every parameter showed a statistically significant change relative to CT1 burn. SO_3 and Blaine specific surface area did not show any significant difference for all burns. None of the alternative fuel burns showed any significant differences in CaO and MgO contents.

The percentage differences for the major parameters for all the fuel burns relative to CT1 burn are plotted in Figure 4.6. The percent differences in Bogue compounds in cement for all fuel burns relative to CT1 burn are plotted in Figure 4.7.

It must be remembered that just because many parameters showed a statistically significant difference, it does not mean that these same parameters have shown a practically significant difference. Practical significance, as mentioned earlier, is determined by the performance of the cement, and whether a statistically significant difference in a parameter significantly alters the behavior of the cement.

The portland cement that was sampled at the cement plant was prepared into daily composite samples each day by personnel from Auburn University. It was these composite samples that were tested by the external laboratory. The external laboratory determined the standard parameters using XRF. Additionally, the total organic carbon (TOC) was determined using a total organic carbon analyzer, and the Bogue Compounds were calculated in accordance with ASTM C 150. The results of these tests, along with the percent difference relative to CT1 burn, are shown in Tables 4.57 and 4.58.

Table 4.55: CPR –All Burns, Summary statistics of cement composition

Parameter	Burn C			Burn CT			Burn CTP			Burn CTB			Burn CTW			Burn CTS		
	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value	Average (wt. %)	C.V. (%)	P-Value
Al_2O_3	4.98	2.8 [1]	0.065	4.66	2.1	0.331	4.85	2.2	0.164	4.87	0.6 [1]	0.045	4.64	0.9	0.216	4.79	0.4	0.123
CaO	63.49	0.5	0.843	62.56	0.7 [1]	0.008	62.79	0.8 [1]	0.009	62.13	0.7	0.305	63.66	0.3	0.150	63.20	0.2	0.100
Fe_2O_3	3.11	3.2 [1]	0.056	3.02	3.0	0.297	3.22	3.8 [1]	<0.005	2.94	0.7	0.315	3.15	1.4 [1]	<0.005	3.18	0.3	0.165
K_2O	0.52	1.9 [1]	<0.005	0.45	3.4 [1]	0.023	0.44	2.5 [1]	0.021	0.48	6.5 [1]	<0.005	0.51	2.0	0.100	0.56	1.1 [1]	0.052
MgO	2.88	2.9 [1]	<0.005	3.28	5.5 [1]	<0.005	3.22	1.8 [1]	0.095	3.22	1.8 [1]	0.025	3.13	0.7 [1]	<0.005	3.25	0.7	0.352
Na_2O	0.09	7.8 [1]	<0.005	0.12	12.0 [1]	<0.005	0.09	8.0 [1]	<0.005	0.09	8.6 [1]	<0.005	0.06	5.0 [1]	<0.005	0.08	7.3 [1]	<0.005
Na_2O_{eq}	0.44	1.6	<0.005	0.41	2.9 [1]	<0.005	0.38	2.1 [1]	<0.005	0.41	6.0 [1]	<0.005	0.40	2.5 [1]	<0.005	0.45	2.4 [1]	<0.005
SiO_2	20.57	0.5	0.646	19.97	1.4	0.810	20.60	1.0 [1]	0.049	20.39	0.7	0.464	20.40	0.5	0.148	20.31	0.5	0.192
SO_3	2.62	6.2 [1]	0.075	2.63	7.5	0.751	2.68	8.8	0.126	2.57	1.7 [1]	0.065	2.65	2.2	0.126	2.64	1.6	0.224
Free CaO	0.94	23.3 [1]	<0.005	0.99	21.5	0.751	1.39	19.6	0.183	1.07	21.3	0.381	1.07	11.5	0.139	1.11	7.5	0.341
LOI	1.04	17.4	0.859	1.22	13.1	0.270	1.25	18.0	0.347	0.89	12.7 [1]	<0.005	1.20	12.6 [1]	<0.005	1.10	14.2 [1]	<0.005
C_3S	56.75	4.7	0.738	59.76	5.6	0.623	54.26	4.0	0.330	53.69	0.9	0.738	60.89	2.3	0.310	58.67	0.7	0.412
C_2S	16.15	13.5	0.380	12.15	26.2	0.281	18.11	10.4	0.732	17.96	0.6	0.380	12.55	1.4	0.251	13.96	0.3	0.278
C_3A	7.94	3.3	0.118	7.24	3.3 [1]	0.030	7.44	4.7	0.413	7.96	3.5	0.201	6.96	1.2	0.323	7.33	0.9	0.524
C_4AF	9.45	3.2 [1]	0.016	9.21	3.0	0.109	9.79	3.8 [1]	<0.005	8.96	9.5	0.200	9.60	6.1 [1]	<0.005	9.67	4.8 [1]	<0.005
Blaine SSA[2]	377	2.9 [1]	<0.005	380.00	3.0	0.376	369.00	5.9	0.927	366	4.7 [1]	<0.005	383.50	1.3	0.143	375.33	2.3	0.729

Notes: [1] Data Not Normally Distributed [2] Units are m^2/kg

Table 4.56: CPR –All Burns, Percentage difference in cement composition relative to CT1 burn

Parameter	C burn			CTP burn			CTB burn			CTW burn			CTS burn		
	% Diff.	**P-Value**	**Significant**	**% Diff.**	**P-Value**	**Significant**	**% Diff.**	**P-Value**	**Significant**	**% Diff.**	**P-Value**	**Significant**	**% Diff.**	**P-Value**	**Significant**
Al_2O_3	6.90	0.000	Yes	4.08	0.000	Yes	4.60	0.000	Yes	-0.51	0.345	No	2.83	0.000	Yes
CaO	1.48	0.000	Yes	0.37	0.158	No	-0.69	0.226	No	1.75	0.232	No	1.02	0.432	No
Fe_2O_3	2.81	0.003	Yes	6.31	0.000	Yes	-2.65	0.000	Yes	4.23	0.689	No	5.03	0.000	Yes
K_2O	16.89	0.000	Yes	-1.36	0.231	No	7.36	0.000	Yes	14.94	0.000	Yes	25.54	0.000	Yes
MgO	-12.17	0.000	Yes	-1.87	0.123	No	-1.69	0.324	No	-4.36	0.123	No	-0.74	0.143	No
Na_2O	-21.05	0.000	Yes	-27.71	0.000	Yes	-22.93	0.000	Yes	-48.48	0.000	Yes	-36.56	0.000	Yes
Na_2O_{eq}	5.97	0.000	Yes	-8.76	0.000	Yes	-1.41	0.123	No	-3.47	0.000	Yes	7.88	0.000	Yes
SiO_2	3.00	0.000	Yes	3.14	0.000	Yes	2.09	0.000	Yes	2.16	0.302	No	1.70	0.512	No
SO_3	-0.55	0.787	No	1.78	0.531	No	-2.47	0.205	No	0.71	0.501	No	0.17	0.237	No
Free CaO	-5.06	0.000	Yes	40.08	0.000	Yes	7.96	0.000	Yes	7.63	0.000	Yes	11.86	0.000	Yes
LOI	-15.07	0.000	Yes	2.14	0.698	No	-27.58	0.000	Yes	-2.11	0.434	No	-10.39	0.000	Yes
C_3S	-5.04	0.000	Yes	-9.20	0.000	Yes	-10.17	0.000	Yes	1.88	0.258	No	-1.83	0.457	No
C_2S	32.94	0.000	Yes	49.05	0.000	Yes	47.78	0.000	Yes	3.31	0.000	Yes	14.88	0.000	Yes
C_3A	9.77	0.000	Yes	2.77	0.046	Yes	9.95	0.046	Yes	-3.85	0.263	No	1.26	0.046	Yes
C_4AF	2.66	0.005	Yes	6.34	0.000	Yes	-2.73	0.000	Yes	4.23	0.000	Yes	5.06	0.000	Yes
Blaine SSA	-0.98	0.271	No	-3.19	0.103	No	-3.68	0.103	No	0.92	0.214	No	-1.23	0.229	No

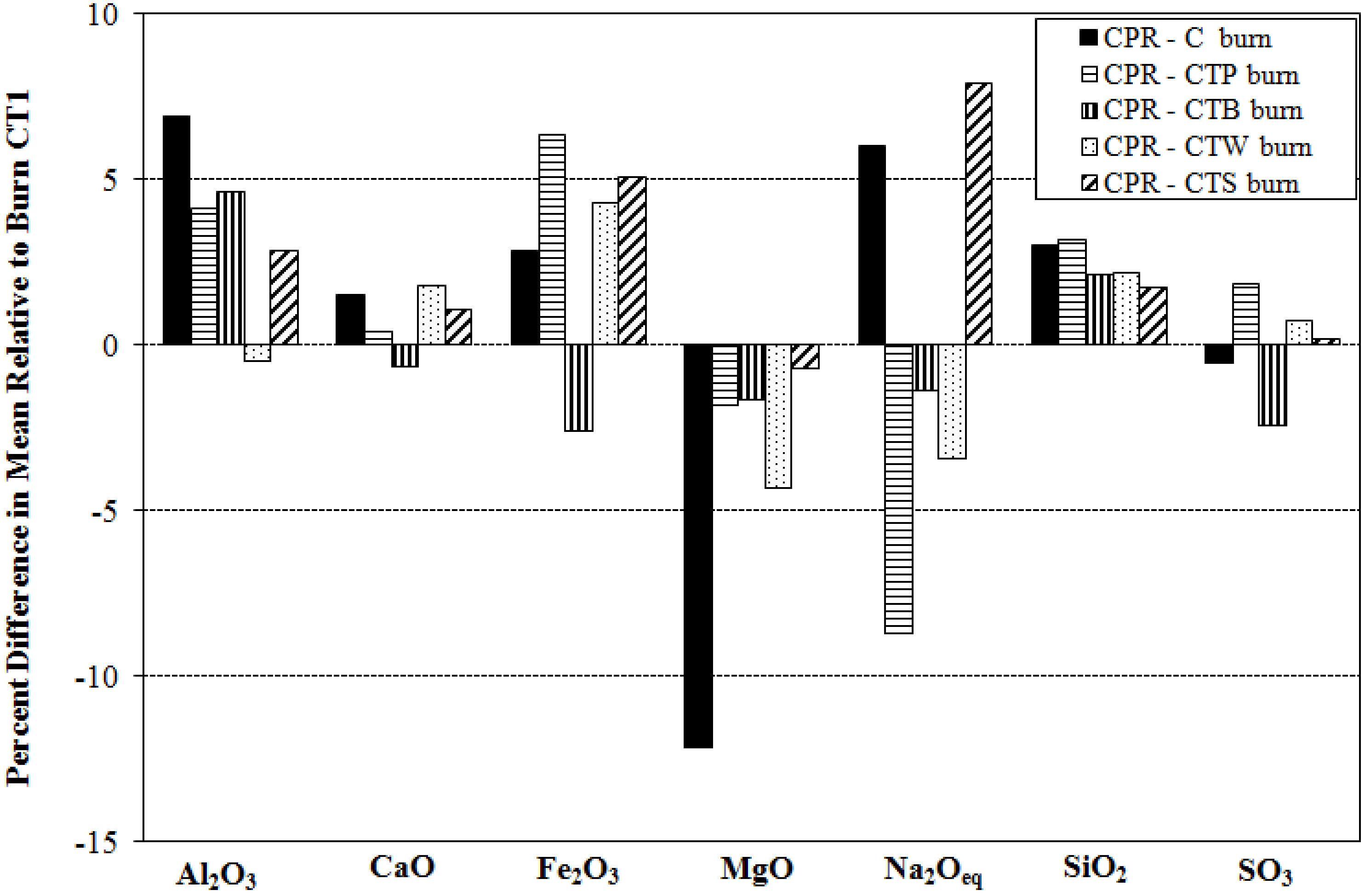


Figure 4.6: CPR- Fuel Burns, Percentage difference in cement composition relative to CT1 burn

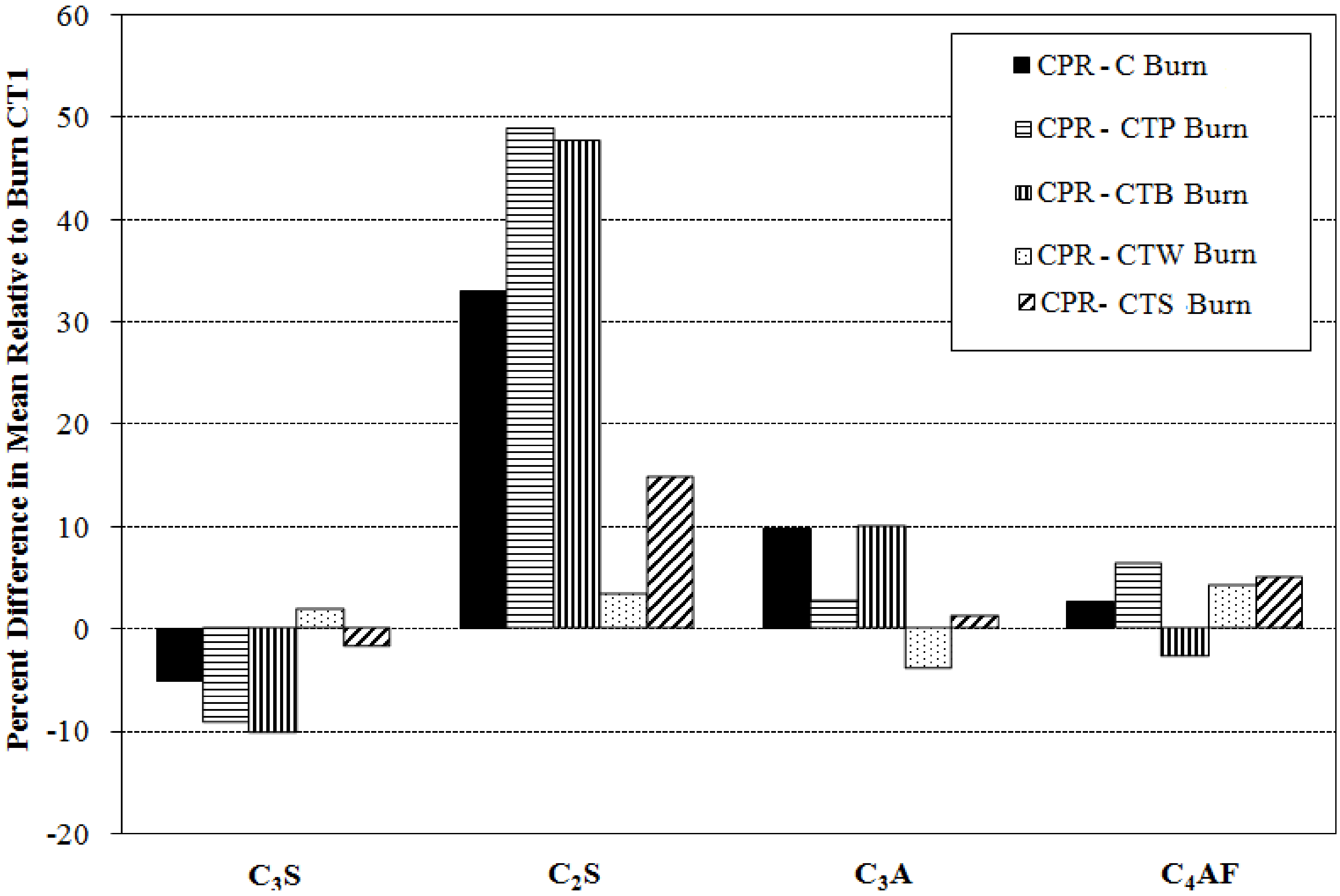


Figure 4.7: CPR- Fuel Burn, Percentage difference in Bogue compounds in cement relative to CT1 burn

The percentage differences determined from the external laboratory results are similar to that from the cement plant. The percentage difference for CaO content is less than 2 percent for all the fuel burns. The change in SiO_2 content too is less than 3 percent for all the fuel burns. SO_3 content seems to have slightly decreased for all the burns involving alternative fuels. Differences in percentages of Bogue compounds can be noticed; the C_3S content was decreased for CTP and CTW burns and was increased for C and CTB burns. The change in C_2S was highest for CTS burn. Total organic carbon (TOC) was not detected within the detection limits set by the external laboratory except for the CTP and CTS burns.

The arsenic content was lowest for C burn and highest for CTP burn. Lead and zinc contents were lowered for all the fuel burns. The percentage differences in Barium, Manganese and Strontium are high for all the burns relative to the CT1 burn.

In addition to the tests conducted at the cement plant and the external laboratory, cement samples, like clinker, were tested for the principle cement compounds using Rietveld analysis at the cement plant's specialty laboratory. The results from the Rietveld analysis are tabulated in Table 4.59.

4.3.6.2 Physical Properties of Cement

The physical properties of the cement were determined by tests performed at the cement plant and at Auburn University. Both testing entities conducted the same tests; the one exception was that the drying shrinkage development of paste prisms was also determined by staff at Auburn University. The results of the physical properties conducted by the cement plant are shown in Table 4.60.

Table 4.57: ELR –All Burns, Percentage difference in major parameters of cement relative to CT1 burn

Parameter	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Al_2O_3	5.05	4.8	4.82	4.93	2.3	4.92	2.0	4.80	-0.5	4.46	-7.4
CaO	64.00	1.5	63.06	63.18	0.2	63.79	1.2	62.85	-0.3	64.38	2.1
Fe_2O_3	3.20	4.3	3.07	3.11	1.4	2.86	-6.8	2.91	-5.1	3.20	4.3
K_2O	0.49	3.2	0.48	0.41	-14.4	0.61	28.9	0.53	10.9	0.58	22.1
MgO	2.89	-14.6	3.39	3.47	2.6	3.29	-2.7	3.26	-3.6	3.16	-6.7
Na_2O	0.02	-78.5	0.08	0.13	63.1	0.12	48.6	0.06	-18.5	0.12	48.0
P_2O_5	0.08	32.3	0.06	0.06	4.7	0.10	63.2	0.05	-17.4	0.07	7.4
SiO_2	20.53	-2.5	21.06	21.51	2.2	21.16	0.5	21.14	0.4	19.93	-5.4
SO_3	2.78	-4.3	2.91	2.71	-6.6	2.69	-7.3	2.80	-3.7	2.75	-5.3
TiO_2	0.27	8.4	0.25	0.26	5.7	0.22	-9.1	0.24	-3.8	0.21	-16.7
Moisture	0.29	-40.5	0.48	0.39	-19.0	0	-100	0.20	-59.2	0.23	-53.3
LOI	0.69	-18.3	0.85	0.91	7.3	0.92	8.7	1.09	28.9	0.95	12.0
C_3S	58.07	12.5	51.63	48.40	-6.3	54.12	4.8	50.81	-1.6	68.28	32.3
C_2S	15.06	-29.7	21.42	25.17	17.5	19.83	-7.5	22.29	4.0	5.61	-73.8
C_3A	7.96	5.1	7.58	7.80	3.0	8.19	8.0	7.79	2.8	6.40	-15.5
C_4AF	9.74	4.3	9.34	9.46	1.4	8.70	-6.8	8.86	-5.1	9.74	4.3
TOC	ND	NA	ND	0.05	NA	ND	NA	NR	NA	1.20	NA

Notes: ND - Not Detected NR- Not Reported NA- Not Applicable

Table 4.58: ELR –All Burns, Percentage difference in minor parameters of cement relative to CT1 burn

Parameter	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Value (ppm)	% Diff.	Value (ppm)	Value (ppm)	% Diff.	Value (ppm)	% Diff.	Value (ppm)	% Diff.	Value (ppm)	% Diff.
As (ppm)	8	-56.0	18	27	48.3	17	-4.1	16	-13.3	22	20.8
Ba (ppm)	321	133.5	138	300	118.2	400	191	333	142.4	350	154.5
Cd (ppm)	ND	NA	ND	NR	NA	ND	NA	NA	NA	ND	NA
Cl (ppm)	80	-85.2	541	57	-89.5	138	-74.5	76	-86.0	82	-84.9
Co (ppm)	14	NA	ND	13	NA	12	NA	9	NA	15	NA
Cr (ppm)	82	3.5	80	92	15.7	90	13.7	97	21.6	104	30.1
Cu (ppm)	64	105.4	31	14	-55.1	9	-70.5	ND	NA	28	-11.8
Hg (ppm)	0.01	-33.3	0.02	NR	NA	1	6233	0	266.7	0	155.0
Mn (ppm)	958	91.0	502	1600	219	1577	214.4	2033	305.3	1450	189.1
Mo (ppm)	9	NA	ND	2	NA	4	NA	3	NA	30	NA
Ni (ppm)	ND	NA	ND	12	NA	10	NA	NA	NA	174	NA
Pb (ppm)	33	-10.7	37	27	-27.7	15	-59.6	12	-67.0	13	-65.2
Sb (ppm)	51	-19.2	63	NR	NA	NR	NA	NR	NA	NR	NA
Se (ppm)	1	-12.5	2	NR	NA	ND	NA	ND	NA	ND	NA
Sr (ppm)	410	1.9	402	500	24.4	500	24.4	400	-0.5	400	-0.5
V (ppm)	62	17.7	53	69	30.9	66	26.1	62	17.3	68	29.0
Zn (ppm)	126	-30.9	183	62	-66.0	89	-51.3	83	-54.6	75	-59.2

Notes: ND - Not Detected NR- Not Reported NA- Not Applicable

Table 4.59: SLR –All Burns, Rietveld analysis of cement

Parameter	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	(wt. %)	% Diff.	Value (wt.%)	Value (wt.%)	% Diff.	Value (wt.%)	% Diff.	Value (wt.%)	% Diff.	Value (wt.%)	% Diff.
Alite (C_3S)	68.23	17.75	57.94	47.63	-17.80	55.81	-3.69	60.86	5.03	61.97	6.94
Belite (C_2S)	13.17	-28.15	18.33	28.75	56.86	21.87	19.29	16.84	-8.13	14.97	-18.36
Ferrite (C_4AF)	10.23	-0.10	10.24	10.66	4.14	9.99	-2.41	10.60	3.52	11.03	7.75
Aluminate (C_3A)	5.17	23.19	4.20	3.11	-25.89	4.68	11.60	2.71	-35.5	2.69	-35.90

Note: All percentage differences relative to Burn CT1

The results from the physical property tests conducted by Auburn University are shown in Table 4.61. The properties of cement that showed practically significant changes relative to CT1 burn, when tested at Auburn University, are graphically presented in Figure 4.8.

The compressive strength and drying shrinkage results were plotted on their own, and are discussed later in this section.

As shown in Figure 4.8, the autoclave expansion of paste prisms was found to be increased when alternative fuels were used. An increase in autoclave expansion can be found for all fuel burns from Auburn University results, while an increase for Burns C and CTB only is reported by the cement plant. All the fuel burns except CTP burn showed a retarded initial and final setting times in both Gillmore and Vicat setting test, as found by Auburn University. Cement plant results too report that the CTP burn has retarded setting times in both the tests. The normal consistency and cube flow did not show any practically significant changes as reported by both testing agencies.

The final property that showed noticeable change relative to CT1 burn is the air content in mortar, as shown in Table 4.60. This test was only conducted by the cement plant. All fuel burns showed a percentage change (increase or decrease) of more than 10 percent; CTS burn showed a decrease while all other fuel burns showed an increase. However, this change may be attributed to laboratory conditions and mixing procedure as much as anything else. Therefore, this property cannot be directly attributed to the chemical composition of cement, and is not practically significant to this study.

The compressive strength of mortar cubes was tested by staff at both Auburn University and the cement plant. The most notable aspect of these results is that the results reported by the cement plant are all higher than those obtained by Auburn University. This result may be simply attributed to differences in laboratory practices and/or conditions at the time of mixing and placement. However, the aspect worth noting is the relative difference between each burn from both testing entities. The acceptable range of test results, based on ASTM C 109, within a single laboratory is approximately 11 percent, for mortar ages of three and seven days, and for multiple laboratories is about 19 percent. Based on those criteria, none of the results presented by the *cement plant* are unacceptably different between burns. However, the results presented by Auburn University show that the compressive strength of especially the three- and seven-day cubes for CT1 burn are considerably higher than all the fuel burns. The compressive strength results from Auburn University are graphically presented in Figure 4.9. These results will be compared with the compressive strength results associated with concrete in Section 4.3.8.

Table 4.60: CPR –All Burns, Physical properties and percentage change for cement

Property	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Value	% Diff.	Value	Value	% Diff.	Value	% Diff.	Value	% Diff.	Value	% Diff.
Air in Mortar (%)	6.7	15.5	5.8	6.6	13.8	6.6	13.8	6.4	10.0	5.2	-11.2
Blaine Specific Surface Area (m^2/kg)	366	-3.9	381	374	-1.8	367	-3.7	372	-2.4	373	-2.2
Autoclave Expansion (% Exp.)	0.06	-40.0	0.10	0.18	80.0	0.15	50.0	0.06	-42.0	0.06	-41.5
Cube Flow (%)	125.7	2.2	123.0	122.5	-0.4	127.0	3.3	130.0	5.7	105.0	-14.6
Compressive Strength (MPa)											
1 day	15.3	-0.6	15.4	13.6	-11.7	14.9	-3.2	14.3	-7.3	15.4	-0.3
3 days	24.3	-2.8	25.0	22.2	-11.2	23.5	-6.0	23.9	-4.5	24.6	-1.8
7 days	31.9	-2.1	32.6	30.7	-5.8	31.1	-4.6	30.6	-6.1	31.6	-3.1
28 days	42.7	-3.0	44.0	42.8	-2.7	42.0	-4.5	43.3	-1.5	41.3	-6.3
Normal Consistency (%)	25.6	-0.4	25.7	25.9	0.8	25.7	0.0	25.2	-2.1	25.0	-2.7
Gillmore Initial Set (Min.)	105	-8.7	115	98	-15.2	131	13.9	NR	NA	120.0	4.3
Gillmore Final Set (Min.)	275	3.0	267	263	-1.5	225	-15.7	NR	NA	240	-10.1
Vicat Initial Set (Min.)	80	9.6	73	62	-15.1	74	1.4	71	-2.7	66	-10.3
Vicat Final Set (Min.)	180	-23.4	235	225	-4.3	199	-15.3	228	-3.0	225	-4.3

Notes: NR- Not Reported NA - Not Applicable

Table 4.61: AUR –All Burns – Physical properties and percentage change for cement

Property	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Value	% Diff.	Value	Value	% Diff.	Value	% Diff.	Value	% Diff.	Value	% Diff.
Autoclave Expansion (% Exp.)	0.05	66.7	0.03	0.04	33.3	0.06	100.0	0.05	66.7	0.05	66.7
Cube Flow (%)	91	-7.1	98	111	13.3	101	3.1	106	8.2	106	8.2
Compressive Strength (MPa)											
1 day	9.30	-15.5	11.0	11.5	4.5	12.0	9.1	10.9	-0.9	10.5	-4.5
3 days	17.2	-25.5	23.1	17.1	-26.0	21.5	-6.9	22.8	-1.3	21.3	-7.8
7 days	25.8	-13.4	29.8	24.8	-16.8	26.5	-11.1	28.3	-5.0	26.3	-11.7
28 days	35.1	-11.1	39.5	38.8	-1.8	32.9	-16.7	35.1	-11.1	32.7	-17.2
Normal Consistency (%)	25.4	-3.1	26.2	26.2	0.0	26.2	0.0	26.2	0.0	26.2	0.0
Gillmore Initial Set (Min.)	150	108.3	72	72	0.0	102	41.7	108	50.0	110	52.8
Gillmore Final Set (Min.)	238	64.1	145	105	-27.6	202	39.3	205	41.4	210	44.8
Vicat Initial Set (Min.)	106	53.6	69	66	-4.3	75	8.7	84	21.7	94	36.2
Vicat Final Set (Min.)	236	72.3	137	115	-16.1	180	31.4	150	9.5	180	31.4
Drying Shrinkage (%)											
7 days	-0.042	-17.6	-0.051	-0.045	-11.8	-0.035	-30.9	-0.045	-11.8	-0.047	-7.8
14 days	-0.068	-5.6	-0.072	-0.069	-4.2	-0.073	1.4	-0.070	-2.8	-0.071	-1.4
21 days	-0.079	-4.8	-0.083	-0.081	-2.4	-0.080	-3.6	-0.080	-3.6	-0.082	-1.2
28 days	-0.087	-7.4	-0.094	-0.089	-5.3	-0.082	-13.3	-0.088	-6.4	-0.090	-4.3

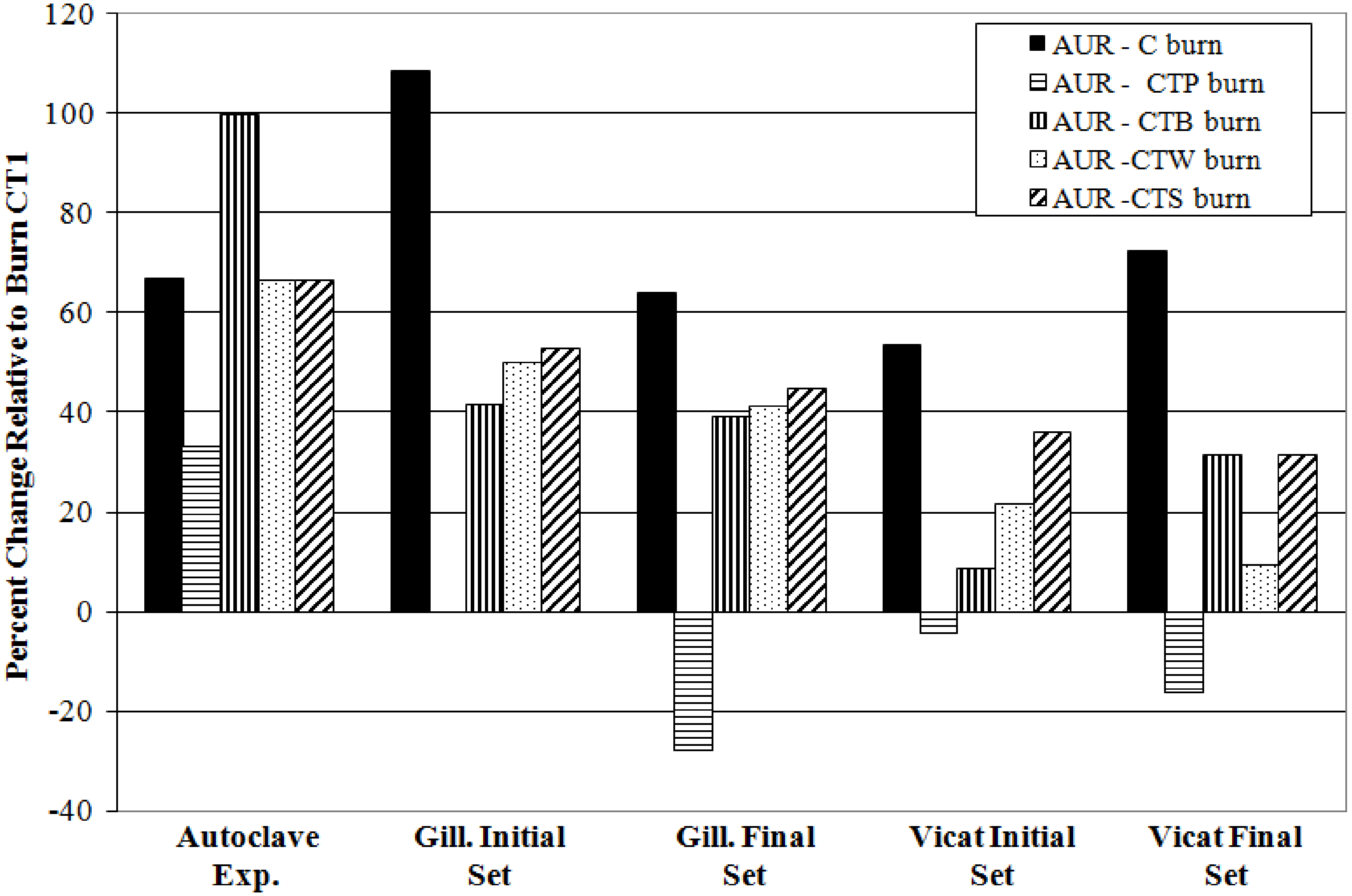


Figure 4.8: AUR- Fuel Burns, Percentage difference in physical properties of cement relative to CT1 burn

Another property measured at Auburn University was drying shrinkage of mortar prisms. Cement plant did not test for the property. The results from Auburn University are plotted in Figure 4.10. The ages associated with these results are drying ages. The specimens were cured for three days prior to exposure to drying conditions. In Figure 4.10, these results are presented with a shrinkage value reported as a positive percentage of the original length. From the graph, it can be seen that the results obtained are not too different. The CTB burn had the least 28-day shrinkage while CT1 burn had the most 28-day shrinkage, the difference being about 13 percent. The results from rest of the burns are all interspersed in the difference gap. The 7-day and 14-day shrinkages are nearly the same for all burns with about 5 percent or less variation. These results will be compared with the drying shrinkage results exhibited by concrete in Section 4.3.8.

The final physical property determined for cement was the particle size distribution. This result is truly independent of the fuels used, but completely based on the grinding process. This fineness of the cement is adjusted by the cement plant to achieve the desired setting and strength gain behavior in the cement. However, the results in Figure 4.11 may help to explain some of the differences in some of the physical properties of the cement and concrete. From this result, it can be deduced that the particle distribution of CTS burn is on the coarser side compared to the other burns, with that of cement from CT1 burn being the finest of all. However, the particle distribution curves of cement from C, CTP, CTB, CTW, and CTS burns are nearly identical. The increased fineness of the cement produced in the CT1 burn may explain why it set earlier and exhibited higher strength gains. The finer the cement, the more rapid is the rate of hydration, which will accelerate setting and strength development.

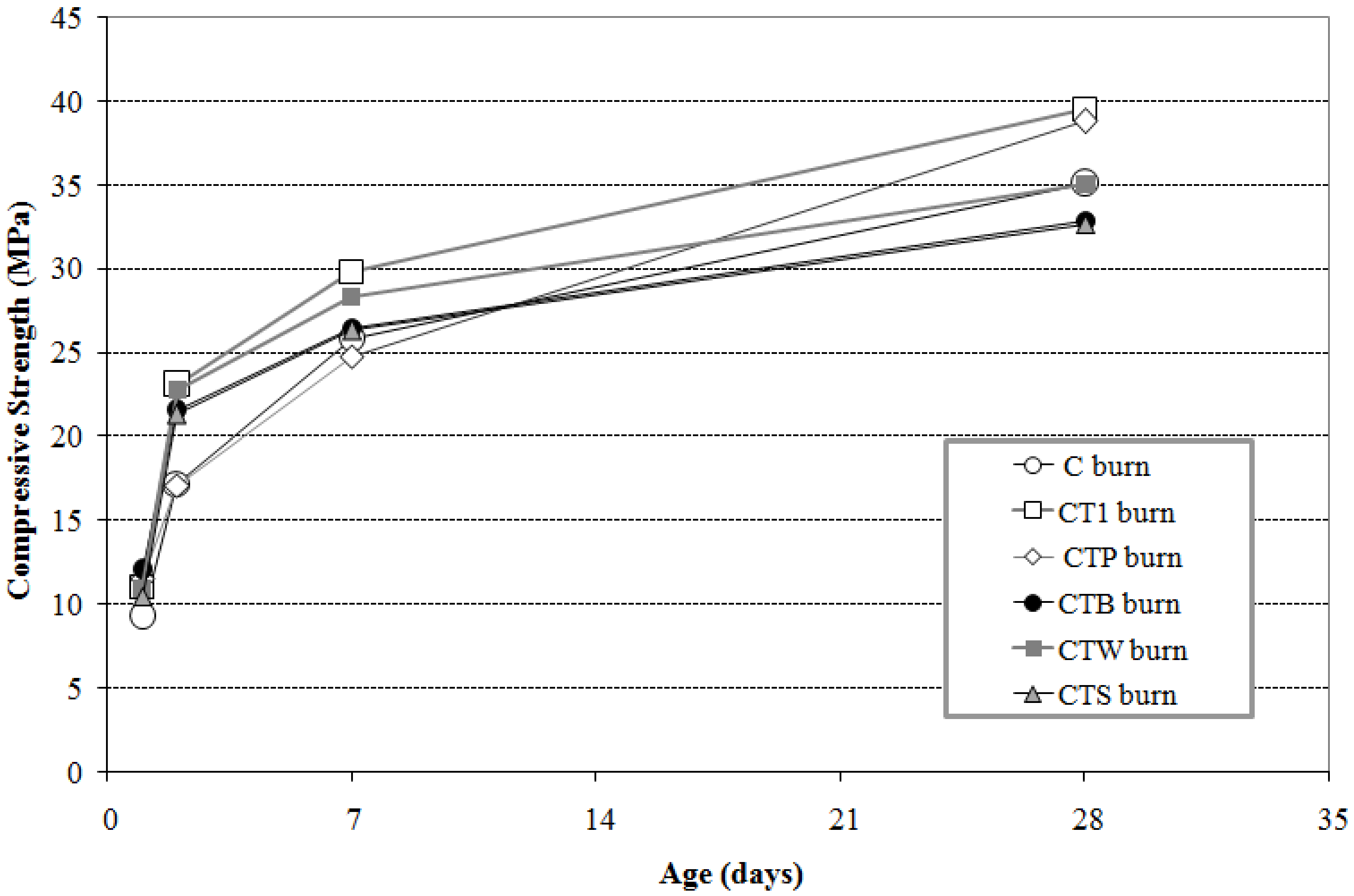


Figure 4.9: AUR- All Burns, Compressive strength of mortar cubes

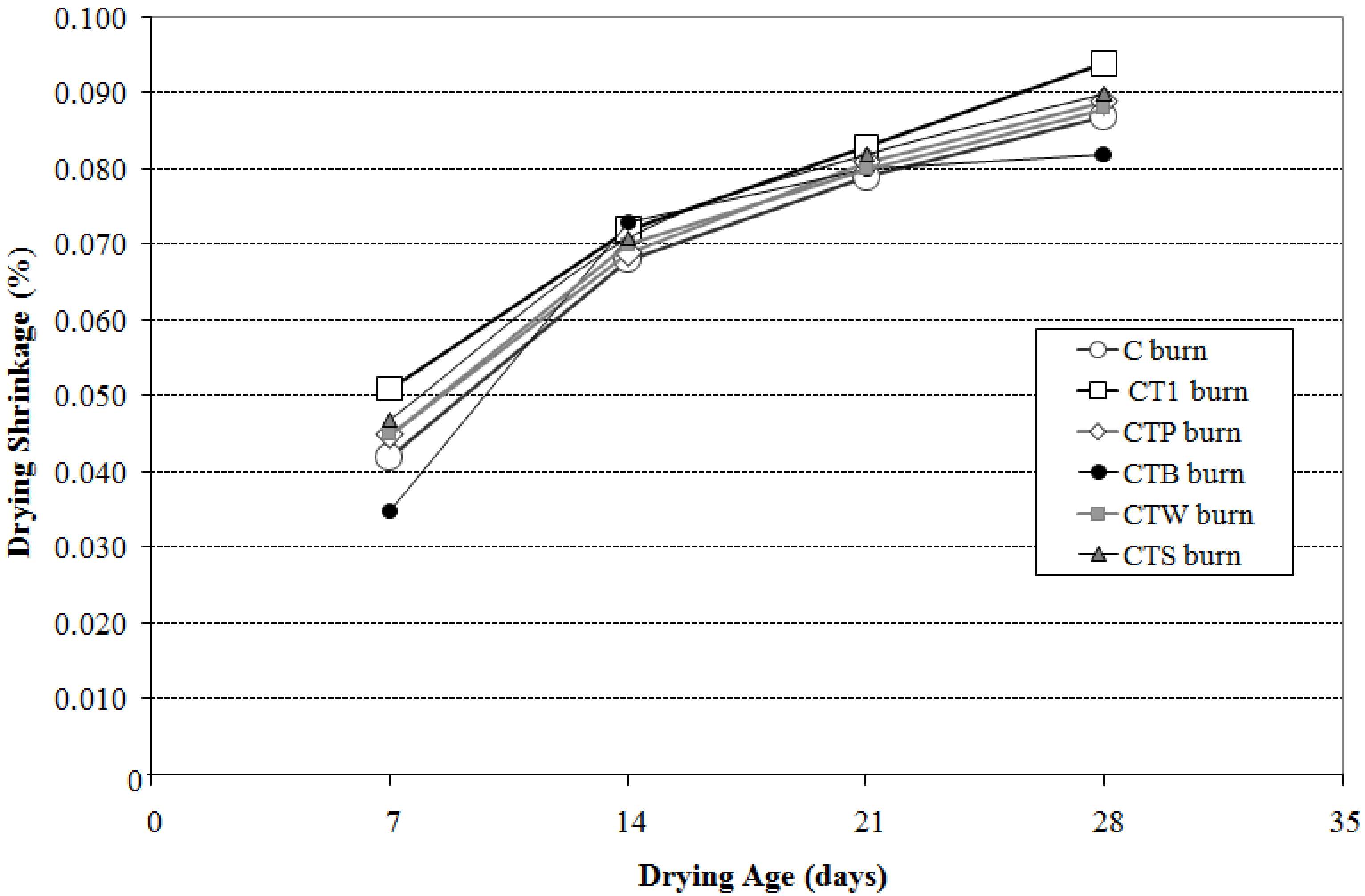


Figure 4.10: AUR- All Burns- Drying shrinkage of mortar prisms

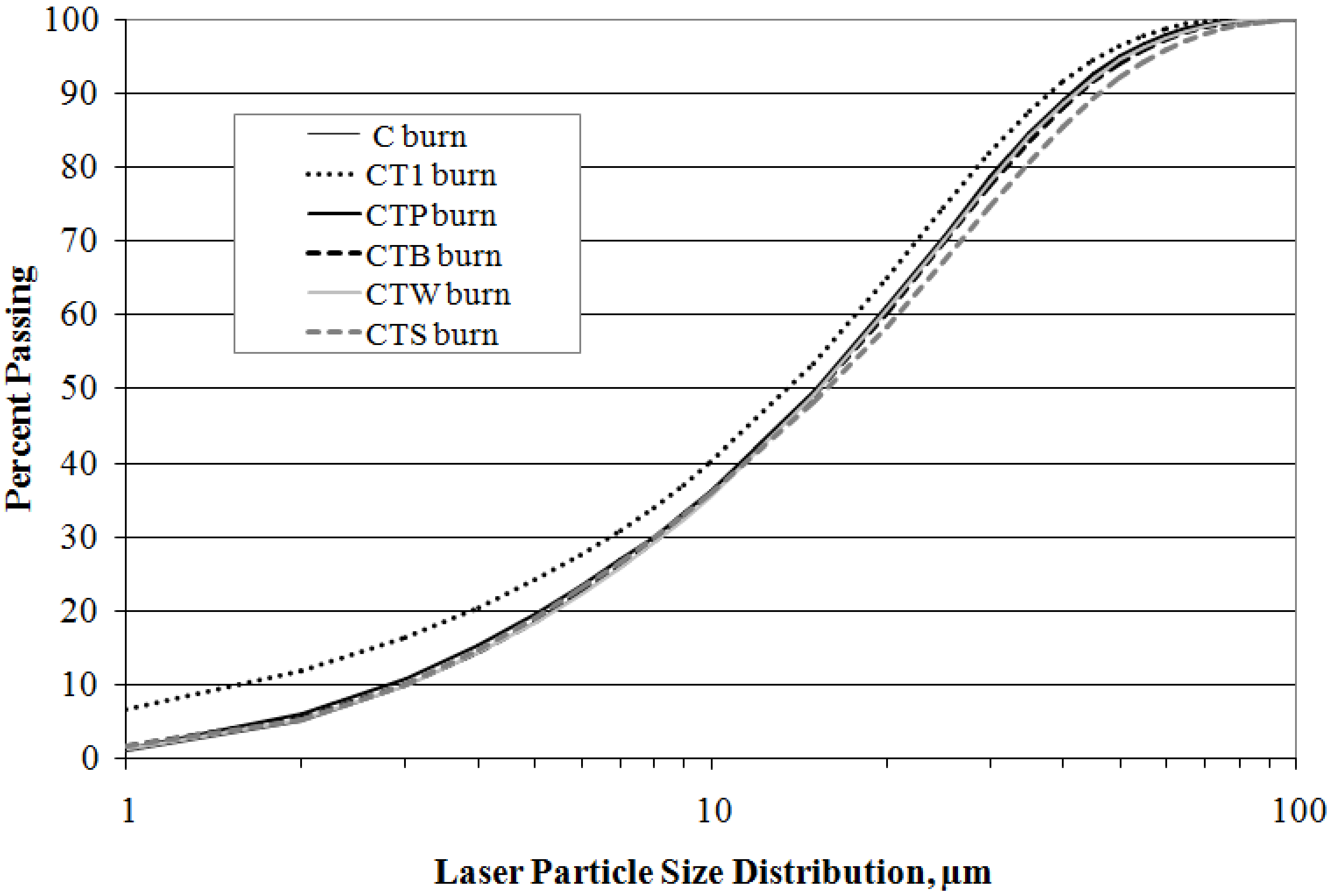


Figure 4.11: SLR- All Burns- Particle size distribution of Cement

4.3.7 Properties of Concrete

Concrete was produced using the cement collected during each trial burn. There were two different concrete mixtures that were produced from the cement collected during each trial burn. The results for each type of mixture are discussed individually due to the fact that proportions of the mixtures were different and therefore, results cannot be compared with one another. This was done to observe the behavior of concrete in both high and low water-to-cement (w/c) ratio conditions.

4.3.7.1 Concrete with moderate water-to-cement ratio (Mix A)

The first mixture, Mix A, was a conventional mixture with a water-to-cement ratio of 0.44, and it only utilized an air-entraining admixture. This mixture was made at Auburn University for all burns and at the concrete laboratory of the cement plant for Burns C, CT1, CTP and CTB. The setting time and splitting tensile strength data were not determined by the cement plant's laboratory.

The percent difference for each concrete property reported in Table 4.62 is calculated relative to the concrete mixture produced at Auburn University using cement from the CT1 burn. These differences for all properties except for compressive strength and splitting tensile strength are shown in Figure 4.12. The development of compressive and splitting tensile strength is shown in Figures 4.13 and Figure 4.14, respectively. It can be observed that the slump for all burns with alternative fuels is lower than that for Burns C, CT and CTP. Also, accelerated setting times and higher early-age (1-day and 3-day) compressive strength can be observed for burns with alternative fuels from Figure 4.13. There is a slight difference in air content too. All the burns except CTW burn tend to have lower air content than CT1 burn. Even though a difference in permeability can be noticed, it is not practically significant since the acceptable within-test repeatability for permeability from ASTM C 1202 is on the order of 1000 Coulombs.

In Table 4.63, the concrete data from the concrete laboratory of the cement plant is presented. Concrete was mixed and tested by the concrete laboratory of the cement plant for only four burns, C, CT1, CTP and CTB burns. It is observed that the cement plant results are somewhat different from the Auburn University results. The slump at the cement plant laboratory is much lower than that at Auburn University. This difference can most likely be attributed to differences in laboratory practices and/or conditions between the cement plant laboratory and Auburn University. Therefore, it is not a property attributable to only the cement used, and these results can only be used to evaluate the effect of the different cements on the *relative* strength differences.

The concrete made at the cement plant also seems to have lower air content and higher unit weight for CTP and CTB burns, which can be attributed to variation in concrete mixing methods. However, the compressive strength, setting times and permeability from both the testing agencies are fairly comparable.

Compressive strength is the primary property of concrete, and the most often specified by engineers. Because of that, it is a high priority of this project to determine if the utilization of alternative fuels in the production of portland cement has any effect on the compressive strength of concrete produced from that cement. The compressive strength development results of Mix A are shown in Table 4.62. These results are plotted relative to one another in Figure 4.13.

The concrete from CT1 burn has the least compressive strength followed by C Burn. The compressive strength of concrete was observed to be higher when alternative fuels were used. Concrete from CTB burn is found to have the highest early-age compressive strength of all the burns. This observation seems reasonable since the slump and setting time were found to be least for CTB burn among all the burns. The 91-day compressive strength of concrete from the CTP and CTB burns were recorded the highest for all ages.

Table 4.62: AUR –All Burns, Physical properties and percentage change for concrete Mix A

Property	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	AUR	%	AUR	AUR	% Diff.	AUR	% Diff.	AUR	% Diff.	AUR	% Diff.
Total Air Content (%)	4.0	-5.9	4.25	4.0	-5.9	3.5	-17.6	5	17.6	4	-5.9
Slump (mm)	100	11.1	90	90	0.0	50	-44.4	80	-11.1	60	-33.3
Unit Weight (kg/m^3)	2394	-1.8	2439	2464	1.0	2460	0.9	2370	-2.8	2441	0.1
Initial Set (Min.)	211	-3.2	218	216	-0.9	154	-29.4	216	-0.9	154	-29.4
Final Set (Min.)	298	9.2	273	266	-2.6	231	-15.4	269	-1.5	227	-16.8
Compressive Strength (MPa)											
1 day	12.3	-11.5	13.9	14.0	0.7	16.8	20.9	14.8	6.5	16.5	18.7
3 days	22.7	9.7	20.7	23.1	11.6	25.1	21.3	22.4	8.2	20.9	1.0
7 days	25.2	-11.3	28.4	28.5	0.4	34.7	22.2	32.5	14.4	30.1	6.0
28 days	35.0	-5.7	37.1	39.0	5.1	42.5	14.6	42.4	14.3	40.1	8.1
91 days	41.6	0.5	41.4	50.4	21.7	49.6	19.8	47.2	14.0	48.5	17.1
Splitting Tensile Strength (MPa)											
1 day	1.7	-15.0	2.0	1.7	-15.0	2.2	10.0	1.8	-10.0	1.7	-15.0
3 days	2.4	4.3	2.3	2.3	0.0	2.8	21.7	2.1	-8.7	2.0	-13.0
7 days	2.6	-7.1	2.8	2.8	0.0	3.3	17.9	2.7	-3.6	2.5	-10.7
28 days	3.2	-3.0	3.3	3.5	6.1	3.9	18.2	3.1	-6.1	3.4	3.0
91 days	3.7	-7.5	4.0	4.3	7.5	4.2	5.0	3.9	-2.5	4.0	0.0
Permeability @ 91 days (Coulombs)	2650	-9.6	2930	2600	-11.3	2730	-6.8	2550	-13.0	2750	-6.1

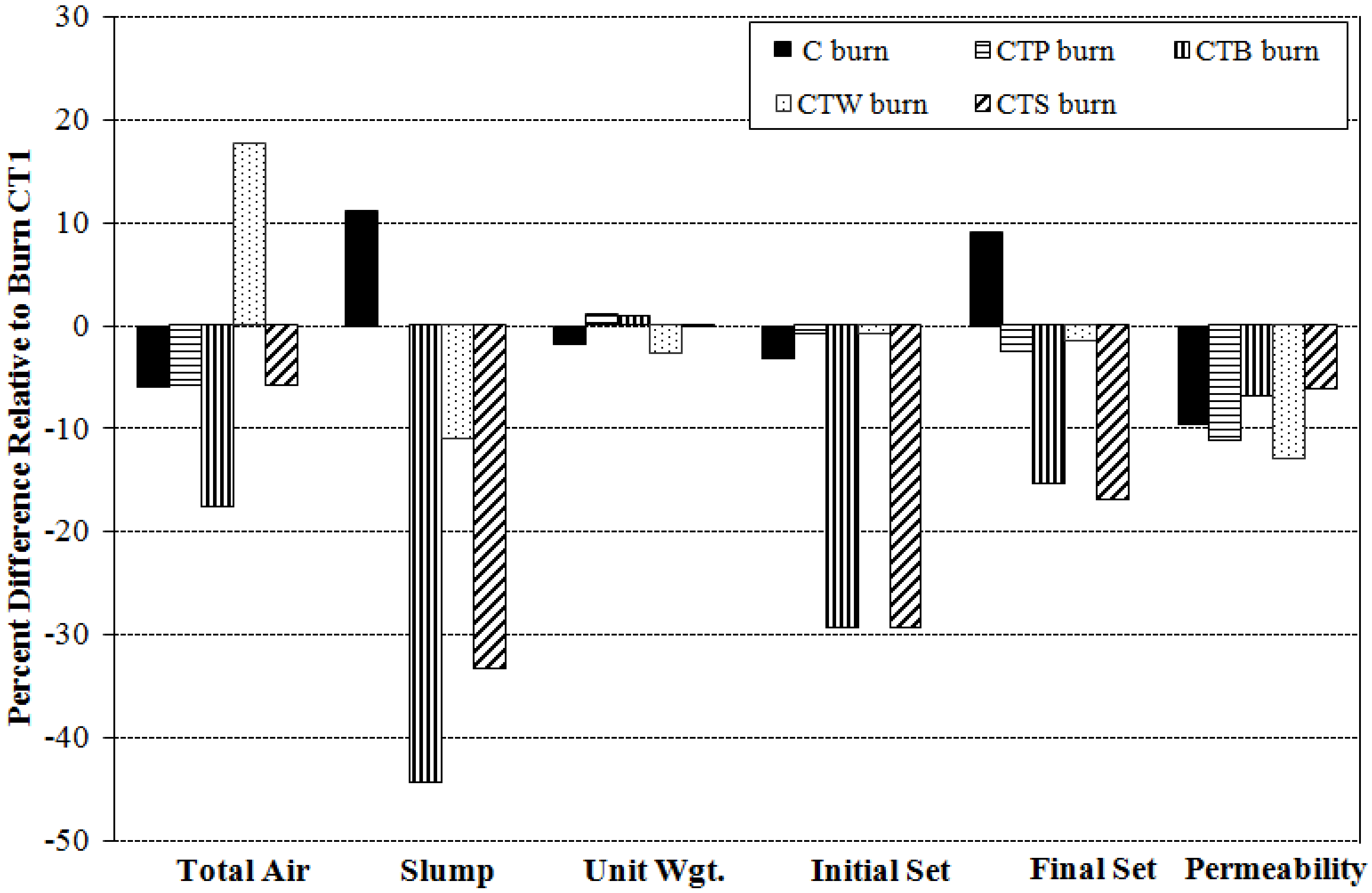


Figure 4.12: AUR- All Burns, Percentage difference in Mix A concrete results relative to CT1 burn

Table 4.63: CPR –All Burns, Physical properties and percentage change for concrete Mix A

Property	C burn		CT1 burn	CTP burn		CTB burn	
	CPR	% Diff.	CPR	CPR	% Diff.	CPR	% Diff.
Total Air Content (%)	3.6	12.5	3.2	3.3	3.12	3.4	6.25
Slump (mm)	30	0.0	30	40	33.33	40	33.33
Unit Weight (kg/m^3)	2450	0.1	2448	2454	0.25	2448	0.00
Initial Set (Min.)	218	-11.7	247	NC	NA	NC	NA
Final Set (Min.)	322	NA	NC	263.0	NA	273.0	NA
Compressive Strength (MPa)							
1 day	15.8	4.6	15.1	11	-27.15	6.1	-59.60
3 days	23.3	6.4	21.9	20.7	-5.48	23.1	5.48
7 days	33.3	1.5	32.8	29.4	-10.37	30.9	-5.79
28 days	43.3	2.6	42.2	43	1.90	43.8	3.79
91 days	48.2	-2.8	49.6	49.3	-0.60	49.8	0.40
Permeability @ 91 days (Coulombs)	2530	-4.9	2660	2460	-7.52	2500	-6.02

A similar trend is found in the cement plant results as well, where the concrete from alternative fuel burns was found, in general, to be higher in strength than that from the C or CT1 burns. However, the gain in strengths cannot be conclusively attributed to the use of alternative fuels, as many of the plant conditions were changed between these burns.

Another important property tested is the splitting tensile strength. The Auburn University results are listed in Table 4.62 and are graphically presented in Figure 4.14. The trend among the burns is quite similar to the one found for compressive strength. The Burns CTP and CTB exhibited the highest splitting tensile strengths among all the burns, while Burn C had the least. Again, the tensile strength tends to be higher when alternative fuels are used to produce cement. However, it must be noted that according to ASTM C 496, the acceptable range of results of splitting tensile strength tests within a single laboratory is 14 percent. Based on this criterion, there were no appreciable changes in the 91-day splitting tensile strength between any of the burns.

The drying shrinkage development of concrete Mix A is shown in Table 4.64. The results are presented with drying shrinkage values reported as positive numbers. All values are given as a percent length change relative to the original length. The concrete was exposed to drying conditions after seven days of saturated curing after concrete placement. Due to the timing of the burns, all shrinkage results for the concrete mixture ages could not be reported for all burns.

The results in Table 4.64 are presented graphically in Figure 4.15, where shrinkage values are reported as a positive percent length change. According to ASTM C 157, the allowable percent length change difference between results is 0.0266. This value is percentage of length change, not relative difference between the results for each burn. Based on this allowable value, there was no significant difference in drying shrinkage between any of the burns.

Another test conducted by personnel at Auburn University was to measure the degree of hydration development with semi-adiabatic conditions. The results of this test for concrete Mix A can be seen in Figure 4.16. This plot shows the degree of hydration experienced by the concrete relative to concrete equivalent age. The concrete equivalent age is a property that quantifies the maturity of concrete, and is a measurement that includes both actual concrete age, and a multiplication factor to account for the effect of temperature. The equivalent age is shown on a logarithmic scale.

It can be seen in Figure 4.15 that the degree of hydration for concrete at early age (up to equivalent age of about 100 hours) from all the burns is reasonably similar, which perhaps explains the similar setting times and early age strengths for the concrete.

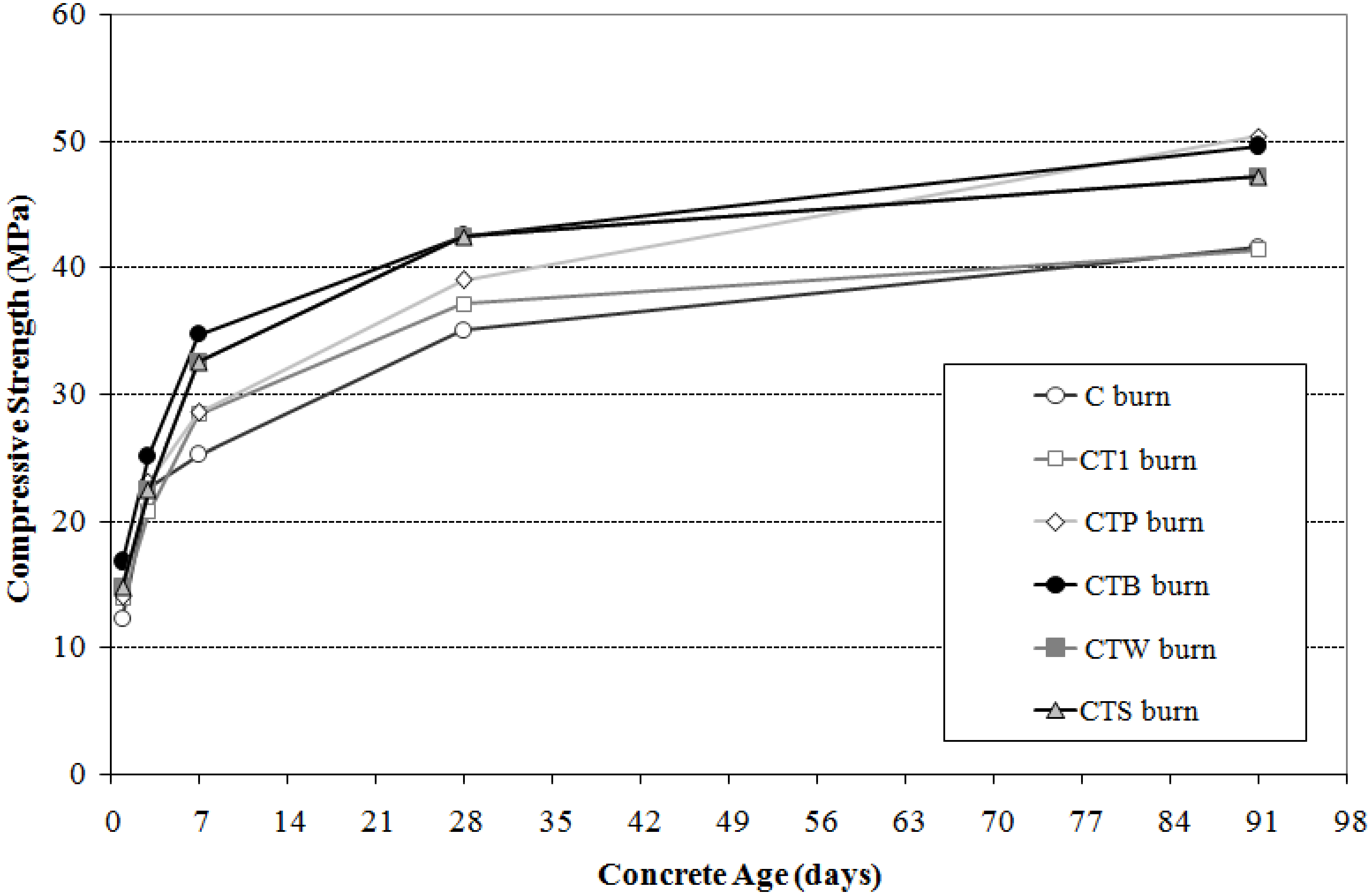


Figure 4.13: AUR- All Burns, Compressive strength of concrete Mix A

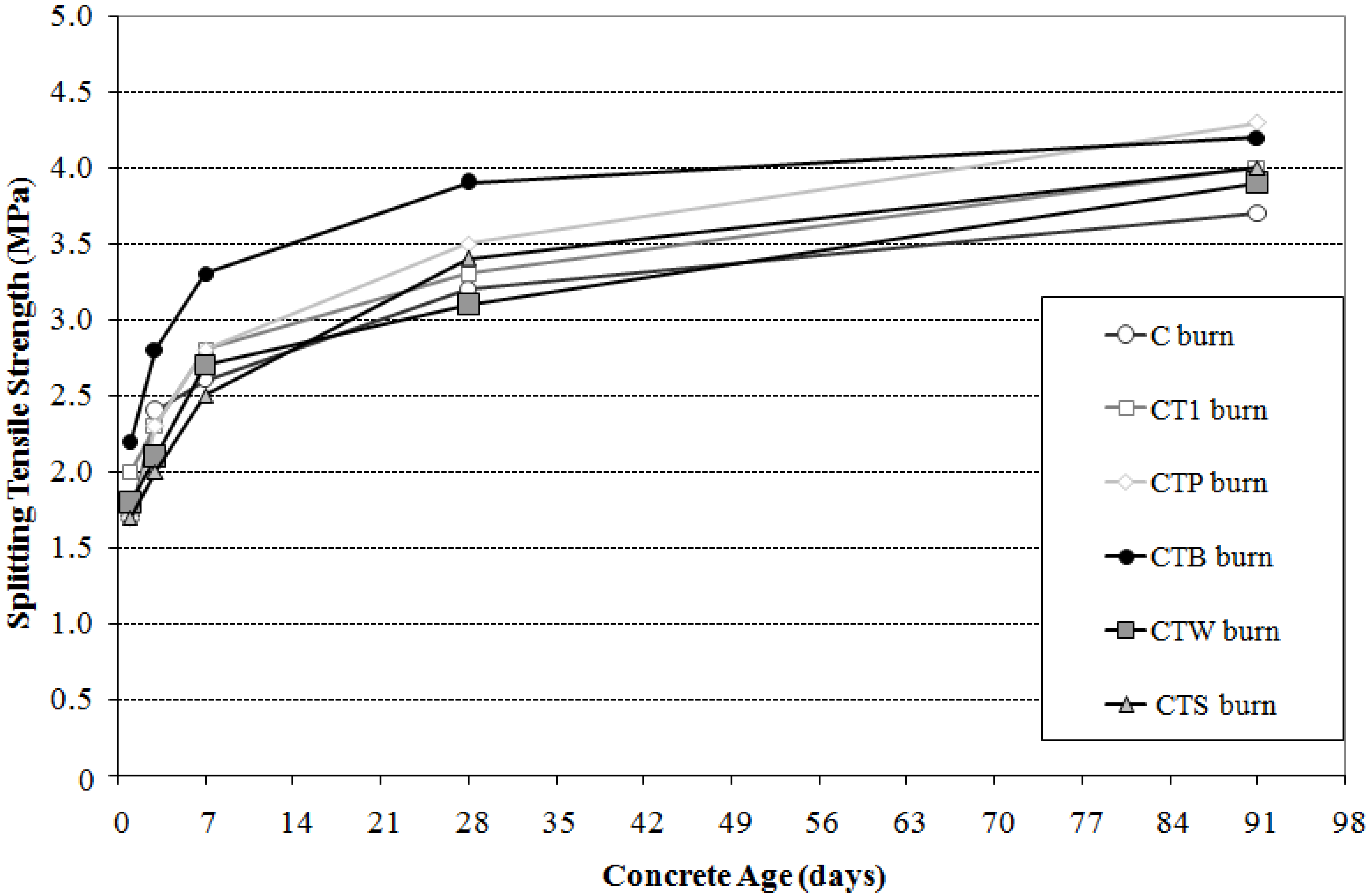


Figure 4.14: AUR- All Burns, Splitting tensile strength of concrete Mix A

Table 4.64: AUR –All Burns, Drying shrinkage development for Mix A

Drying Age (days)	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Length Change (%)	% Diff	Length Change (%)	Length Change (%)	% Diff	Length Chage (%)	% Diff	Length Change (%)	% Diff	Length Change (%)	% Diff
4	0.009	-50.0	0.018	0.008	-55.6	0.010	-44.4	0.010	-44.4	0.009	-50.0
7	0.018	-33.3	0.027	0.011	-59.3	0.013	-51.9	0.018	-33.3	0.012	-55.6
14	0.028	-17.6	0.034	0.020	-41.2	0.020	-41.2	0.025	-26.5	0.019	-44.1
28	0.029	-17.1	0.035	0.029	-17.1	0.028	-20.0	0.032	-8.6	0.024	-31.4
56	0.038	5.6	0.036	0.035	-2.8	0.034	-5.6	0.038	5.6	0.032	-11.1
112	0.045	2.3	0.044	0.046	4.5	0.043	-2.3	0.045	2.3	CIP	NA
224	0.049	4.3	0.047	0.049	4.3	0.048	2.1	CIP	NA	CIP	NA
448	0.050	2.0	0.049	CIP	NA	CIP	NA	CIP	NA	CIP	NA

Notes: CIP - Collection in Process NA - Not Applicable

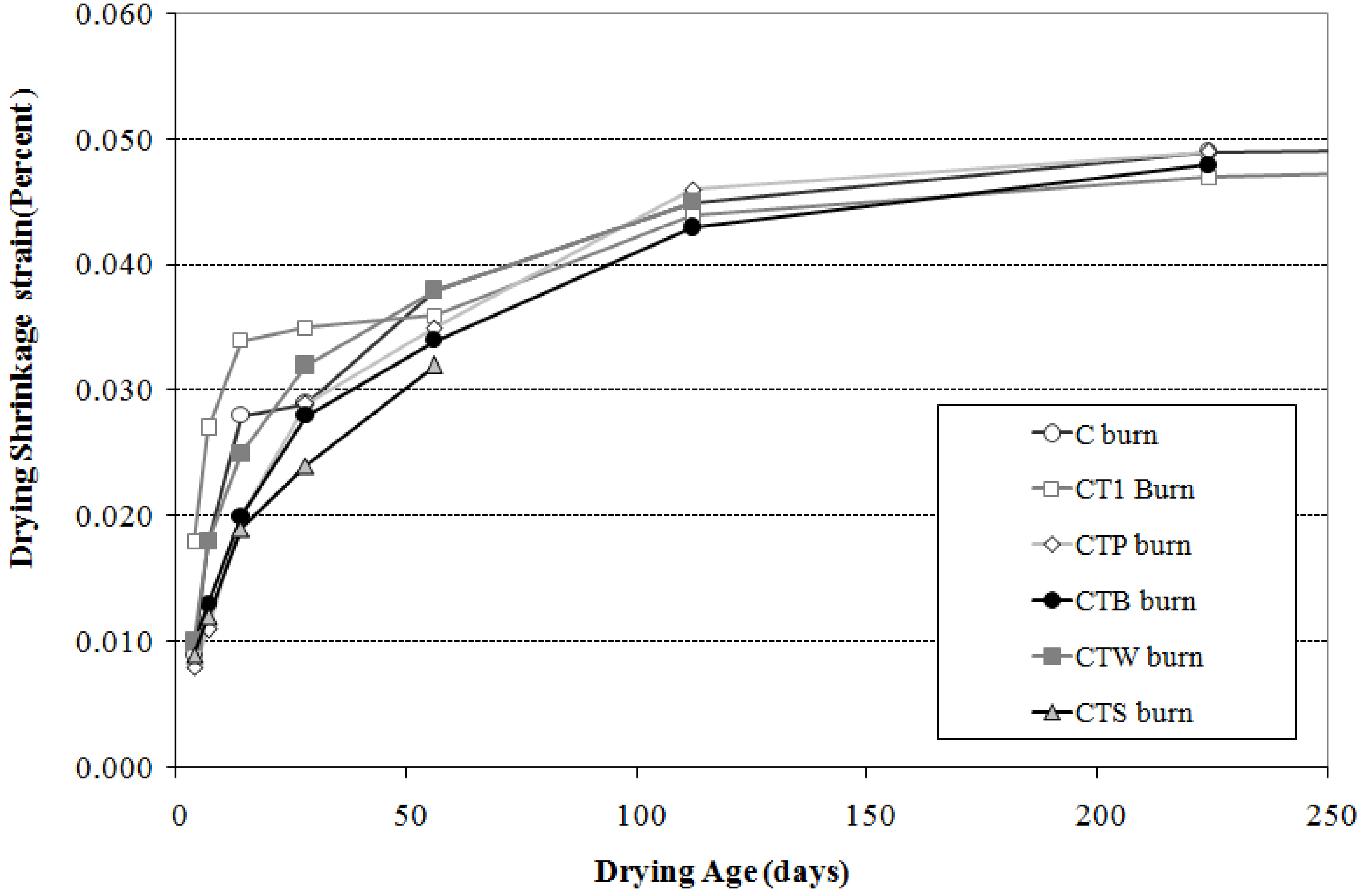


Figure 4.15: AUR- All Burns, Drying shrinkage development of concrete Mix A

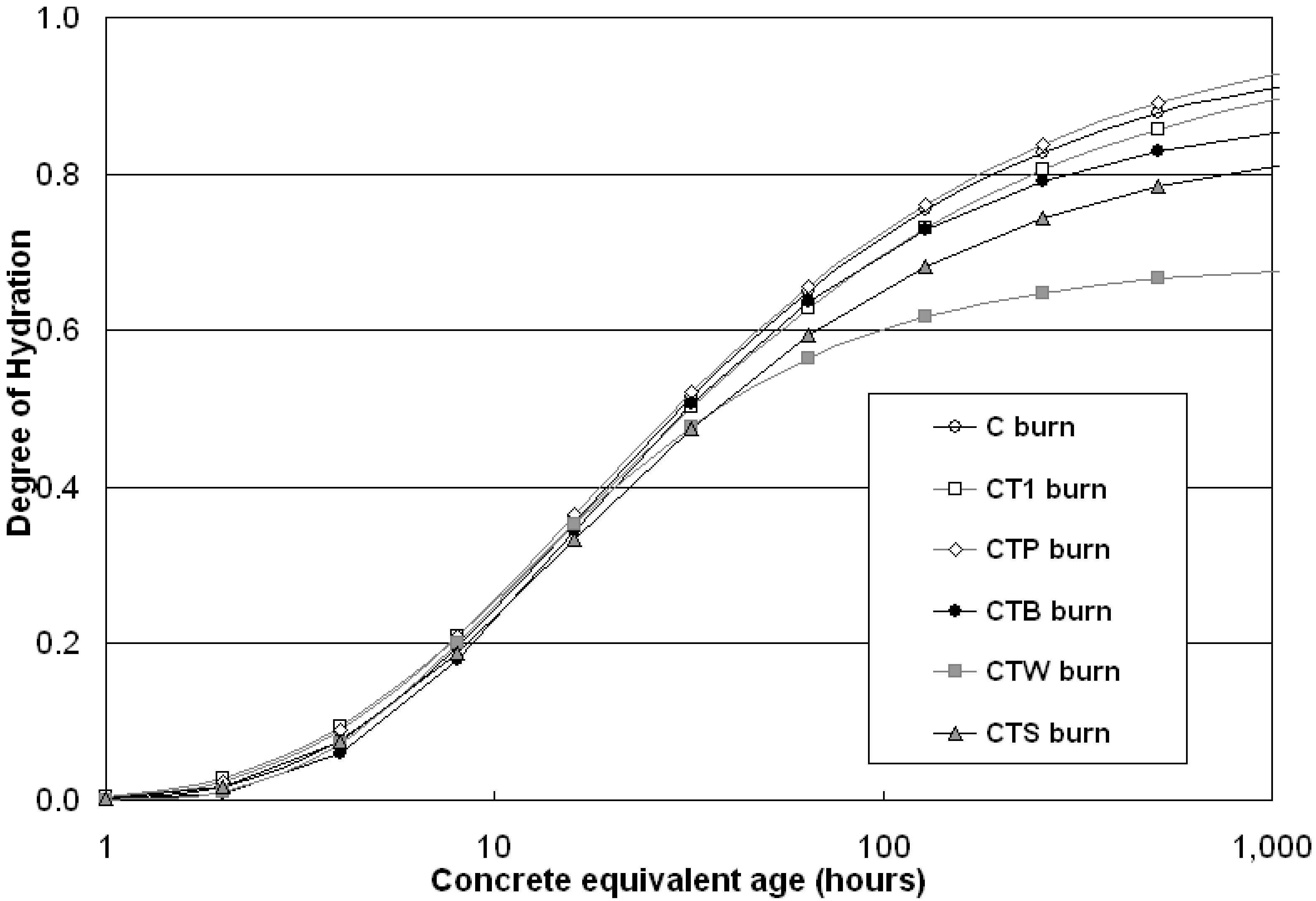


Figure 4.16: AUR –All Burns, Semi-adiabatic degree of hydration development for Mix A

However, at an equivalent age of 1,000 hours, the degree of hydration is markedly different; especially the concrete from CTW burn seems to have a low degree of hydration.

4.3.7.2 Concrete with low water-to-cement ratio (Mix B)

The second mixture, Mix B, was a high-strength mixture with a water-to-cement ratio of 0.37. An air-entraining admixture and a water-reducing admixture were added to this concrete mixture. Mix B was only prepared by personnel at Auburn University. The results of tests on Mix B are shown in Table 4.65. Once again CT1 burn was considered the baseline, and therefore is used as the reference for the percent differences. The change in properties relative to that measured for the CT1 burn except compressive strength and splitting tensile strength, is presented graphically in Figure 4.17.

Mix B showed an increase in total air content for all burns except the CTW burn. In fact, Burn C showed a 50 percent increase in this property over CT1 burn. However, these differences do not match with those encountered for Mix A. This is an indication that the differences are probably not caused by changes in the cement itself.

The slumps for all the burns showed a decrease except for CTW burn. The maximum decrease was of about 19 percent for CTB burn. CTW burn showed an increase of about 12 percent. The final property was setting time, which showed a similar change in both initial and final times for all the burns except C burn and this effect was also detected in Mix A. Burn C showed retardation while all other burns showed acceleration in the setting times. Permeability changes for all the burns were not significant since they were all well within the repeatability limit of 1000 coulombs specified in ASTM C 1202 which matches the conclusion reached for Mix A.

Table 4.65: AUR –All Burns, Physical properties and percentage change for concrete Mix B

Property	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Value	% Diff.	Value	Value	% Diff.	Value	% Diff.	Value	% Diff.	Value	% Diff.
Total Air Content (%)	6.0	50.0	4.0	5.0	25.0	5.0	25.0	3.0	-25.0	5.0	25.0
Slump (mm)	150	-6.3	160	150	-6.3	130	-18.8	180	12.5	150	-6.3
Unit Weight (kg/m^3)	2374	-2.2	2427	2413	-0.6	2410	-0.7	2440	0.5	2395	-1.3
Initial Set (Min.)	318	33.1	239	229	-4.2	199	-16.7	230	-3.8	200	-16.3
Final Set (Min.)	405	39.7	290	291	0.3	262	-9.7	288	-0.7	259	-10.7
Compressive Strength (MPa)											
1 day	20.8	-19.7	25.9	22.3	-13.9	29.9	15.4	23.3	-10.0	23.0	-11.2
3 days	31.9	-11.6	36.1	33.1	-8.3	34.8	-3.6	32.5	-10.0	31.2	-13.6
7 days	37.7	-5.7	40.0	38.0	-5.0	45.2	13.0	37.2	-7.0	38.2	-4.5
28 days	44.3	-10.9	49.7	51.0	2.6	52.7	6.0	48.8	-1.8	49.8	0.2
91 days	51.5	-12.9	59.1	58.0	-1.9	59.0	-0.2	53.8	-9.0	CIP	NA
Splitting Tensile Strength (MPa)											
1 day	2.5	-16.7	3.0	2.7	-10.0	3.0	0.0	2.6	-13.3	2.8	-6.7
3 days	3.3	-10.8	3.7	3.4	-8.1	3.1	-16.2	3.1	-16.2	3.3	-10.8
7 days	3.7	-5.1	3.9	3.5	-10.3	3.4	-12.8	3.4	-12.8	3.8	-2.6
28 days	4.1	-4.7	4.3	4.0	-7.0	4.0	-7.0	3.8	-11.6	4.2	-2.3
91 days	4.3	-12.2	4.9	4.6	-6.1	4.3	-12.2	4.2	-14.3	CIP	NA
Permeability @ 91 days (Coulombs)	2650	3.9	2550	2670	4.7	2700	5.9	2350	-7.8	CIP	NA

Notes: CIP - Collection in Process NA - Not Applicable

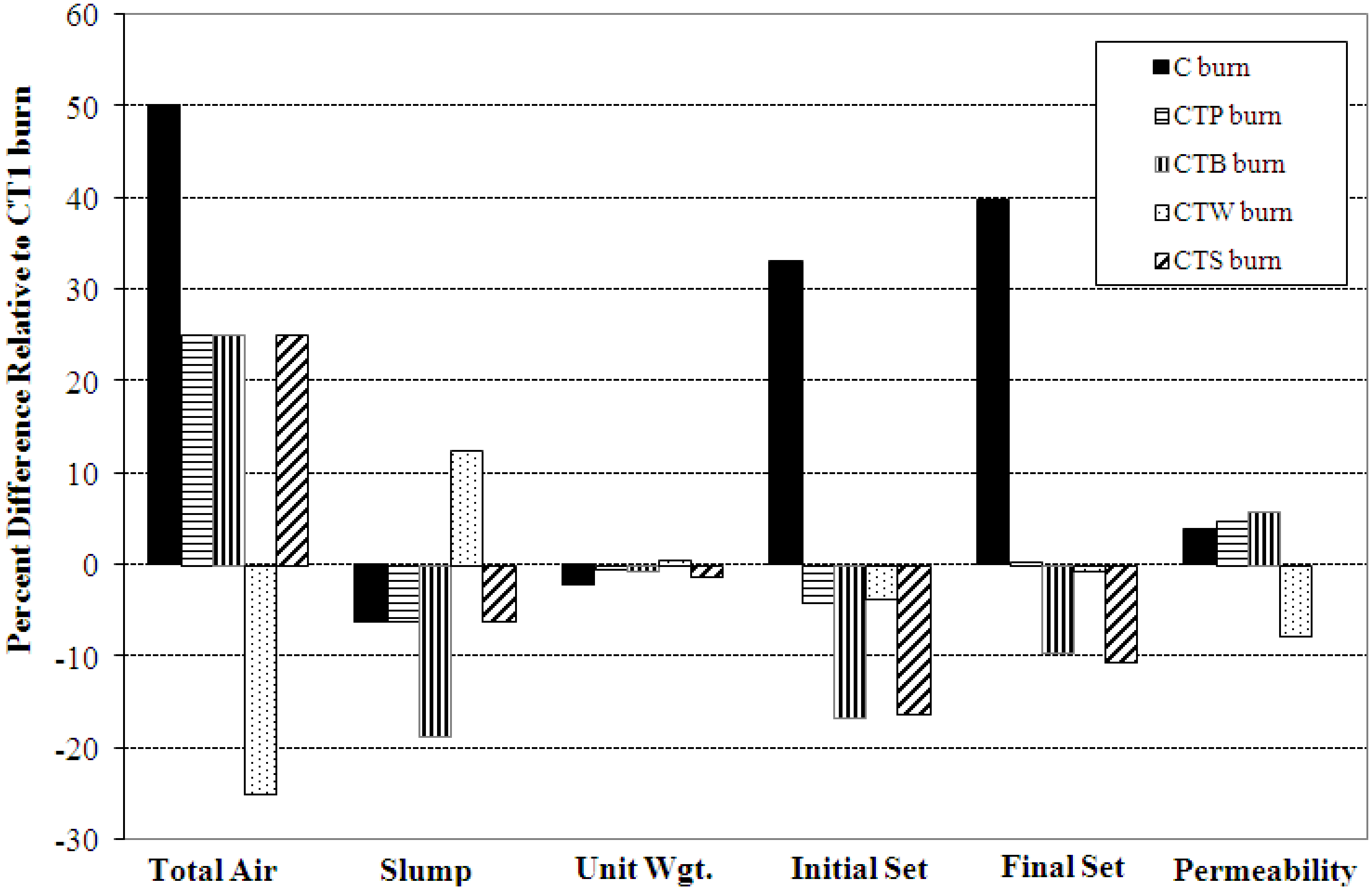


Figure 4.17: AUR –All-Burns, Percent difference in concrete properties for Mix B

The compressive strengths for different batches of Mix B, as reported by Auburn University, are shown in Figure 4.18. Based on the acceptable range of results presented in ASTM C 39, the concrete made from C burn was significantly weaker than the concrete made from all other burns at all ages except for seven days. Based on this result, it is fairly conclusive that Burn C produced concrete with appreciably lower compressive strengths. This is mostly in agreement with the compressive strength results from Mix A, which showed a decrease in compressive strength at most ages. CTB burn showed the highest compressive strength, as also observed for Mix A.

A graphical presentation of the splitting tensile strength of Mix B, conducted by Auburn University, can be seen in Figure 4.19. Just as with the splitting tensile strength results presented in Mix A, Burn C produced lower strengths than CT1 burn. However, it is interesting to note that CTB burn had a lower 91-day splitting tensile strength than all the burns except C and CTW burn, which is different from the expected result, given the high compressive strength for CTB burn in both Mixes A and B, and high splitting tensile strength in Mix A. But again, based on the acceptable range of results provided by ASTM C 496, there is no significant difference in 91-day splitting tensile strength results for Mix B.

The results of the drying shrinkage development test conducted at Auburn University on Mix B concrete can be seen in Table 4.66. Just as with the Mix A results, shrinkage values are reported as a positive percentage length change. Some of the results of drying shrinkage of the recent burns are yet to be collected.

The drying shrinkage development data for concrete Mix B is shown in Figure 4.20.

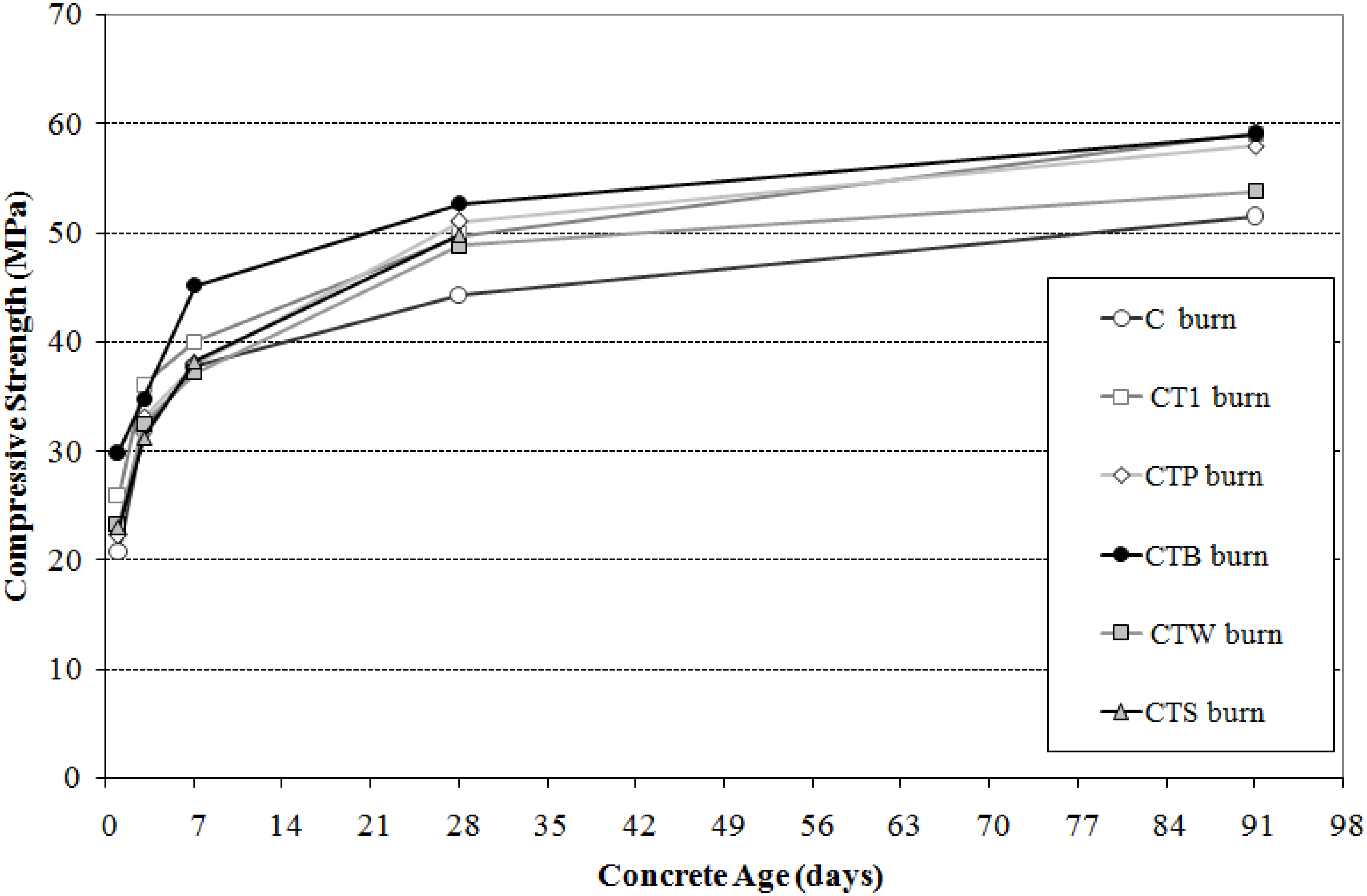


Figure 4.18: AUR –All Burns, Compressive strength for concrete Mix B

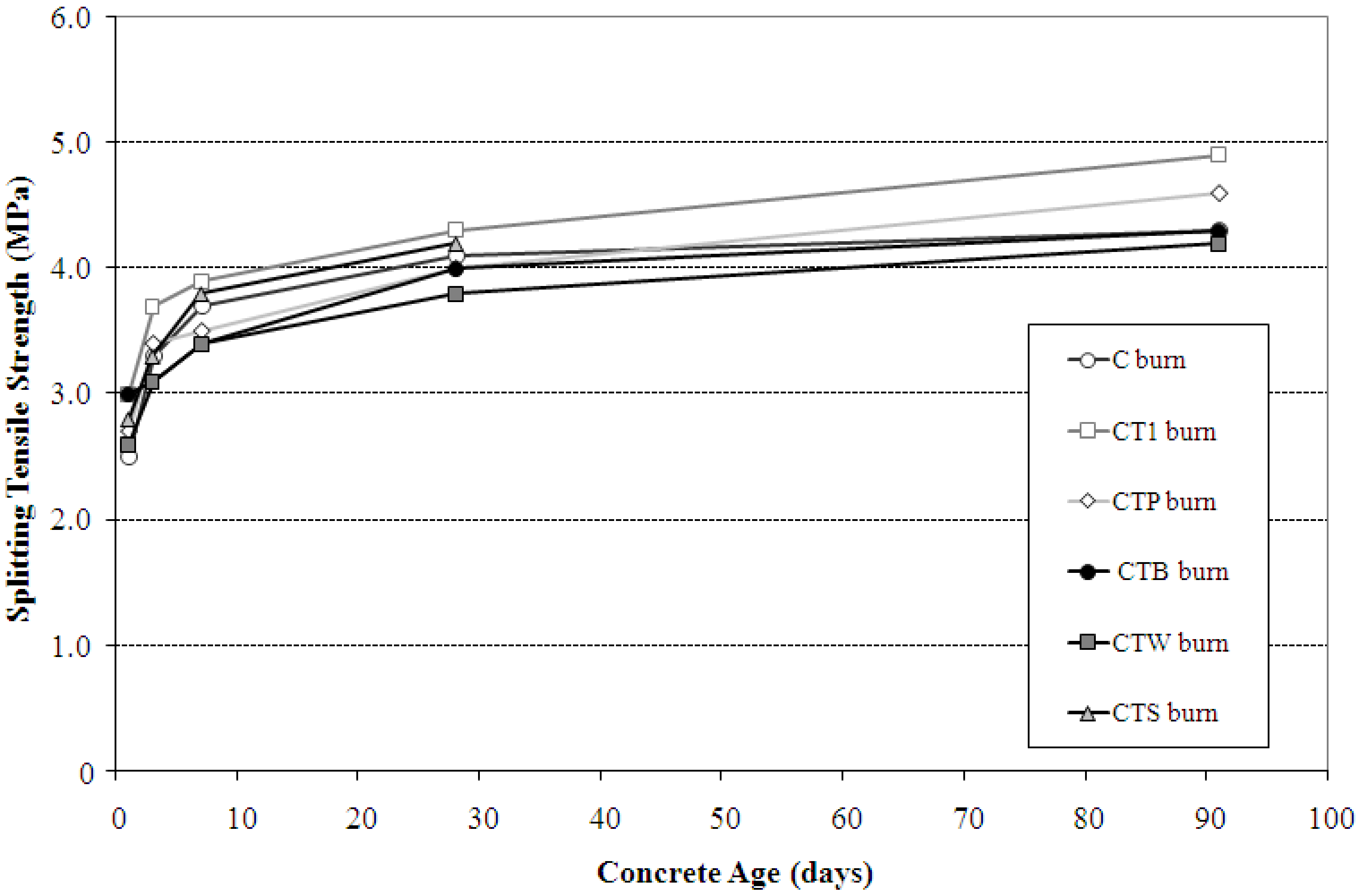


Figure 4.19: AUR – All- Burns, Splitting tensile strength for concrete Mix B

Table 4.66: AUR –All Burns, Drying Shrinkage development for Mix B

Drying Age (days)	C burn		CT1 burn	CTP burn		CTB burn		CTW burn		CTS burn	
	Length Change (%)	**% Diff**	**Length Change (%)**	**Length Change (%)**	**% Diff**	**Length Change (%)**	**% Diff**	**Length Change (%)**	**% Diff**	**Length Change (%)**	**% Diff**
4	0.013	18.2	0.011	0.016	45.5	0.010	-9.1	0.009	-18.2	0.010	-9.1
7	0.019	-5.0	0.020	0.018	-10.0	0.016	-20.0	0.013	-35.0	0.018	-10.0
14	0.032	28.0	0.025	0.023	-8.0	0.022	-12.0	0.019	-24.0	0.022	-12.0
28	0.037	23.3	0.030	0.036	20.0	0.033	10.0	0.026	-13.3	0.030	0.0
56	0.043	10.3	0.039	0.042	7.7	0.039	0.0	0.032	-17.9	0.036	NA
112	0.051	27.5	0.040	0.045	12.5	0.043	7.5	CIP	NA	CIP	NA
224	0.053	17.8	0.045	0.047	4.4	0.046	2.2	CIP	NA	CIP	NA
448	0.054	14.9	0.047	CIP	NA	CIP	NA	CIP	NA	CIP	NA

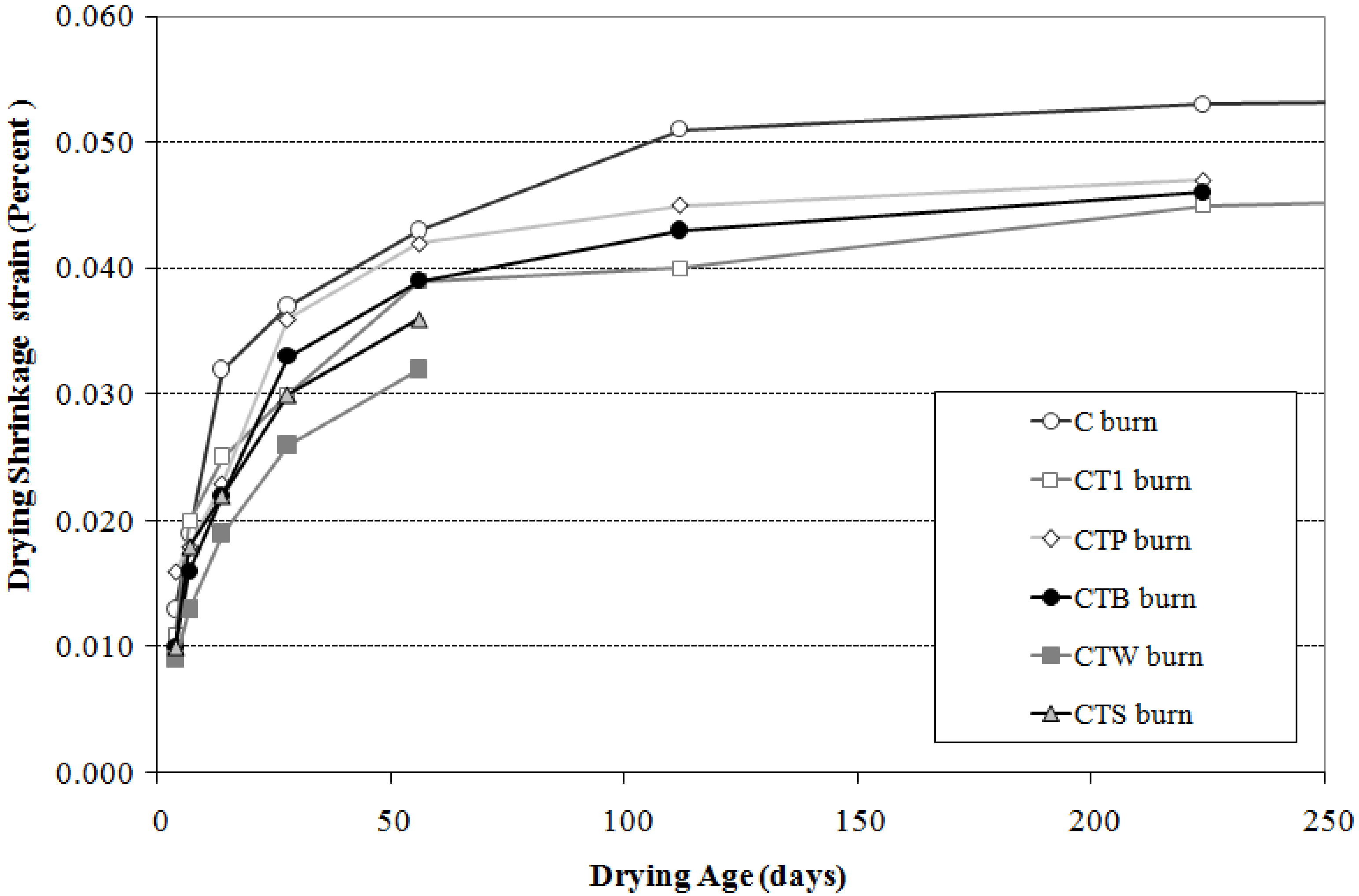


Figure 4.20: AUR- All Burns, Drying shrinkage development of concrete Mix B

Based on the criteria given in ASTM C 157, none of the drying shrinkage results showed significant changes. This result was also found for Mix A. Therefore, it seems as though the drying shrinkage properties of the concrete were not significantly altered by use of alternative fuels to produce these cements.

Figure 4.21 shows the results of the degree of hydration development measured under semi-adiabatic conditions test for concrete Mix B. It is evident from the plot that the degree of hydration development for concrete at early-age (up to equivalent age of about 30 hours) from all the burns is the same, which perhaps explains the similar setting times and early age strengths for the concrete. However, at an equivalent age of 1,000 hours, the degree of hydration is markedly different; the concrete from CTW burn seems to have an especially low degree of hydration. These results are similar to those found for Mix A in Figure 4.16.

4.3.8 Emissions

The emissions from the process are one of the primary outputs with which the cement plant is concerned. Due to the fact that the emissions are pollutants, they must be closely monitored, and maintained within certain limits. The emissions are collected on a real-time basis by an instrument called the "Continuous Emissions Monitoring System" (CEMS). The CEMS is a certified device that measures various pollutants in accordance with Environmental Protection Agency (EPA) requirements. The results were reported by the cement plant as five-minute averages. Table 4.67 shows the summary statistics for these data.

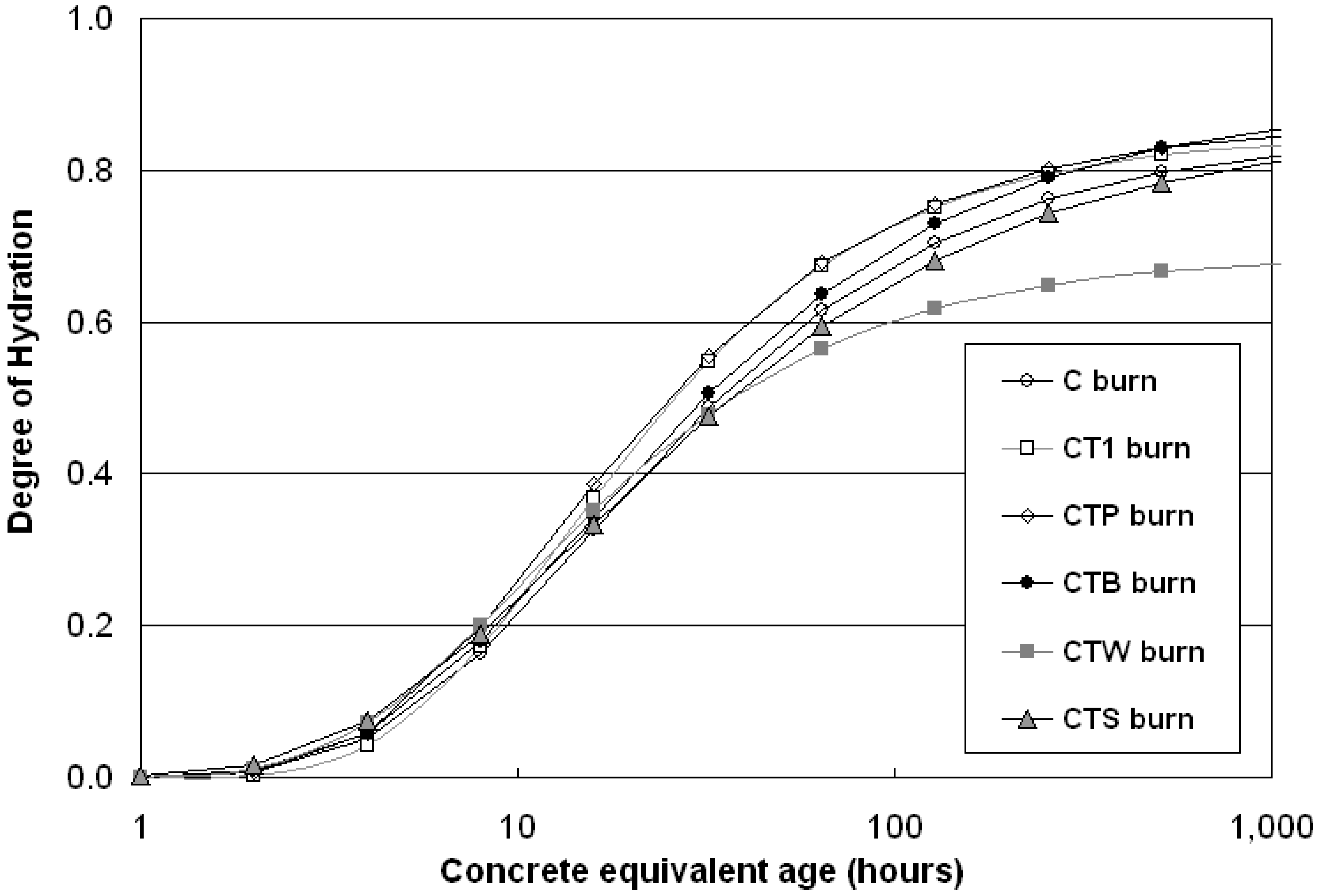


Figure 4.21: AUR –All Burns, Semi-adiabatic degree of hydration development for Mix B

The emissions were reported in terms of tons per hour released. In order to account for variations in production rates between the burns, Auburn University researchers normalized these results so that they are presented in terms of tons per ton of clinker produced.

In Table 4.67, the allowable limits set by Alabama Department of Environmental Management specified in ADEM (2006) are shown to provide some means to evaluate these data. These are the limits set for the specific cement plant where the three-day trials were performed. It is important to note that all the emissions from all the burns were well within ADEM limits.

As discussed in Section 4.1, emissions from each burn will be studied with reference to the individual baseline burns as shown in Figure 4.1. This is done because emissions are sensitive to changes in raw material and fuel composition. Hence it would only be appropriate to compare the results of a fuel with the baseline burn that is similar to the burn in most aspects except for the use of alternative fuel itself.

In Table 4.68, the three baseline burns are compared for any significant differences in the emissions. As shown in the Table 4.68, the emissions are significantly different for all the baselines burns. Hence statistical comparisons were made between the fuel burns and their respective baseline burns, and are presented in Table 4.69. The percentage differences are plotted in Figure 4.22.

From Table 4.69 and Figure 4.22, many interesting conclusions can be drawn. NO_x emissions were lowered for the C, CTP and CTB burns, while they were increased by about 5 percent for CTW burn and by about 59 percent for CTS burn.

Table 4.67: CPR - Summary statistics for emissions

Emissions		ADEM Limit [3]	Burn C	Burn CT1	Burn CTP	Burn CT2	Burn CTB	Burn CT3	Burn CTW	Burn CTS
NO_x (tons/ton clinker)	**Average (10^{-6})**	**166**	81.79	120.99	105.12	112.80	81.00	90.00	93.71	142.9
	Coefficient of Variation (%)		8.3	8.0	9.4	9.8	11.0	6.4	16.7	0.21
	P-Value[1]		0.064 [2]	0.015 [2]	0.035 [2]	0.105	0.269	0.431	0.011	0.169
SO_2 (tons/ton clinker)	**Average (10^{-6})**	**152**	0.04	1.12	0.04	0.09	0.63	2.51	0.37	0.62
	Coefficient of Variation (%)		218.9	145.6	163.7	49.8	189.5	34.9	73.4	29.0
	P-Value[1]		<0.005 [2]	<0.005 [2]	<0.005 [2]	0.201	<0.005 [2]	<0.005 [2]	<0.005 [2]	<0.005 [2]
VOC (tons/ton clinker)	**Average (10^{-6})**	**3.6**	2.31	3.42	2.61	2.18	3.55	3.35	2.61	2.06
	Coefficient of Variation (%)		64.5	35.8	22.4	17.0	48.9	64.3	29.1	10.1
	P-Value[1]		<0.005 [2]	0.008 [2]	0.023 [2]	0.073 [2]	<0.005 [2]	0.095 [2]	0.065 [2]	0.09 [2]
CO (tons/ton clinker)	**Average (10^{-6})**	**200**	76.77	54.14	56.72	37.95	50.08	52.10	58.88	36.63
	Coefficient of Variation (%)		9.9	10.8	22.0	11.6	10.2	14.5	19.7	9.1
	P-Value[1]		0.060 [2]	0.214	0.375	0.774	0.378	<0.005 [2]	0.278	0.314

Notes: [1] Based on Anderson-Darling Statistics [2] Not Normally Distributed [3] ADEM(2006)

Table 4.68: CPR – Emissions, Significant difference between baseline burns

Emissions		Burn CT2 [1]	Burn CT3 [1]
NO_x	**Percent Difference**	-6.8	-26.0
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
SO_2	**Percent Difference**	-92.3	123.6
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
VOC	**Percent Difference**	-36.5	-2.2
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
CO	**Percent Difference**	-29.9	-3.7
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000

Note: [1] Relative to CT1 burn.

The results for NO_x emissions being lower than the ADEM limits is noteworthy, considering the concerns about the NO_x emissions being substantially increased when tires were used an fuel, reported by Martinez (1996) based on a study in California (see Section 2.3.3). The NO_x emissions collected for the one burn that did *not* use scrap tires were the lowest and this in agreement with the findings of Martinez (1996). The NO_x emissions were increased when switchgrass was used as alternative fuel.

SO_2 emissions were reduced for all the burns by more than 50 percent. This is a significant reduction in SO_2, but the measured SO_2 values are already very low at this plant. At other plants where a reduction in SO_2 is required, one could consider the use of some of these alternative fuels that are locally available to reduce the SO_2 emissions.

Volatile organic compounds (VOC) have been problematic because of the narrow gap between the emissions measured and the allowable ADEM limits (as small as 5 percent in case of the baseline CT1 burn). Hence it is an objective to reduce the VOC levels at this plant. The VOC levels were lowered for both CTW and CTP burns, by 22 percent and 38 percent, respectively. However they were increased for Burns CTP and CTB, by 20 percent and 6 percent, respectively.

The CO emissions showed mixed results as they increased for CTP and CTW burns by 49 percent and 13 percent, respectively. However, the CO emissions decreased by 30 percent and 4 percent for CTS and CTB burns, respectively.

Table 4.69: CPR – Emissions, Significant difference between fuel burns relative to their respective baseline burns

Emissions		**Fuel Burns**				
		C burn [1]	**CTP burn** [2]	**CTB burn**[3]	**CTW burn**[3]	**CTS burn** [3]
NO_x	**Percent Difference**	-32.4	-6.8	-9.3	4.6	58.7
	Statistically Different	Yes	Yes	Yes	No	No
	P-Value	0.000	0.000	0.000	0.542	0.542
SO_2	**Percent Difference**	-96.4	-52.9	-74.3	-84.7	-75.4
	Statistically Different	Yes	Yes	Yes	Yes	Yes
	P-Value	0.000	0.000	0.000	0.000	0.000
VOC	**Percent Difference**	-32.5	20.0	5.9	-22.0	-38.5
	Statistically Different	Yes	Yes	No	Yes	Yes
	P-Value	0.000	0.000	0.542	0.000	0.000
CO	**Percent Difference**	41.8	49.5	-3.9	13.0	-29.7
	Statistically Different	Yes	Yes	Yes	Yes	Yes
	P-Value	0.000	0.000	0.061	0.000	0.000

Note: [1] Relative to CT1 burn [2] Relative to CT2 burn [3] Relative to CT3 burn

The emission results for all alternative fuel burns are below the ADEM limits, and this addresses the concerns generally associated with high emission levels for the non-biodegradable waste-fuels such as plastics. Maker (2004) observed that Woodchips produce little SO_x gases and their combustion creates NO_x, CO and VOC emissions at levels comparable to fossil fuels (Section 2.3.4.4). The emission results for the CTW burn are in agreement with the results reported by Maker (2004)

4.5 *Conclusions*

The production of portland cement utilizes many complex materials, facilities, and processes. The nature of the production process results in numerous variables that have an effect on both the chemical and physical properties of the cement that is manufactured. Therefore, it is very difficult to conclusively attribute any changes in these properties directly to the utilization of alternative fuels. Regardless, this study has provided many conclusions regarding the use of alternative fuels in the portland cement production process.

One aspect of the utilization of alternative fuels that the cement plant was acutely concerned with was the ability of the facilities to maintain production while consuming these fuels. In this regard, it was found that the maximum allowable rate that tires could be utilized was controlled by sulfur build-ups inside the calciner system. These build-ups were primarily composed of sulfur-derived compounds, and were directly responsible for limiting the air flow through the kiln, which reduced oxygen levels necessary for good combustion in the kiln. The feed rate of the plastics was also limited by the feed equipment used. In this case, the feed system had problems conveying the low-density (5.26 lb/ft^3) plastic fuels that were being used. Broiler litter and Woodchips did not cause any feed problems. The bales of switchgrass had to be shredded before feeding into the system which proved to be labor-intensive. In spite of the limitations associated with these fuels, the results shown in Section 4.3.3 showed some promising results. The most prominent of these was the energy content of the alternative fuels. The range of heat values of each of the fuels were determined to be as follows:

1. Coal: 11,157 to 12,476 BTU/lb,
2. Tires: 14,467 to 14,687 BTU/lb,
3. Plastics: 11,327 to 14,446 BTU/lb,
4. Broiler litter: 6,484 to 7,188 BTU/lb,
5. Woodchips: 8,170 to 8549 BTU/lb, and
6. Switchgrass: 7,888 to 8393 BTU/lb.

These results indicate that the tires and plastics have good combustion properties as they produce more heat per pound than the coal. Broiler litter and woodchips, despite the low heat values, are available in abundance and are sustainable bio-fuels. Most of the proximate and ultimate analyses of these fuels provided desirable results as per the fuel requirements of the cement plant stated in Section 4.3.3. The chemical and combustion properties, along with the costs associated with acquisition, imply that the cement plant may consider the use of these fuels in the future.

The second goal of this study was to determine if the utilization of alternative fuels has a direct impact on the chemical composition of the product. Based on the results presented in Sections 4.3.5 and 4.3.6, statistically significant changes in the chemical composition of the clinker and the cement did occur between burns. However, based on the results shown in Sections 4.3.1 and 4.3.2, there were also significant changes in the chemical composition of the raw materials and the kiln feed.

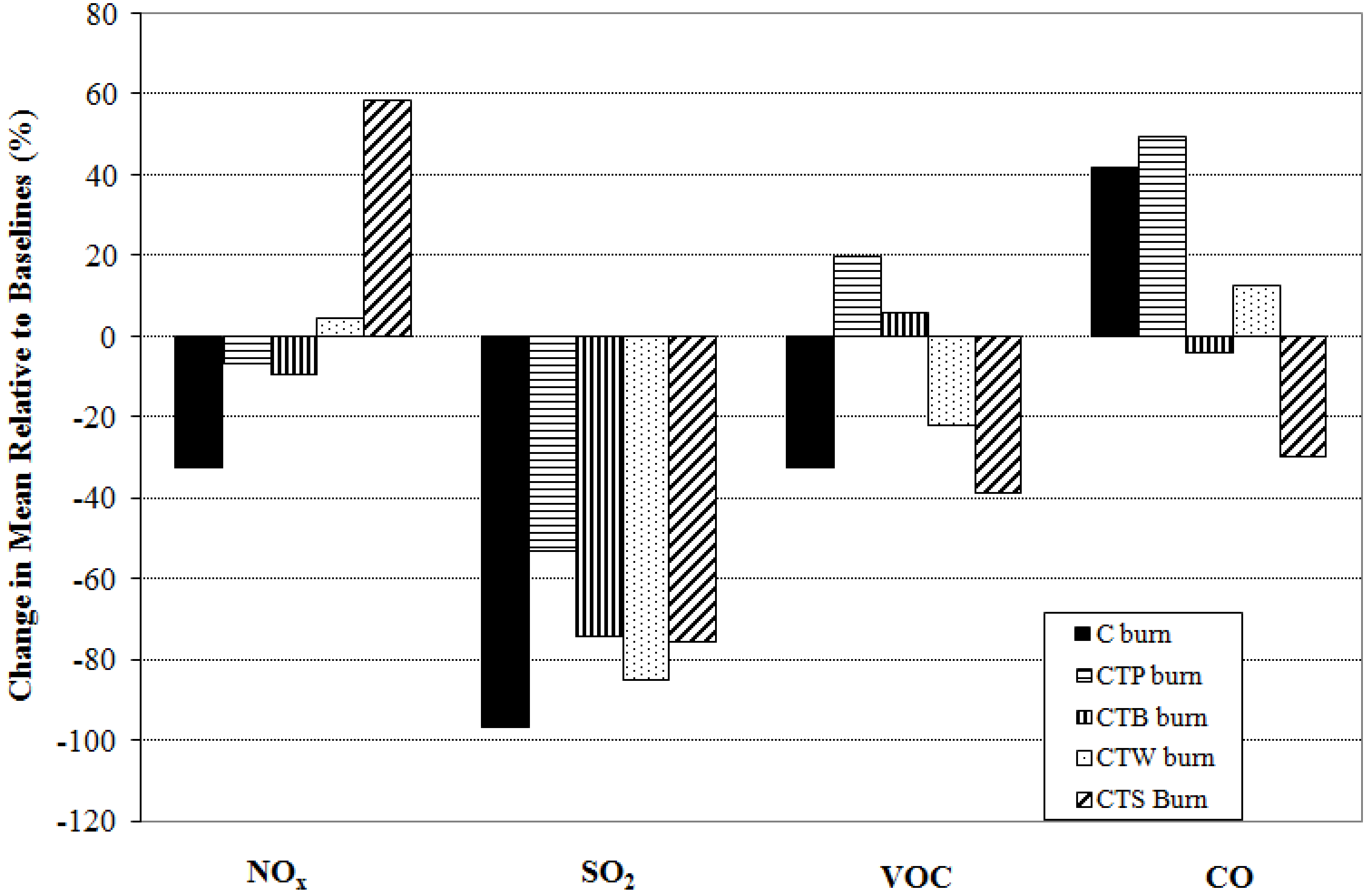


Figure 4.22: CPR – Emissions, Percent difference between fuel burns relative to respective baseline burn

These results, along with an understanding of the inherent variability of the portland cement production process itself, make it impossible to conclude that the changes in chemical composition of the final product were directly related to the type of fuel that was used.

Additionally, the primary compounds in the clinker and cement, Al_2O_3, CaO, Fe_2O_3, and SiO_2, showed no practically significant changes. These results suggest that the cement plant is able maintain consistent concentrations in these parameters when burning each of the fuels used in this study. These are significant results, because these parameters are those that have the greatest effect on the properties of the cement and concrete.

The third and fourth goals of this study were to determine if the utilization of alternative fuels directly impacts the physical properties of the cement, and concrete produced from that cement. Again, based on the chemical composition results, it was not possible to conclude that the alternative fuels directly impacted the composition of the cement. Therefore, it was not possible to conclude that use of the alternative fuels directly impacted any of the physical properties of the cement or concrete. Additionally, many of these physical properties showed no practically significant change between burns.

The air content in mortar, Blaine specific surface area, mortar cube flow, and the normal consistency were all minor physical properties of cement that showed no practically significant change between burns. For the concrete, the air content, slump, and unit weight were all properties that were not consistently affected in the same way between the two types of mixtures made from the same cement. Another property of concrete, permeability, showed no significant change between burns. This is a significant result. Because there was no significant change, it can be concluded that the same degree of permeability can be obtained using the cement from each of these burns.

Another property that is important to cement and concrete is how susceptible it is to length change when it dries. Drying shrinkage tests were conducted on mortar, as well as on two different water-to-cement ratio concrete mixtures. In each case, no significant change was measured between each of the burns. This shows conclusively that each of the cements used in this study behaved similarly when exposed to drying conditions.

The splitting tensile strength of concrete also showed no significant difference between burns. Some of the results did show minor differences, but none of these exceeded the acceptable range of results inherent to the test.

Although the fuels used cannot be conclusively attributed with affecting the properties of cement or concrete, there were a number properties that did show significant changes between burns. First, the autoclave expansion of paste prisms determined at Auburn University showed an increase relative to CT1 burn in all cases. The setting times for cement and concrete showed some significant changes. In the Gillmore and Vicat setting tests of cement pastes, the cement of CTP burn showed significant acceleration relative to that of CT1 burn, while cement from all other burns showed retardation. The concrete made from all burns except Burn C showed acceleration for both Mix A and Mix B. However, this result was not corroborated by the cement paste results.

In both the concrete mixtures, Burn C showed a trend in that it consistently produced the lowest compressive strengths. Similar results were also found for the early age strengths of mortar cubes. This is a significant result because it implies that compressive strengths are likely to improve for cement produced using tires or other alternative fuels when compared to cement produced using coal as the only fuel (C Burn); however, to establish this as a direct impact of using alternative fuels, further research is necessary.

The final goal of this study was to determine whether the utilization of alternative fuels directly impacts the emissions released by the cement plant. Just as found for the chemical composition of the cement, it is difficult to say that the fuels used were directly responsible for any changes that may have been seen in emission characteristics. Many variables within the production process have an effect on the emissions. However, each of the emissions monitored showed changes between burns.

The NO_x emissions were lowered for Burns C, CTP and CTB, but increased for Burns CTW and CTS. The NO_x emissions were the lowest for the burn condition that did not use scrap tires which agrees with the findings of Martinez (1996). The SO_2 emissions were reduced for all the burns by more than 50 percent. The VOC levels were reduced for both Burns CTW and CTS, but were increased for Burns CTP and CTB. The CO emissions decreased for Burns CTS and CTB, but were increased for Burns CTP and CTW.

However, it is important to note that despite all the changes in the emission levels, all the emissions monitored were below the allowable limits set by the Alabama Department of Environmental Management (ADEM 2006).

Unfortunately, the variable nature of the cement production process makes it very difficult to conclusively state that the use of alternative fuels has a significant effect on cement and concrete properties, or on emissions characteristics. Although there were changes in some of these properties between burns, further research is necessary to determine whether these changes are a direct result of the use of only the alternative fuels.

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

In the production of portland cement, a variety of raw materials are chemically fused in the presence of temperatures on the order of 1500 °C to produce a product known as clinker. Clinker is ground down, with sulfates, to produce portland cement. Large quantities of fuels are required to maintain the high temperatures involved in the process. Historically, the fuel sources used have been nonrenewable fossil fuels such as coal and oil. The idea of supplementing some of these traditional fuels with alternative fuels may be both economically profitable and environmentally beneficial.

Many of the alternative fuels that can be used in the portland cement industry are waste products from some other industry. In this study, whole tires, waste post-industrial plastics, broiler litter, woodchips, and switchgrass were examined to determine their viability as alternatives to traditional fuels. Tires have been used in the cement industry for some years, particularly in European cement plants. Recycled industrial plastics are waste products from many different industries. Typically, they would be either disposed of in a landfill, or incinerated. Their consumption by a cement plant both decreases the amount of landfill space occupied, and makes use of the heat generated through the incineration process. Typical incineration does not use the heat generated, and is therefore not as efficient.

Broiler litter is a byproduct of the broiler farming industry. Traditionally, broiler litter is applied to land as a fertilizer. However, due to the over application of broiler litter in regions where broiler production is high, the land and groundwater are suffering from over-saturation of phosphorus and nitrogen (Dávalos et al. 2002). The use of broiler litter as fuel in a cement plant gives the broiler industry another option to dispose of this material and it may release some of the pressure that the environment may feel from land application.

Woodchips are solid waste fuels obtained while processing lumber. Woodchip prices are relatively stable. They can be transported and unloaded by dump trucks. Because they are available locally, long distance haulage and packaging costs can be reduced. Woodchips have primarily been used as fuel in commercial heating systems, manufacturing plants, and power plants. The low ash content of woodchips is particularly suitable for the cement kiln.

Switchgrass is considered to be one of the most valuable native bio-fuels in the United States. It requires little fertilization and herbicide, and can be harvested twice a year with existing farm equipment. The grass is tough and has high productivity (Boylan et al. 2000). It is also valuable for soil stabilization, erosion control and as a windbreak. It has been co-fired successfully with coal in power generating plants before, but the high content of potassium, sodium, chlorine and silica caused problems when burned due to erosion, slagging and fouling, which can be avoided in cement kilns by incorporating the ash into the clinker (Sami et al. 2001).

In this study, a full-scale, operational cement plant was used as the testing site. During normal production, the aforementioned alternative fuels were burned in eight different test periods. Each of these test periods was called a trial burn, and each utilized different combinations of these fuels. They are as follows:

1. **C** burn utilized only coal as fuel.
2. **CT1** burn utilized coal and tires. This is the standard fuel combination used at the cement plant, and was therefore considered the baseline for comparison purposes. This is the first baseline burn.
3. **CTP** burn used coal, tires, and waste plastics. These plastics were considered alternative fuel one.
4. **CT2** burn utilized coal and tires. Again, the standard fuel combination was used and this is the second baseline burn.
5. **CTB** burn used coal, tires, and broiler litter. Broiler litter was the second alternative fuel tested.
6. **CT3** burn utilized coal and tires. Again, the standard fuel combination was used and this is the third baseline burn.
7. **CTW** burn used coal, tires, and woodchips. Woodchips was the third alternative fuel tested.
8. **CTS** burn used coal, tires, and switchgrass. Switchgrass was the fourth alternative fuel tested.

Due to the timing of the last trial burn, some of the long-term results have not been collected and only the available data are reported in this document. However, the rest of the results will be presented in future work.

Within each trial burn, samples of each material involved in the production process were collected, including the traditional and alternative fuels. The chemical composition of each of these materials was determined by two testing agencies. The composition of the clinker and cement were then compared between burns. Due to the fact that most of the incombustible material is incorporated into the clinker, an attempt was made to determine if the chemical composition of the fuels had a direct effect on the composition of the clinker and cement. The cement was then tested for various physical properties. Concrete was then made with the cement collected from each burn, and various concrete properties were tested. These physical properties of cement and concrete were compared between burns in order to determine if the fuels had any impact. Finally, the emissions released by the cement plant were monitored during each trial burn. These emissions were then compared between trial burns in order to determine if any correlations could be made between the alternative fuels and the emissions profiles.

5.2 Conclusions

The first objective of this study was to determine if the utilization of alternative fuels had an impact on the ability of a full-scale cement plant to maintain productive operations. Some problems did occur when the fuels other than coal were used. The quantity of tires that could be burned was limited by the development of sulfur-based build-ups within the calciner system. These build-ups limited the amount of airflow, and effectively choked the system. The quantity of plastics that could be burned was limited by the ability of the fuel equipment to move the low-density material into the kiln. The shredding of switchgrass bales before feeding into the kiln proved to be quite labor-intensive.

Despite the limiting factors, all of these fuels showed potential, in that they both had low acquisition costs and high energy content. The range of heat values of each of the fuels were determined to be as follows:

1. Coal: 11,157 to 12,476 BTU/lb,
2. Tires: 14,467 to 14,687 BTU/lb,
3. Plastics: 11,327 to 14,446 BTU/lb,
4. Broiler litter: 6,484 to 7,188 BTU/lb,
5. Woodchips: 8,170 to 8549 BTU/lb, and
6. Switchgrass: 7,888 to 8393 BTU/lb.

Broiler litter and woodchips, though low in energy content, burnt well and did not cause any problems during production. Based on the energy content, local availability, and the cost of acquisition relative to the coal, the cement plant may in the future consider the use of these alternative fuels.

The second objective of this study was to determine if the utilization of alternative fuels had an impact on the chemical composition of the clinker and/or cement. Based on the results presented in Chapter Four, the chemical composition of both of these materials showed significant differences between each of the trial burns in many of the parameters that were measured. However, the kiln feed and raw materials also showed significant changes in chemical composition. Additionally, the process of producing portland cement is inherently variable. Therefore, it is not possible to conclude that the changes in chemical composition of the clinker and cement were directly affected by the use of these alternative fuels.

The most significant results concerning the chemical composition of clinker and cement were that the concentrations of Al_2O_3, CaO, Fe_2O_3, and SiO_2 showed no practically significant changes. This is important because these compounds are the primary components of the clinker and cement, and they have the greatest effect on the properties of cement and concrete. These results suggest that the cement plant is capable of maintaining consistent concentrations of these compounds while using raw materials with different composition and while burning any of the fuels used in this study.

The third goal of this study was to determine if the utilization of alternative fuels directly impacted the physical properties of the cement it produced. Many of the physical properties of cement that were tested did not show a significant difference between trial burns. Drying shrinkage of paste prisms were the most prominent results that showed no practically significant change. These results revealed that the drying shrinkage behavior of these cements was not altered by the use of alternative fuels. However the autoclave expansion of paste prisms was found to be increased when alternative fuels were used

One property that did show a significant change in the cement was the setting time. The cement produced using coal, tires, and plastics showed acceleration in final setting times of as much as 27 percent relative to the cement produced using coal plus tires. The cements produced using other alternative fuels showed retardation in initial and final setting times. The final result that showed a significant change was the mortar cube compressive strength. The cement produced in the CT1 burn showed a trend of higher strengths than the other burns, at all ages, while the cement produced in the C burn showed lower strengths, especially in early ages. Although differences were found in the physical properties of cement between the trial burns, it was not possible to conclude that these effects were a direct result of the use of these alternative fuels.

The fourth objective of this study was to determine if the utilization of alternative fuels directly impacted the properties of concrete made from these portland cements. Two different concrete mixture designs with water-cement ratios of 0.37 and 0.44 were made from the cement produced during each trial burn. Just as with the physical properties of the cement, there were some properties that showed significant changes, and some that did not. One notable property that did not show any significant changes between burns was the permeability. The 91-day results from both concrete mixtures showed no significant change in permeability between any of the trial burns. Additionally, the drying shrinkage development of both concrete mixtures did not show any significant changes between any trial burns. This result agreed with that for the drying shrinkage development of paste prisms.

The splitting tensile strength of both concrete mixtures also showed almost similar trends for the trial burns for both the mixes. The C burn produced lower strengths than the CT1 burn. The CTB burn had lower 91-day splitting tensile strength for Mix B but a higher 91-day splitting tensile strength for Mix A, relative to the results from the CT1 burn. However it is important to note that, based on the acceptable range of results provided by ASTM C 496, there is no significant difference in 91-day splitting tensile strength between the trial burns.

Some concrete properties did show significant difference, one of which was the setting time. The concrete made from all burns except Burn C showed acceleration for both Mix A and Mix B. However, this result was not corroborated by the cement paste results.

The compressive strength of concrete cylinders is the primary property specified by engineers. This property did show a significant trend for the concrete made using the cement by only burning coal. The concrete produced from this cement had lower compressive strength at most ages, than the concrete made from the cement produced when alternative fuels were used. Based on these results, it is concluded that the compressive strengths are likely to improve for cement produced using tires or other alternative fuels when compared to cement produced using coal as the only fuel (C Burn).

The final objective of this study was to determine the impact of using alternative fuels on emissions released by the cement plant. The results of this study did show conclusively that the emissions were significantly different between each of the burn phases.

The NO_x emissions were lowered for C, CTP and CTB burns, but increased for the CTW and CTS burns. The NO_x emissions were the lowest for the burn condition that did not use scrap tires which agrees with the findings of Martinez (1996). The SO_2 emissions were reduced for all the burns by more than 50 percent. The VOC levels were reduced for both the CTW and CTS burns, but were increased for the CTP and CTB burns. The CO emissions decreased for the CTS and CTB burns, but were increased for the CTP and CTW burns.

The variable nature of the production process once again limited the ability of the author to state conclusively that the fuels used were directly responsible for any changes that were seen in the emissions. However, it is important to note that despite all the changes in the emission levels, all the emissions monitored were well within the allowable limits set by the Alabama Department of Environmental Management (ADEM 2006).

The fact that the cement plant was able to produce cement, with the substantial use of alternative fuels, with no detrimental effects on either the production process or the final product itself and at the same time, keeping the emissions well within the permissible limits, is a significant finding for the portland cement industry. This can lay the foundation for further exploration, research, and implementation in the future. Overall, it can be concluded that scrap tires, waste plastics, broiler litter, woodchips and switchgrass have the potential to become sustainable alternative fuel sources for use in cement production. The final decision on the use of a specific alternative fuel will depend on the availability of the fuel, its cost, and its compatibility with the particular cement plant

5.3 Recommendations

Although the sampling and testing plan used in this project was thorough, it was very difficult to make conclusions concerning some of the objectives that were originally developed. The use of a full-scale portland cement production facility presented a number of problems in attempting to reach these objectives. One major hurdle was the logistics of outfitting the cement plant with the facilities necessary to handle the alternative fuels that were to be studied. Obstacles in this regard resulted in a number of delays in the timing of the burns. Now that the facilities are in place to handle these alternative fuels, it would be beneficial to conduct a number of trial burns using similar fuels within close proximity (time wise) to one another. Due to the delays experienced in this study, the burns were spaced months apart. These extended breaks between trial burns allowed the cement plant to make adjustments in the production process, in an attempt to optimize production. These changes removed much of the consistency in production conditions between burns.

In order to satisfy some of the objectives of this project, it would be necessary to maintain consistent inputs to the process. This study found that the kiln feed differed in chemical composition from one trial burn to another. Furthermore, the fuels themselves were not consistent in their chemical composition, and in fact, the source of the coal was completely changed between some burns. Other parameters of the production process, which were not monitored in this project, were also likely altered between burns. Once again, these changes that were made rendered it virtually impossible to determine if the chemical composition of the fuels had any effect on the chemical composition of the clinker and/or cement.

Despite conducting more baseline burns between the fuel burns, the effect of change in sources of raw materials and coal could not be completely addressed, since there were variations in the chemical compositions of inputs even between the fuel burns and their respective baseline burns. Ideally, the issue can be overcome, if the baseline burns were conducted immediately before the fuel burn, which may keep the chemical composition of raw materials and coal fairly consistent, while keeping the feed and production rates reasonably similar, within practical limits. However, this testing scheme would require extra costs associated with the production, sampling and testing of the materials.

Once an ideal baseline burn for an alternative fuel burn is established, it would be interesting to vary the chemical composition of each input and output of the process, taking the actual feed and production rates of the all the materials into consideration. This could allow a researcher to understand exactly how the variation in chemical composition of an input is affecting the chemical composition of the final output of the process. Perhaps some of this work can be conducted under controlled laboratory conditions that have been designed to accurately simulate the cement manufacturing process.

Another aspect of this project that one would ideally alter is simply the number of tests conducted. Every facet, be it chemical compositions or physical properties, would benefit from increased repetitions. This was limited, however, by finances, personnel, and time.

Further, collection of more cement would give an opportunity to repeat the concrete mixtures and thereby, establishing the concrete results. Also, study of effect of admixtures may provide an insight into the variation in some properties of cement compared to the properties of concrete made from the cement.

The emphasis of this project was the effect that alternative fuels had on everything from the production process of cement to the physical properties of concrete made from that cement. With that in mind, it would be beneficial to continue with this study by utilizing many other materials that potentially could be used as an alternative fuel. The options are numerous, and this study would benefit from the use of additional fuels.

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APPENDIX A: TEST PROCEDURE

Table A.1: Analyzing the Chemical Composition of the Raw Materials

Item #	Material Analyzed	Test	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	***Raw Material One***	Standard Cement Plant Parameters (Table A.8) [1]	1 / burn	Discrete	During Each Burn	Cement Plant	Yes
2	***Raw Material Two***						
3	***Raw Material Three*** [3]						
4	***Raw Material Four***						
5	***Raw Material Five***						
6	***Raw Material One***	Standard External Lab Parameters (Table A.10)	1 / burn	Discrete	During Each Burn	External Lab	No
7	***Raw Material Two***						
8	***Raw Material Three*** [3]						
9	***Raw Material Four***						
10	***Raw Material Five***						
11	***Kiln Feed (Raw Material Seven)***	Standard Cement Plant Parameters (Table A.8) [2]	2 / day	Discrete	Standard Sampling Period	Cement Plant	Yes
12	***Kiln Feed (Raw Material Seven)***	Standard External Lab Parameters (Table A.10)	2 / day	3-Day Composites	Standard Sampling Period	External Lab	No
13	***Raw Material Six***	Standard Cement Plant Parameters (Table A.8) [1]	1 / burn	Discrete	During Each Grinding Period	Cement Plant	Yes
14	***Raw Material Six***	Standard External Lab Parameters (Table A.10)	1 / burn	3-Day Composites	During Each Grinding Period	External Lab	No

Notes: [1] Na$_2$O$_{eq}$ is not collected [2] Moisture is not collected [3] Moisture and LOI is not collected

Table A.2.a: Analyzing the Chemical Composition of Fuels

Item #	Material Analyzed	Test	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	*Pulverized Coal*	Proximate Analysis (Table A.9)	2 / day	3-Day Composites	Standard Sampling Period	Cement Plant	Yes
2	*Pulverized Coal*	Ultimate Analysis (Table A.9)				Cement Plant	Yes
3	*Pulverized Coal*	Standard Cement Plant Parameters (Table A.8) [1]				Cement Plant	Yes
4	*Pulverized Coal*	Combustion Analysis (Table A.9)				Cement Plant	Yes
5	*Pulverized Coal*	Proximate Analysis (Table A.9)	2 / day	3-Day Composites	Standard Sampling Period	External Lab	No
6	*Pulverized Coal*	Ultimate Analysis (Table A.9)				External Lab	No
7	*Pulverized Coal*	Standard External Lab Parameters (Table A.10) [2]				External Lab	No
8	*Pulverized Coal*	Combustion Analysis (Table A.9)				External Lab	No

Notes:

[1] Moisture, LOI, and Na_2O_{eq} is not collected

[2] Moisture is not collected

Table A.2.b: Analyzing the Chemical Composition of Fuels

Item #	Material Analyzed	Test	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	*Tires*	Proximate Analysis (Table A.9)	1 / burn	One Composite Sample Prepared from 8 Discrete Radial Section Samples Removed from Random Tires	During Each Burn [2]	External Lab	No
2	*Tires*	Ultimate Analysis (Table A.9)				External Lab	No
3	*Tires*	Standard External Lab Parameters (Table A.10) [1]				External Lab	No
4	*Tires*	Combustion Analysis (Table A.9)				External Lab	No
5	*Plastics*	Proximate Analysis. (Table A.9)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Burn CTP	External Lab	No
6	*Plastics*	Ultimate Analysis (Table A.9)				External Lab	No
7	*Plastics*	Standard External Lab Parameters (Table A.10) [1]				External Lab	No
8	*Plastics*	Combustion Analysis (Table A.9)				External Lab	No

Notes:

[1] To be determined for both the fuel and the fuel's ash after combustion

[2] Tires are not collected during the coal only burn period

Table A.2.c: Analyzing the Chemical Composition of Fuels

Item #	Material Analyzed	Test	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
9	*Broiler Litter*	Proximate Analysis (Table A.9)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Burn CTB	External Lab	No
10	*Broiler Litter*	Ultimate Analysis (Table A.9)				External Lab	No
11	*Broiler Litter*	Standard External Lab Parameters (Table A.10) [1]				External Lab	No
12	*Broiler Litter*	Combustion Analysis (Table A.9)				External Lab	No
13	*Woodchips*	Proximate Analysis (Table A.9)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Burn CTW	External Lab	No
14	*Woodchips*	Ultimate Analysis (Table A.9)				External Lab	No
16	*Woodchips*	Standard External Lab Parameters (Table A.10) [1]				External Lab	No
17	*Woodchips*	Combustion Analysis (Table A.9)				External Lab	No

Notes:

[1] To be determined for both the fuel and the fuel's ash after combustion

Table A.2.d: Analyzing the Chemical Composition of Fuels

Item #	Material Analyzed	Test	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
18	*Switchgrass*	Proximate Analysis (Table A.9)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Burn CTS	External Lab	No
19	*Switchgrass*	Ultimate Analysis (Table A.9)				External Lab	No
20	*Switchgrass*	Standard External Lab Parameters (Table A.10) [1]				External Lab	No
21	*Switchgrasss*	Combustion Analysis (Table A.9)				External Lab	No

Table A.3: Analyzing the Chemical Composition of Cement Kiln Dust (CKD)

Item #	Test	Sampling Frequency	Specimen Preparation Method	Sample Period	Tested by	Routine?
1	Standard Cement Plant Parameters (Table A.8) [1]	2 / day	Discrete	Standard Sampling Period	Cement Plant	Yes
2	Standard External Lab Parameters (Table A.10)	2 / day	Discrete	Standard Sampling Period	External Lab	No

Notes:

[1] Na_2O_{eq}, Moisture, and LOI are not collected

Table A.2: Analyzing the Chemical Composition of Clinker

Item #	Test	Specification	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	***Chemical Composition:*** Standard Cement Plant Parameters (Table A.8) [1]	XRF	12 / day	Discrete	Standard Sampling Period	Cement Plant	Yes
2	***Additional Chemical Composition:*** Free CaO	ASTM C 114	12 / day	Discrete		Cement Plant	Yes
3	***Clinker Phase Composition:*** C_3S, C_2S, C_3A, C_4AF	ASTM C 150	N/A	N/A	N/A	Cement Plant	Yes
4	***Clinker Phase Composition:*** C_3S, C_2S, C_3A, C_4AF	Rietveld Analysis	12 / day	1-Day Composites	Standard Sampling Period	Cement Plant Specialty Lab	No
5	***Trace Element Content of Clinker:*** Standard External Lab Parameters (Table A.10)	XRF				External Lab	No

Notes:

[1] Moisture and LOI are not collected

Table A.3: Analyzing the Chemical Composition of Cement

Item #	Test	Specification	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	***Chemical Composition:*** Standard Cement Plant Parameters (Table A.8) [1]	XRF	8 / day	Discrete	Standard Sampling Period	Cement Plant	Yes
2	***Additional Chemical Composition:*** Free CaO Blaine Specific Surface Area	ASTM C 114 ASTM C 204	8 / day	Discrete		Cement Plant	Yes
3	***Clinker Phase Composition:*** C_3S, C_2S, C_3A, C_4AF	ASTM C 150	N/A	N/A		Cement Plant	Yes
4	***Clinker Phase Composition:*** C_3S, C_2S, C_3A, C_4AF	Rietveld Analysis	8 / day	1-Day Composites		Cement Plant Specialty Lab	No
5	***Chemical Composition:*** Standard Cement Plant Parameters (Table A.8) [2]	XRF	8 / day	1-Day Composites		Cement Plant	Yes
6	***Trace Element Content of Cement:*** Standard External Lab Parameters (Table A.10)	XRF	8 / day	1-Day Composites		External Lab	No
7	***Additional Chemical Analysis:*** Total organic carbon (TOC)	TOC Analyzer	8 / day	1-Day Composites		External Lab	No

Notes:

[1] Moisture is not collected.

[2] Moisture is not collected. FCaO is collected

Table A.4: Analyzing the Physical Properties of Cement

Item #	Test	Specification	Sampling Frequency	Specimen Preparation Method	Sampling Period	Tested by	Routine?
1	***Standard Physical Properties:*** Air content of mortar (%) Blaine specific surface area (m^2/kg)	ASTM C 185 ASTM C 204	8 / day	1-Day Composites	Standard Sampling Period)	Cement Plant	Yes
2	***Standard Physical Properties:*** Normal Consistency (%) Autoclave expansion (%) Compressive strength (MPa): 1, 3, 7, 28 days Cube Flow (%) Gillmore Test: Initial and Final Set Times Vicat Test: Initial and Final Set Times	ASTM C 187 ASTM C 151 ASTM C 109 ASTM C 230 ASTM C 266 ASTM C 191	8 / day	1-Day Composites[1]	Standard Sampling Period	Cement Plant, and Auburn University	Yes
4	***Additional Physical Properties:*** Particle Size Distribution Heat of hydration (kJ/kg): 7 and 28 days	Laser Diffraction ASTM C 186	8 / day	1-Day Composites	Standard Sampling Period	Cement Plant Specialty Lab	No
5	***Additional Physical Properties:*** Drying Shrinkage of Mortar Prisms (%): 4, 11, 18, and 25 days	ASTM C 596	8 / day	3-Day Composites	Standard Sampling Period	Auburn University	No

Notes: [1] Auburn University conducts these tests on one three-day composite sample during each burn period

Table A.5: Analyzing the Properties of Concrete to be Conducted by Auburn University and the Cement Plant

Item #	Test	Specification	Material Type	Concrete Age (days)	Sampling Frequency	Sample Method
1	***Fresh Properties:*** Total Air Content Slump Setting Time Unit Weight	ASTM C 231 ASTM C 143 ASTM C 403 ASTM C 138	Concrete Concrete Mortar Concrete	Fresh State Fresh State Early-age Fresh State	8 / day	Single Composite Over Entire Burn Phase
2	***Physical Properties:*** Compressive strength Splitting Tensile Strength [1] Drying Shrinkage Development Heat of Hydration Under Semi-Adiabatic Conditions [1]	ASTM C 39 ASTM C 496 ASTM C 157 RILEM 119-TCE	Concrete Concrete Concrete Concrete	1, 3, 7, 28, 91 1, 3, 7, 28, 91 4 to 448 0.1 to 7		
3	***Durability:*** Permeability (RCPT)	ASTM C 1202	Concrete	91		

<u>Notes</u>:

[1] Test conducted by the cement plant

Two standard concrete mixtures developed to evaluate the response of the cement:

(A) Cement only, w/c = 0.44 (For AEA)
(B) Cement only, w/c = 0.37 (For AEA and Type F Admixtures)

Table A.6: Analyzing Emissions

Item #	Material Analyzed	Test	Spec.	Sampling Frequency	Specimen Preparation Method	Data Collection Period	Tested by	Routine?
1	Main Stack Emissions	CO NO_x SO_2 VOC	CEMS	Continuous	Real - Time	Standard Emissions Sampling Frequency	Cement Plant	Yes

Table A.7: ASTM Methods

Method Number	Method Title
C39	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C109	Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)
C151	Standard Test Method for Autoclave Expansion of Hydraulic Cement
C157	Standard Test Method for Length Change of Hardened Hydraulic-Cement, Mortar, and Concrete
C185	Standard Test Method for Air Content of Hydraulic Cement Mortar
C186	Standard Test Method for Heat of Hydration of Hydraulic Cement
C191	Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle
C204	Standard Test Method for Fineness of Hydraulic Cement by Air Permeability Apparatus
C230	Standard Specification for Flow Table for Use in Tests of Hydraulic Cement
C231	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C266	Standard Test Method for Time of Setting of Hydraulic-Cement Paste by Gillmore Needles
C403	Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance
C496	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C596	Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement
C1202	Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration

Table A.8: Standard Cement Plant Parameters

Parameter	Analysis Technique
Al_2O_3	ASTM C 114 and XRF
CaO	
Fe_2O_3	
K_2O	
MgO	
Na_2O	
Na_2O_{eq}	
SiO_2	
SO_3	
Loss On Ignition	ASTM C 114
Moisture	

Table A.9: Fuel Test Parameters

Test	Parameter
Proximate Analysis	Volatile Matter, Fixed Carbon, Percent Ash, Percent Moisture
Ultimate Analysis	Carbon, Hydrogen, Oxygen, Sulfur, Nitrogen
Combustion Analysis	Energy Content

Table A.10: Standard External Lab Parameters

Parameter	Analysis Technique
Al_2O_3	ASTM C 114 and XRF
CaO	
Fe_2O_3	
K_2O	
MgO	
Na_2O	
P_2O_5	
SiO_2	
SO_3	
TiO_2	
As	
Ba	
Cd	
Cl	
Co	
Cr	
Cu	
Hg	
Mn	
Mo	
Ni	
Pb	
Sb	
Se	
Sr	
V	
Zn	
Loss On Ignition	ASTM C 114
Moisture	

Table A.11: Abbreviations

Abbreviation	Definition
% NC	% Normal Consistency
AEA	Air entraining agent
ASTM	American Society for Testing and Materials
C_2S	Dicalcium silicate
C_3A	Tricalcium aluminate
C_3S	Tricalcium silicate
C_4AF	Tetracalcium aluminoferrite
CEMS	Continuous emissions monitoring system
CKD	Cement kiln dust
LOI	Loss on ignition
RCPT	Rapid chloride permeability test
T Alkalis	Total alkalis
TOC	Total organic carbon
VOC	Volatile organic compounds
XRF	X-ray fluorescence

APPENDIX B.3

RAW DATA FOR *CTP BURN*

B.3.1. GENERAL COMMENTS

- The raw data from the CTP burn are presented in this appendix.
- Coal, scrap tires, and waste plastics are the fuels used in the burn
- The burn period lasted from 7 AM on April 3, 2007 to 7 AM April 6, 2007.

B.3.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.3.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.3.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	23.22	0.39	2.98	7.60	1.14	2.62
CaO	4.27	52.85	41.59	38.10	1.66	32.57
Fe_2O_3	14.41	0.00	1.30	14.50	1.63	0.25
K_2O	2.15	0.07	0.26	0.05	0.28	0.25
MgO	2.21	0.97	3.29	12.90	0.19	3.15
Na_2O	0.42	0.03	0.10	NR	NR	0.20
SiO_2	43.03	2.04	13.77	24.60	95.90	13.56
SO_3	0.13	0.10	0.15	0.41	0.21	34.95
Moisture	34.60	3.00	NR	6.50	3.40	10.40
LOI	7.10	43.20	NR	0.10	0.40	11.40

Notes:

NC - Not Collected

NR - Not Reported

Table B.3.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	26.87	0.87	8.09	4.27	1.00	2.71
CaO (wt. %)	3.20	91.85	43.79	29.01	0.41	38.80
Fe_2O_3 (wt. %)	12.35	0.47	3.56	34.03	0.59	0.50
K_2O (wt. %)	2.69	0.14	0.69	0.20	0.17	0.26
MgO (wt. %)	1.52	3.04	1.86	12.16	0.18	2.78
Na_2O (wt. %)	0.60	0.47	0.11	0.13	0.04	0.16
P_2O_5 (wt. %)	0.63	0.01	0.04	0.47	0.00	0.03
SiO_2 (wt. %)	50.21	2.86	41.12	15.27	97.37	13.21
SO_3 (wt. %)	0.09	0.20	0.12	0.30	0.00	41.23
TiO_2 (wt. %)	1.37	0.00	0.43	0.25	0.20	0.10
Moisture (wt. %)	22.26	2.93	6.51	6.01	2.29	4.06
LOI (wt. %)	11.99	42.91	27.56	ND	0.35	18.06
As (ppm)	299	6	23	4	4	< 2
Ba (ppm)	2000	2000	3000	2000	2000	3000
Cd (ppm)	ND	ND	ND	ND	ND	ND
Cl (ppm)	25	29	34	100	13	30
Co (ppm)	64	12	15	4	5	7
Cr (ppm)	203	16	54	3249	9	32
Cu (ppm)	219	18	46	61	33	< 10
Hg (ppm)	ND	ND	ND	ND	ND	ND
Mn (ppm)	1000	3000	12000	38700	2000	12000
Mo (ppm)	40	12	13	90	23	23
Ni (ppm)	122	14	16	75	< 5	5
Pb (ppm)	195	4	27	21	9	23
Sb (ppm)	ND	ND	ND	ND	ND	ND
Se (ppm)	ND	ND	ND	ND	ND	ND
Sr (ppm)	1800	400	400	200	100	800
V (ppm)	325	17	74	604	20	18
Zn (ppm)	363	26	52	198	2	8

Notes:

ND - Not Detected

B.3.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.3.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	4/3/2007		4/4/2007		4/5/2007			Average	C. V. (%)	Normality P-Value[1]
	4:52 AM	1:54 PM	1:32 AM	1:40 PM	1:40 AM	1:46 PM	1:43 AM			
Al_2O_3	2.97	2.95	3.03	3.13	3.04	2.96	3.05	3.02	2.1	0.386
CaO	43.53	43.48	43.52	43.6	43.85	44.11	44.11	43.74	0.6[2]	0.078
Fe_2O_3	1.96	1.84	1.77	1.98	1.96	1.91	1.9	1.90	4.0	0.356
K_2O	0.29	0.28	0.29	0.29	0.29	0.28	0.29	0.29	1.7[2]	<0.005
MgO	2.06	2.11	2.01	2.18	2.1	2.03	2.03	2.07	2.9	0.440
Na_2O	0.05	0.04	0.05	0.05	0.03	0.05	0.04	0.04	17.8[2]	0.021
Na_2O_{eq}	0.24	0.22	0.24	0.24	0.22	0.23	0.23	0.23	3.9[2]	0.091
SiO_2	13.83	13.88	13.83	13.74	13.47	13.52	13.41	13.67	1.4	0.156
SO_3	0.11	0.11	0.08	0.11	0.14	0.14	0.13	0.12	18.3	0.223
LOI	34.9	34.9	35	34.4	34.4	34.8	34.7	34.73	0.7	0.183

Notes:

NC - Not Collected	[1] Based on Anderson-Darling Normality Test
NA - Not Applicable	[2] Data not normally distributed

Table B.3.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	4.91
CaO (wt. %)	65.27
Fe_2O_3 (wt. %)	3.01
K_2O (wt. %)	0.50
MgO (wt. %)	3.35
Na_2O (wt. %)	0.02
P_2O_5 (wt. %)	0.07
SiO_2 (wt. %)	21.87
SO_3 (wt. %)	0.34
TiO_2 (wt. %)	0.24
Moisture (wt. %)	0.10
LOI (wt. %)	34.67
As (ppm)	18
Ba (ppm)	400
Cd (ppm)	NR
Cl (ppm)	63
Co (ppm)	14
Cr (ppm)	86
Cu (ppm)	41
Hg (ppm)	NR
Mn (ppm)	1700
Mo (ppm)	16
Ni (ppm)	12
Pb (ppm)	< 4
Sb (ppm)	NR
Se (ppm)	NR
Sr (ppm)	500
V (ppm)	73
Zn (ppm)	37

Notes:

NR - Not Reported

B.3.5. CHEMICAL COMPOSITION OF FUELS

Table B.3.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	23.43
	Fixed Carbon	48.43
	Volatile Matter	28.14
Ultimate Analysis	**Carbon**	64.41
	Hydrogen	4.01
	Nitrogen	1.31
	Oxygen	3.05
	Sulfur	3.79
Standard Parameters	Al_2O_3	15.43
	CaO	3.23
	Fe_2O_3	36.24
	K_2O	1.94
	MgO	1.04
	Na_2O	0.36
	SiO_2	36.17
	SO_3	4.40
Heat Value [1]		11255

Notes:

[1] Value is Reported as BTU/lb

Table B.3.6: ELR - Proximate, Ultimate, and Combustion of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	24.54
	Fixed Carbon	47.68
	Volatile Matter	27.78
Ultimate Analysis	**Carbon**	64.68
	Hydrogen	3.93
	Nitrogen	1.08
	Oxygen	4.11
	Sulfur	1.66
Heat Value [1]		11369

Notes:

[1] Value is Reported as BTU/lb

Table B.3.7: ELR - Standard Parameters of Coal

Property	3-Day Composite
Al_2O_3 (wt. %)	21.04
CaO (wt. %)	8.25
Fe_2O_3 (wt. %)	15.16
K_2O (wt. %)	2.49
MgO (wt. %)	1.25
Na_2O (wt. %)	0.36
P_2O_5 (wt. %)	0.23
SiO_2 (wt. %)	43.44
SO_3 (wt. %)	6.50
TiO_2 (wt. %)	0.96
As (ppm)	316
Ba (ppm)	1300
Cd (ppm)	5
Cl (ppm)	134
Co (ppm)	44
Cr (ppm)	117
Cu (ppm)	103
Hg (ppm)	0.022
Mn (ppm)	1500
Mo (ppm)	39
Ni (ppm)	92
Pb (ppm)	45
Sb (ppm)	NR
Se (ppm)	1
Sr (ppm)	500
V (ppm)	214
Zn (ppm)	197

Notes:

ND - Not Detected

Table B.3.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	14.56
	Fixed Carbon	26.38
	Moisture [1]	0.07
	Volatile Matter	59.06
Ultimate Analysis	**Carbon**	75.94
	Hydrogen	6.52
	Nitrogen	0.52
	Oxygen	0.46
	Sulfur	2.00
Heat Value [2]		14687

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.3.9: ELR - Standard Parameters of Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	1.15
CaO (wt. %)	1.68
Fe_2O_3 (wt. %)	84.72
K_2O (wt. %)	0.17
MgO (wt. %)	0.33
Na_2O (wt. %)	0.19
P_2O_5 (wt. %)	0.12
SiO_2 (wt. %)	4.91
SO_3 (wt. %)	0.51
TiO_2 (wt. %)	0.56
As (ppm)	5
Ba (ppm)	300
Cd (ppm)	3
Cl (ppm)	NR
Co (ppm)	536
Cr (ppm)	178
Cu (ppm)	900
Hg (ppm)	<0.001
Mn (ppm)	5200
Mo (ppm)	23
Ni (ppm)	239
Pb (ppm)	13
Sb (ppm)	NR
Se (ppm)	<1
Sr (ppm)	100
V (ppm)	50
Zn (ppm)	48400

Notes:

NR - Not Reported

Table B.3.10: ELR - Proximate, Ultimate, and Combustion Analysis of Plastics

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	8.75
	Fixed Carbon	2.95
	Moisture [1]	0.32
	Volatile Matter	88.30
Ultimate Analysis	**Carbon**	65.25
	Hydrogen	8.21
	Nitrogen	1.27
	Oxygen	17.46
	Sulfur	0.22
Heat Value [2]		12754

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.3.11: ELR - Standard Parameters of Plastics

Property	3-Day Composite
Al_2O_3 (wt. %)	0.48
CaO (wt. %)	92.00
Fe_2O_3 (wt. %)	0.54
K_2O (wt. %)	0.13
MgO (wt. %)	1.75
Na_2O (wt. %)	0.17
P_2O_5 (wt. %)	0.14
SiO_2 (wt. %)	2.12
SO_3 (wt. %)	0.41
TiO_2 (wt. %)	1.77
As (ppm)	62
Ba (ppm)	4093
Cd (ppm)	7
Cl (ppm)	54
Co (ppm)	142
Cr (ppm)	356
Cu (ppm)	369
Hg (ppm)	<0.001
Mn (ppm)	283
Mo (ppm)	6
Ni (ppm)	50
Pb (ppm)	628
Sb (ppm)	NR
Se (ppm)	NR
Sr (ppm)	593
V (ppm)	66
Zn (ppm)	283

Notes:

ND - Not Detected
NR - Not Reported

Table B.3.12: AUR - Density of Plastics

Sample #	Density (kg/m^3)
1	95.1
2	101.3
3	112.7
4	94.5
5	91.1
6	87.7
7	81.1
8	96.0
9	87.2
10	68.3
11	69.1
12	94.4
13	94.7
14	91.7
15	74.0
16	79.7
17	77.6
18	71.2
19	83.1
20	72.6
21	74.5
22	80.3
23	73.4
24	72.5
Average	**84.3**

B.3.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.3.13: CPR - Chemical Composition of Cement Kiln Dust

Property (wt. %)	4/3/2007		4/4/2007		4/5/2007	4/6/2007		Average
	8:24 AM	7:38 PM	7:56 AM	7:39 PM	9:32 AM	1:47 AM	6:15 AM	
Al_2O_3	4.03	4.21	4.08	3.04	3.11	3.49	3.62	3.65
CaO	43.36	45.18	47.41	51	51.41	48.59	46.49	47.63
Fe_2O_3	1.93	1.93	1.76	1.55	1.56	1.68	1.75	1.74
K_2O	0.4	0.4	0.37	0.34	0.42	0.39	0.37	0.38
MgO	1.19	1.96	2.25	1.8	2.48	1.67	1.31	1.81
Na_2O	0.03	0.07	0.07	0.05	0.06	0.05	0.03	0.05
SiO_2	12.4	13.43	14.15	9.67	9.34	10.61	11.37	11.57
SO_3	0.36	0.57	0.64	0.8	2.43	0.88	0.24	0.85

Table B.3.14: ELR - Chemical Composition of Cement Kiln Dust

Property	4/3/2007		4/4/2007		4/5/2007		Average
	8:24 AM	7:38 PM	7:56 AM	7:39 PM	9:32 AM	1:47 AM	
Al_2O_3 (wt. %)	6.33	5.82	4.86	3.96	4.63	5.09	5.12
CaO (wt. %)	67.34	68.92	72.99	76.21	74.05	72.57	72.01
Fe_2O_3 (wt. %)	2.88	2.95	2.47	2.23	2.41	2.51	2.58
K_2O (wt. %)	0.42	0.57	0.49	0.41	0.45	0.46	0.47
MgO (wt. %)	1.99	2.42	2.73	3.16	2.66	2.30	2.54
Na_2O (wt. %)	0.11	0.08	0.08	0.06	0.06	0.09	0.08
P_2O_5 (wt. %)	0.11	0.08	0.06	0.04	0.04	0.06	0.07
SiO_2 (wt. %)	19.66	17.53	14.52	12.34	14.27	15.92	15.71
SO_3 (wt. %)	0.62	1.10	1.43	1.26	1.05	0.61	1.01
TiO_2 (wt. %)	0.36	0.30	0.22	0.18	0.22	0.23	0.25
Moisture (wt. %)	0.11	0.14	0.13	0.12	0.16	0.16	0.14
LOI (wt. %)	35.44	34.49	32.21	29.67	32.62	35.09	33.25
As (ppm)	32	31	23	33	27	30	29
Ba (ppm)	400	500	300	300	300	200	333
Cd (ppm)	NR	NR	NR	NR	NR	NR	NA
Cl (ppm)	80	124	213	137	115	115	131
Co (ppm)	13	14	18	8	13	12	13
Cr (ppm)	62	77	44	37	50	54	54
Cu (ppm)	85	38	54	43	21	41	47
Hg (ppm)	NR	NR	NR	NR	NR	NR	NA
Mn (ppm)	900	1200	800	700	800	900	883
Mo (ppm)	13	27	15	12	21	9	16
Ni (ppm)	15	25	10	10	16	10	14
Pb (ppm)	29	25	33	15	< 4	6	22
Sb (ppm)	NR	NR	NR	NR	NR	NR	NA
Se (ppm)	NR	NR	NR	NR	NR	NR	NA
Sr (ppm)	600	600	500	500	500	500	533
V (ppm)	82	75	61	44	57	67	64
Zn (ppm)	54	47	31	28	32	37	38

Notes:

NA - Not Applicable
ND - Not Detected

B.3.7. CHEMICAL COMPOSITION OF CLINKER

Table B.3.15: CPR - Chemical Composition of Clinker for 4/3/07 and 4/4/07

Property (wt. %)	4/3/2007									4/4/2007											
	7:50 AM	9:30 AM	11:50 AM	1:51 PM	4:47 PM	5:30 PM	7:37 PM	9:35 PM	11:35 PM	1:34 AM	3:35 AM	6:09 AM	7:56 AM	10:03 AM	11:41 AM	1:40 PM	3:56 PM	5:57 PM	7:39 PM	9:57 PM	11:37 PM
Al_2O_3	5.08	5.24	5.15	5.22	5.32	5.10	5.13	5.07	5.12	5.16	5.21	5.16	5.18	5.21	5.19	5.22	5.24	5.14	5.13	4.70	5.39
CaO	64.39	64.22	64.44	64.47	64.20	64.69	64.38	64.07	64.44	64.28	64.08	64.21	64.07	64.36	64.41	64.50	64.51	64.57	64.70	63.26	64.40
Fe_2O_3	3.50	3.53	3.38	3.40	3.42	3.24	3.27	3.31	3.28	3.30	3.28	3.24	3.33	3.34	3.48	3.55	3.67	3.73	3.67	3.24	3.92
K_2O	0.43	0.45	0.48	0.45	0.47	0.45	0.50	0.46	0.41	0.44	0.47	0.47	0.45	0.47	0.43	0.44	0.51	0.47	0.45	0.46	0.47
MgO	3.27	3.24	3.24	3.25	3.23	3.24	3.19	3.14	3.20	3.19	3.18	3.19	3.21	3.30	3.34	3.38	3.46	3.43	3.42	2.98	3.42
Na_2O	0.07	0.07	0.08	0.07	0.07	0.07	0.08	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07
Na_2O_{eq}	0.35	0.37	0.39	0.37	0.38	0.37	0.41	0.37	0.33	0.36	0.38	0.38	0.36	0.38	0.35	0.36	0.41	0.38	0.37	0.37	0.38
SiO_2	21.57	21.43	21.48	21.57	21.45	21.51	21.47	21.30	21.42	21.39	21.37	21.27	21.32	21.41	21.48	21.56	21.51	21.52	21.51	20.22	21.37
SO_3	0.93	0.86	0.98	0.79	0.92	0.58	1.04	1.66	0.49	0.60	0.97	0.88	0.83	0.88	0.69	0.70	1.02	0.94	0.82	0.84	1.03
F CaO	0.33	0.58	1.05	0.75	2.24	1.74	1.68	1.57	0.97	1.10	1.52	1.22	0.86	1.10	0.88	0.58	0.72	0.55	1.10	1.46	0.97
C_3A	7.50	7.90	7.90	8.10	8.30	8.00	8.10	7.80	8.00	8.10	8.30	8.20	8.10	8.20	7.90	7.80	7.70	7.30	7.40	7.00	7.70
C_4AF	10.70	10.70	10.30	10.40	10.40	9.90	9.90	10.10	10.00	10.00	10.00	9.90	10.10	10.10	10.60	10.80	11.20	11.40	11.20	9.90	11.90
C_3S	59.10	58.40	59.70	58.60	57.70	61.00	59.80	60.20	60.40	59.70	58.70	60.40	59.20	59.50	59.20	58.60	58.70	59.50	60.30	67.70	57.90
C_2S	17.30	17.40	16.60	17.70	18.00	15.70	16.50	15.70	15.90	16.30	17.00	15.40	16.40	16.50	16.90	17.60	17.40	16.80	16.20	6.90	17.50

Table B.3.16: CPR - Chemical Composition of Clinker for 4/5/07 and 4/6/07

Property (wt. %)	4/5/2007												4/6/2007			Average	C. V. (%)	Normality P-Value[1]
	3:43 AM	5:41 AM	7:26 AM	8:03 AM	9:51 AM	11:52 AM	1:46 PM	3:46 PM	5:55 PM	7:37 PM	10:32 PM	11:47 PM	1:42 AM	4:19 AM	5:37 AM			
Al_2O_3	5.10	5.14	5.17	5.10	5.19	5.08	5.14	5.19	5.11	5.12	5.03	5.13	5.15	5.22	5.16	5.15	2.0	<0.005
CaO	64.79	64.80	64.77	64.78	64.83	64.88	64.99	64.88	64.98	64.91	65.05	64.97	64.89	64.95	64.88	64.56	0.6	0.039
Fe_2O_3	3.67	3.70	3.90	3.80	3.76	3.81	3.63	3.70	3.72	3.74	3.70	3.81	3.73	3.80	3.83	3.57	6.1	<0.005
K_2O	0.47	0.50	0.45	0.47	0.49	0.45	0.48	0.48	0.47	0.47	0.48	0.45	0.49	0.49	0.47	0.47	4.6	0.077
MgO	3.36	3.36	3.38	3.32	3.32	3.28	3.27	3.27	3.22	3.20	3.19	3.16	3.12	3.12	3.09	3.25	3.3	0.589
Na_2O	0.07	0.08	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	5.8	<0.005
Na_2O_{eq}	0.39	0.40	0.36	0.38	0.39	0.37	0.39	0.39	0.38	0.38	0.38	0.37	0.39	0.40	0.37	0.38	4.4	0.053
SiO_2	21.35	21.19	21.38	21.41	21.12	21.36	21.24	21.22	21.06	21.22	21.22	21.21	21.07	20.98	21.02	21.31	1.2	<0.005
SO_3	1.01	1.07	0.75	0.95	0.98	0.90	0.93	1.09	0.94	0.94	0.97	0.87	1.04	1.11	1.06	0.92	21.1	<0.005
F CaO	1.82	1.96	0.97	0.97	1.88	0.64	1.88	1.44	2.24	1.68	1.27	0.55	1.68	1.52	1.19	1.24	41.0	0.374
C_3A	7.30	7.40	7.10	7.10	7.40	7.00	7.50	7.50	7.20	7.30	7.10	7.20	7.30	7.40	7.20	7.62	5.4	0.021
C_4AF	11.20	11.30	11.90	11.60	11.40	11.60	11.10	11.30	11.30	11.40	11.30	11.60	11.40	11.60	11.60	10.86	6.2	<0.005
C_3S	62.00	62.90	60.90	61.30	63.10	62.20	63.40	62.70	64.80	63.20	64.50	63.40	64.10	64.50	64.20	61.15	3.9	0.033
C_2S	14.50	13.30	15.40	15.10	12.90	14.30	13.00	13.50	11.50	13.10	12.20	13.00	12.10	11.50	11.80	14.97	16.4	0.007

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

Table B.3.17: ELR - Chemical Composition of Clinker

Property	4/3/2007		4/4/2007		4/5/2007		Average
	Comp. 1	Comp. 2	Comp. 1	Comp. 2	Comp. 1	Comp. 2	
Al_2O_3 (wt. %)	4.87	5.01	5.13	5.03	4.84	4.90	4.96
CaO (wt. %)	64.78	64.73	64.16	64.63	65.03	64.93	64.71
Fe_2O_3 (wt. %)	3.21	3.23	3.26	3.24	3.51	3.51	3.33
K_2O (wt. %)	0.43	0.39	0.45	0.38	0.43	0.45	0.42
MgO (wt. %)	3.37	3.40	3.46	3.44	3.37	3.38	3.40
Na_2O (wt. %)	0.19	0.10	0.09	0.07	0.09	0.07	0.10
P_2O_5 (wt. %)	0.08	0.07	0.07	0.07	0.07	0.08	0.07
SiO_2 (wt. %)	21.46	21.71	21.90	21.76	21.08	21.14	21.51
SO_3 (wt. %)	1.11	0.87	0.97	0.87	1.05	1.02	0.98
TiO_2 (wt. %)	0.27	0.27	0.27	0.27	0.24	0.24	0.26
Moisture (wt. %)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
LOI (wt. %)	0.12	0.12	0.16	0.16	0.10	0.12	0.13
As (ppm)	34	40	39	36	30	34	36
Ba (ppm)	400	300	400	400	400	300	367
Cd (ppm)	NR	NR	NR	NR	NR	NR	NA
Cl (ppm)	129	140	273	177	188	154	177
Co (ppm)	14	13	10	11	12	13	12
Cr (ppm)	79	71	90	103	96	100	90
Cu (ppm)	22	34	27	32	29	21	28
Hg (ppm)	NR	NR	NR	NR	NR	NR	NA
Mn (ppm)	1500	1500	1600	1600	1900	2000	1683
Mo (ppm)	23	6	27	14	28	16	19
Ni (ppm)	18	10	21	8	26	9	15
Pb (ppm)	4	6	19	< 4	14	19	12
Sb (ppm)	NR	NR	NR	NR	NR	NR	NA
Se (ppm)	NR	NR	NR	NR	NR	NR	NA
Sr (ppm)	500	500	500	500	500	500	500
V (ppm)	63	63	62	67	74	67	66
Zn (ppm)	64	60	70	75	66	72	68

Notes:

NA - Not Applicable

ND - Not Detected

B.3.8. CHEMICAL COMPOSITION OF CEMENT

Table B.3.18: CPR - Chemical Composition of Cement

Property (wt. %)	**4/9/2007**								**4/10/2007**			**Average**	**C. V. (%)**	**Normality P-Value[1]**
	7:07 AM	**10:12 AM**	**11:34 AM**	**1:09 PM**	**2:39 PM**	**4:01 PM**	**6:43 PM**	**9:54 PM**	**1:13 AM**	**4:12 AM**	**11:53 AM**			
Al_2O_3	4.7	4.68	4.99	4.92	4.87	4.88	4.88	4.93	4.95	4.72	4.83	4.85	2.2	0.164
CaO	63.26	63.21	62.8	62.85	62.96	63.11	63.13	62.6	62.59	61.38	62.83	62.79	0.8	0.009
Fe_2O_3	3.28	3.29	3.21	3.29	3.29	3.28	3.28	3.14	3.02	2.96	3.33	3.22	3.8	<0.005
K_2O	0.44	0.45	0.43	0.44	0.43	0.45	0.42	0.43	0.45	0.45	0.45	0.44	2.5	0.021
MgO	3.2	3.19	3.26	3.23	3.2	3.24	3.24	3.28	3.28	3.07	3.19	3.22	1.8	0.095
Na_2O	0.08	0.08	0.09	0.09	0.09	0.08	0.09	0.09	0.09	0.09	0.07	0.09	8.0	<0.005
Na_2O_{eq}	0.37	0.38	0.37	0.38	0.37	0.38	0.37	0.37	0.39	0.39	0.37	0.38	2.1	<0.005
SiO_2	20.54	20.55	20.82	20.66	20.57	20.51	20.56	20.65	20.84	20.06	20.8	20.60	1.0	0.049
SO_3	2.7	2.75	2.6	2.6	2.46	2.84	2.46	2.44	2.58	3.26	2.8	2.68	8.8	0.126
F CaO	1.44	1.44	NR	0.86	NR	1.38	1.46	1.1	1.41	1.79	1.63	1.39	19.6	0.183
LOI	1.27	1.29	0.97	1.26	NR	1.18	0.81	1.57	1.47	1.41	1.27	1.25	18.0	0.347
C_3A	6.9	6.9	7.8	7.5	7.4	7.4	7.4	7.8	8	7.5	7.2	7.44	4.7	0.413
C_4AF	10	10	9.8	10	10	10	10	9.6	9.2	9	10.1	9.79	3.8	<0.005
C_3S	57.5	57.1	51.9	53.7	55.5	55.5	56.2	53.3	51.5	52.2	52.5	54.26	4.0	0.330
C_2S	15.5	15.8	20.5	18.7	17.1	17	16.5	19	20.9	18.2	20	18.11	10.4	0.732
Blaine SSA (m^2/kg)	366	357	332	408	345	395	357	365	379	379	372	369	5.9	0.927

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not norm

NC - Not Collected

Table B.3.19: ELR - Chemical Composition of Cement

Property	4/9/2007	4/9/2007	4/10/2007	Average
Al_2O_3 (wt. %)	4.86	4.86	5.07	4.93
CaO (wt. %)	63.24	63.54	62.76	63.18
Fe_2O_3 (wt. %)	2.94	3.24	3.15	3.11
K_2O (wt. %)	0.43	0.40	0.39	0.41
MgO (wt. %)	3.40	3.46	3.56	3.47
Na_2O (wt. %)	0.11	0.07	0.20	0.13
P_2O_5 (wt. %)	0.07	0.06	0.06	0.06
SiO_2 (wt. %)	21.60	21.17	21.77	21.51
SO_3 (wt. %)	2.88	2.71	2.55	2.71
TiO_2 (wt. %)	0.26	0.26	0.26	0.26
Moisture (wt. %)	0.22	0.68	0.26	0.39
LOI (wt. %)	1.02	0.80	0.92	0.91
C_3S (wt. %)	--	--	--	48.40
C_2S (wt. %)	--	--	--	25.17
C_3A (wt. %)	--	--	--	7.80
C_4AF (wt. %)	--	--	--	9.46
TOC (wt. %)	0.08	0.03	0.04	0.05
As (ppm)	25	29	27	27
Ba (ppm)	300	300	300	300
Cd (ppm)	NR	NR	NR	NA
Cl (ppm)	53	54	63	57
Co (ppm)	13	15	11	13
Cr (ppm)	78	104	95	92
Cu (ppm)	14	17	12	14
Hg (ppm)	NR	NR	NR	NA
Mn (ppm)	1400	1800	1600	1600
Mo (ppm)	< 1	1	3	2
Ni (ppm)	10	14	12	12
Pb (ppm)	8	42	30	27
Sb (ppm)	NR	NR	NR	NA
Se (ppm)	NR	NR	NR	NA
Sr (ppm)	500	500	500	500
V (ppm)	64	69	74	69
Zn (ppm)	65	67	55	62

Notes:

NA - Not Applicable
NR - Not Reported

B.3.9. PHYSICAL PROPERTIES OF CEMENT

Table B.3.20: CPR - Physical Properties of Cement

Property	4/9/2007	4/10/2007	Average
Air in Mortar (%)	6.4	6.8	6.6
Blaine Specific Surface Area (m^2/kg)	375	372	374
Autoclave Expansion (% Exp.)	0.18	0.19	0.18
Cube Flow (%)	119.0	126.0	122.5
Comp Str 1day (MPa)	13.1	14.0	13.6
Comp Str 3day (MPa)	21.5	22.8	22.2
Comp Str 7day (MPa)	30.7	30.6	30.7
Comp Str 28day (MPa)	42.6	42.9	42.8
Normal Consistency (%)	26.0	25.8	25.9
Gillmore Initial Set (Min)	105	90	98
Gillmore Final Set (Min)	255	270	263
Vicat Initial Set (Min)	65	58	62
Vicat Final Set (Min)	240	210	225

Notes:

% Exp. - % Expansion

Table B.3.21: AUR - Physical Properties of Cement

Property	Composite
Autoclave Expansion (% Exp.)	0.04
Cube Flow (%)	111
Comp Str 1day (MPa)	11.5
Comp Str 3day (MPa)	17.1
Comp Str 7day (MPa)	24.8
Comp Str 28day (MPa)	38.8
Normal Consistency (%)	26.2
Gillmore Initial Set (Min)	72
Gillmore Final Set (Min)	105
Vicat Initial Set (Min)	66
Vicat Final Set (Min)	115
Drying Shrinkage @ 7 days (% LC)	-0.045
Drying Shrinkage @ 14 days (% LC)	-0.069
Drying Shrinkage @ 21 days (% LC)	-0.081
Drying Shrinkage @ 28 days (% LC)	-0.089

Notes:

% LC - Percent Length Change

% Exp. - Percent Expansion

B.3.10. PROPERTIES OF CONCRETE

Table B.3.22: Concrete Properties

Property	**AUR**		**CPR**
	Mix w/c=0.44	**Mix w/c=0.37**	**Mix w/c=0.44**
Total Air Content (%)	4.0	5.0	CIP
Slump (mm)	90.0	150	CIP
Unit Weight (kg/m^3)	2464	2413	CIP
Setting Time (Min)			
Initial Set	216	239	CIP
Final Set	266	290	CIP
Compressive Strength (MPa)			
1 day	14.0	22.3	CIP
3 days	23.1	33.1	CIP
7 days	28.5	38.0	CIP
28 days	39.0	51.0	CIP
91 days	CIP	CIP	CIP
Splitting Tensile Strength (MPa)			
1 day	1.7	2.7	NC
3 days	2.3	3.4	NC
7 days	2.8	3.5	NC
28 days	3.5	4.0	NC
91 days	CIP	CIP	NC
Drying Shrinkage Development (% Length Change)			
7 days	-0.011	-0.018	NC
28 days	-0.029	-0.036	NC
448 days	CIP	CIP	NC
Rapid Chloride Ion Penetration Test Electrical Conductance (Coulombs)			
91 days	CIP	CIP	CIP
365 days	CIP	CIP	CIP

Notes:

CIP - Collection in Progress
NC - Not Collected

AUR - Auburn University Result
CPR - Cement Plant Result

B.3.11. EMISSIONS

Table B.3.23: CPR - Emissions

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
4/3/2007 7:00	6.67E-04	4.81E-06	2.10E-05	3.69E-04
4/3/2007 8:00	7.83E-04	1.82E-06	2.11E-05	4.77E-04
4/3/2007 9:00	9.95E-04	5.92E-08	3.36E-05	6.71E-04
4/3/2007 10:00	1.06E-03	1.12E-07	3.80E-05	7.22E-04
4/3/2007 11:00	NC	NC	NC	5.71E-04
4/3/2007 12:00	NC	NC	NC	7.71E-04
4/3/2007 13:00	9.31E-04	NC	3.64E-05	7.09E-04
4/3/2007 14:00	1.10E-03	6.02E-08	4.43E-05	7.55E-04
4/3/2007 15:00	8.74E-04	4.60E-08	3.62E-05	6.31E-04
4/3/2007 16:00	1.11E-03	7.33E-08	4.73E-05	7.37E-04
4/3/2007 17:00	9.45E-04	5.31E-08	3.36E-05	5.75E-04
4/3/2007 18:00	9.60E-04	6.79E-08	3.09E-05	5.79E-04
4/3/2007 19:00	9.85E-04	NC	3.48E-05	6.75E-04
4/3/2007 20:00	1.16E-03	2.12E-08	3.62E-05	8.22E-04
4/3/2007 21:00	1.14E-03	NC	3.29E-05	7.44E-04
4/3/2007 22:00	9.86E-04	3.22E-07	2.57E-05	6.56E-04
4/3/2007 23:00	1.06E-03	2.37E-07	2.61E-05	7.54E-04
4/4/2007 0:00	9.55E-04	2.70E-07	2.35E-05	6.86E-04
4/4/2007 1:00	9.85E-04	3.15E-07	2.81E-05	7.92E-04
4/4/2007 2:00	1.21E-03	3.74E-07	2.79E-05	7.00E-04
4/4/2007 3:00	9.93E-04	3.11E-07	2.16E-05	6.69E-04
4/4/2007 4:00	1.00E-03	2.95E-07	2.42E-05	6.87E-04
4/4/2007 5:00	1.10E-03	4.36E-07	2.60E-05	6.54E-04
4/4/2007 6:00	6.20E-04	4.43E-07	1.26E-05	3.12E-04
4/4/2007 7:00	1.12E-03	9.63E-09	2.40E-05	7.65E-04
4/4/2007 8:00	1.02E-03	2.82E-08	2.67E-05	8.14E-04
4/4/2007 9:00	1.00E-03	1.58E-07	2.71E-05	6.37E-04
4/4/2007 10:00	1.00E-03	1.57E-07	2.70E-05	6.43E-04
4/4/2007 11:00	1.00E-03	1.14E-07	2.80E-05	5.58E-04
4/4/2007 12:00	1.04E-03	1.15E-07	2.78E-05	5.47E-04
4/4/2007 13:00	9.97E-04	8.75E-08	2.83E-05	5.45E-04
4/4/2007 14:00	9.78E-04	1.01E-07	3.05E-05	5.74E-04
4/4/2007 15:00	9.61E-04	1.08E-07	3.08E-05	5.88E-04
4/4/2007 16:00	1.10E-03	9.19E-08	3.31E-05	5.96E-04
4/4/2007 17:00	9.93E-04	1.07E-07	2.76E-05	5.42E-04
4/4/2007 18:00	9.82E-04	1.56E-07	2.45E-05	5.39E-04
4/4/2007 19:00	1.01E-03	1.28E-07	2.66E-05	6.14E-04
4/4/2007 20:00	9.22E-04	1.30E-07	2.33E-05	5.82E-04
4/4/2007 21:00	1.10E-03	1.43E-07	2.43E-05	6.17E-04
4/4/2007 22:00	9.83E-04	2.97E-07	2.10E-05	5.58E-04
4/4/2007 23:00	1.09E-03	2.44E-07	2.29E-05	5.48E-04
4/5/2007 0:00	9.28E-04	9.20E-08	1.99E-05	3.83E-04
4/5/2007 1:00	9.39E-04	1.20E-07	1.92E-05	4.90E-04
4/5/2007 2:00	1.09E-03	6.11E-07	2.10E-05	6.14E-04
4/5/2007 3:00	1.00E-03	3.10E-07	1.84E-05	5.36E-04
4/5/2007 4:00	1.23E-03	5.41E-07	2.24E-05	5.40E-04
4/5/2007 5:00	1.17E-03	3.85E-07	1.93E-05	5.65E-04
4/5/2007 6:00	1.11E-03	1.11E-07	1.64E-05	4.45E-04

Table B.3.24: CPR - Emissions

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
4/5/2007 7:00	1.06E-03	1.16E-07	1.55E-05	4.21E-04
4/5/2007 8:00	9.97E-04	1.07E-07	1.97E-05	4.04E-04
4/5/2007 9:00	9.59E-04	1.30E-07	1.94E-05	3.93E-04
4/5/2007 10:00	1.04E-03	9.41E-08	2.14E-05	4.14E-04
4/5/2007 11:00	1.01E-03	2.02E-07	2.23E-05	4.48E-04
4/5/2007 12:00	1.09E-03	1.80E-07	2.30E-05	4.47E-04
4/5/2007 13:00	1.04E-03	1.23E-07	2.29E-05	3.64E-04
4/5/2007 14:00	1.03E-03	2.64E-07	2.39E-05	3.92E-04
4/5/2007 15:00	1.15E-03	1.83E-07	2.66E-05	4.26E-04
4/5/2007 16:00	1.15E-03	3.77E-07	2.77E-05	4.23E-04
4/5/2007 17:00	1.36E-03	1.51E-06	2.80E-05	5.86E-04
4/5/2007 18:00	1.09E-03	3.24E-07	2.38E-05	3.88E-04
4/5/2007 19:00	9.63E-04	NC	4.04E-05	6.48E-04
4/5/2007 20:00	1.12E-03	1.34E-06	2.55E-05	4.98E-04
4/5/2007 21:00	1.02E-03	5.49E-07	2.33E-05	4.11E-04
4/5/2007 22:00	1.04E-03	5.29E-07	2.27E-05	3.98E-04
4/5/2007 23:00	1.08E-03	5.36E-07	2.49E-05	4.39E-04
4/6/2007 0:00	1.11E-03	1.02E-06	2.67E-05	4.98E-04
4/6/2007 1:00	1.26E-03	1.59E-06	3.08E-05	6.39E-04
4/6/2007 2:00	1.15E-03	6.08E-07	2.56E-05	5.89E-04
4/6/2007 3:00	1.22E-03	6.04E-07	2.61E-05	5.51E-04
4/6/2007 4:00	1.26E-03	9.08E-07	2.86E-05	5.65E-04
4/6/2007 5:00	1.11E-03	6.93E-07	2.44E-05	4.85E-04
4/6/2007 6:00	1.07E-03	5.09E-07	2.35E-05	4.57E-04
Average	1.04E-03	4.08E-07	2.64E-05	5.67E-04
C. V. (%)	11.4	163.7	24.0	22.0
Normality P-Value[1]	0.035	<0.005	0.023	0.375

Notes:

[1] Based on Anderson Darling Normality Test

NC - Not Collected

APPENDIX B.1

RAW DATA FOR *C BURN*

B.1.1. GENERAL COMMENTS

- The raw data from the C burn are presented in this appendix.
- Coal is the only fuel used in this burn.
- The burn lasted from 7 AM on April 17, 2006 to 7 AM on April 21, 2006.

B.1.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.1.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.1.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	25.80	0.33	2.68	4.22	1.79	0.87
CaO	3.95	54.00	41.54	28.90	0.87	36.80
Fe_2O_3	10.20	0.14	NR	34.70	1.72	0.45
K_2O	2.57	0.07	0.18	0.19	0.32	0.11
MgO	1.21	1.15	3.50	8.80	0.08	1.05
Na_2O	0.38	0.00	0.01	0.00	0.03	0.00
SiO_2	43.70	0.96	14.00	15.40	93.70	3.98
SO_3	0.66	0.18	0.12	1.27	0.38	44.40
Moisture	9.07	5.80	NC	8.00	7.70	12.30
LOI	9.07	43.18	NC	2.99	0.48	12.24

Notes:

NC - Not Collected

NR - Not Reported

Table B.1.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	24.76	0.19	3.23	3.64	1.47	1.22
CaO (wt. %)	2.95	50.49	43.00	5.57	0.19	33.31
Fe_2O_3 (wt. %)	9.96	0.13	1.89	52.83	0.91	0.74
K_2O (wt. %)	2.25	0.06	0.34	0.79	0.43	0.13
MgO (wt. %)	1.26	0.77	1.17	1.66	0.30	1.50
Na_2O (wt. %)	0.53	0.00	0.00	0.20	0.00	0.03
P_2O_5 (wt. %)	0.63	0.01	0.03	0.56	0.01	0.03
SiO_2 (wt. %)	43.44	0.51	15.92	13.51	95.59	5.93
SO_3 (wt. %)	0.30	0.12	0.29	0.69	0.25	38.60
TiO_2 (wt. %)	1.15	0.01	0.23	0.16	0.43	0.05
Moisture (wt. %)	17.71	2.54	4.53	12.49	4.31	2.09
LOI (wt. %)	12.77	47.72	33.93	20.39	0.45	18.44
As (ppm)	173	ND	7	6	ND	ND
Ba (ppm)	1867	68	316	308	131	73
Cd (ppm)	ND	ND	ND	6	ND	ND
Cl (ppm)	23	24	42	114	43	7
Co (ppm)	43	ND	26	38	ND	ND
Cr (ppm)	139	ND	62	285	ND	ND
Cu (ppm)	269	ND	21	545	23	36
Hg (ppm)	0.07	0.01	0.04	0.01	0.01	0.09
Mn (ppm)	280	24	801	7919	153	340
Mo (ppm)	ND	ND	ND	18	ND	ND
Ni (ppm)	112	ND	ND	192	ND	ND
Pb (ppm)	63	12	17	450	40	8
Sb (ppm)	20	32	82	ND	ND	ND
Se (ppm)	3	1	1	2	ND	1
Sr (ppm)	1432	172	240	127	50	573
V (ppm)	303	ND	49	97	ND	ND
Zn (ppm)	84	ND	27	6464	80	ND

Notes:

ND - Not Detected

B.1.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.1.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	4/18/2006		4/19/2006				4/20/2006			4/21/2006	Average	C. V. (%)	Normality P-Value[1]
	8:21 AM	2:30 PM	1:49 AM	8:41 AM	2:22 PM	8:27 PM	2:23 AM	8:08 AM	3:32 PM	2:17 AM			
Al_2O_3	3.13	3.00	3.10	3.10	3.15	3.25	3.18	3.11	3.00	3.08	3.11	2.4	0.561
CaO	43.90	43.70	43.63	44.25	43.93	44.10	44.00	44.11	43.77	44.11	43.95	0.5	0.642
Fe_2O_3	2.03	2.00	2.21	1.93	1.98	1.96	2.06	2.08	2.08	2.05	2.04	3.9	0.526
K_2O	0.35	0.33	0.35	0.33	0.33	0.34	0.33	0.33	0.32	0.33	0.33	2.9 [2]	0.005
MgO	1.98	2.00	1.95	1.90	1.94	1.89	1.91	1.92	1.88	1.85	1.92	2.4	0.954
Na_2O	0.06	0.05	0.05	0.05	0.04	0.05	0.04	0.05	0.04	0.04	0.05	14.4 [2]	0.008
Na_2O_{eq}	0.29	0.27	0.28	0.27	0.26	0.27	0.26	0.27	0.25	0.26	0.27	4.2	0.241
SiO_2	13.77	13.80	13.93	13.44	13.70	13.53	13.73	13.62	13.66	13.52	13.67	1.1	0.960
SO_3	0.26	0.22	0.29	0.32	0.31	0.35	0.31	0.31	0.29	0.27	0.29	12.4	0.502
LOI	36.61	36.47	36.37	36.80	36.60	36.67	36.62	36.71	36.41	36.64	36.59	0.4	0.430

Notes:

NC - Not Collected	[1] Based on Anderson-Darling Normality Test
NA - Not Applicable	[2] Data not normally distributed

Table B.1.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	3.05
CaO (wt. %)	44.18
Fe_2O_3 (wt. %)	2.15
K_2O (wt. %)	0.33
MgO (wt. %)	1.90
Na_2O (wt. %)	0.01
P_2O_5 (wt. %)	0.05
SiO_2 (wt. %)	13.38
SO_3 (wt. %)	0.35
TiO_2 (wt. %)	0.17
Moisture (wt. %)	0.06
LOI (wt. %)	34.44
As (ppm)	3
Ba (ppm)	192
Cd (ppm)	ND
Cl (ppm)	111
Co (ppm)	ND
Cr (ppm)	51
Cu (ppm)	43
Hg (ppm)	0.02
Mn (ppm)	664
Mo (ppm)	ND
Ni (ppm)	ND
Pb (ppm)	24
Sb (ppm)	33
Se (ppm)	1
Sr (ppm)	261
V (ppm)	39
Zn (ppm)	113

Notes:

ND - Not Detected

B.1.5. CHEMICAL COMPOSITION OF FUELS

Table B.1.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	18.9
	Fixed Carbon	50.17
	Volatile Matter	30.93
Ultimate Analysis	**Carbon**	69.06
	Hydrogen	4.25
	Nitrogen	1.51
	Oxygen	5.22
	Sulfur	1.06
Standard Parameters	Al_2O_3	24.67
	CaO	13.32
	Fe_2O_3	5.83
	K_2O	1.97
	MgO	1.18
	Na_2O	0.39
	SiO_2	42.89
	SO_3	8.36
Heat Value [1]		12102

Notes:

[1] Value is Reported as BTU/lb

Table B.1.6: ELR - Proximate, Ultimate, and Combustion Analysis of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	22.45
	Fixed Carbon	49.58
	Volatile Matter	27.97
Ultimate Analysis	**Carbon**	67.61
	Hydrogen	3.61
	Nitrogen	1.1
	Oxygen	3.95
	Sulfur	1.28
Heat Value [1]		11698

Notes:

[1] Value is Reported as BTU/lb

Table B.1.7: ELR - Standard Parameters of Coal

Property	**3-Day Composite**
Al_2O_3 (wt. %)	25.08
CaO (wt. %)	7.53
Fe_2O_3 (wt. %)	7.61
K_2O (wt. %)	2.58
MgO (wt. %)	1.35
Na_2O (wt. %)	0.22
P_2O_5 (wt. %)	0.18
SiO_2 (wt. %)	47.39
SO_3 (wt. %)	6.95
TiO_2 (wt. %)	1.12
As (ppm)	325
Ba (ppm)	1274
Cd (ppm)	ND
Cl (ppm)	-
Co (ppm)	ND
Cr (ppm)	109
Cu (ppm)	150
Hg (ppm)	-
Mn (ppm)	221
Mo (ppm)	ND
Ni (ppm)	81
Pb (ppm)	42
Sb (ppm)	ND
Se (ppm)	ND
Sr (ppm)	487
V (ppm)	226
Zn (ppm)	68

Notes:

ND - Not Detected

B.1.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.1.8: CPR - Chemical Composition of CKD

Property (wt. %)	4/18/2006		4/19/2006		4/20/2006		Average
	8:00 AM	7:00 PM	7:00 AM	7:00 PM	7:00 AM	7:00 PM	
Al_2O_3	3.64	3.42	4.04	3.08	3.61	4.37	3.69
CaO	49.46	47.2	44.87	52.22	46.85	44.68	47.55
Fe_2O_3	1.73	1.81	1.92	1.48	1.89	2.08	1.82
K_2O	0.71	0.45	0.46	0.39	0.39	0.49	0.48
MgO	2.29	1.59	1.22	1.85	1.47	1.53	1.66
Na_2O	0.08	0.07	0.07	0.06	0.06	0.08	0.07
SiO_2	10.06	11	12.42	9.58	12.83	14.2	11.68
SO_3	2.74	1.21	0.42	1.48	0.34	0.59	1.13

Table B.1.9: ELR - Chemical Composition of CKD

Property	4/18/2006		4/19/2006		4/20/2006		Average
	8:00 AM	7:00 PM	7:00 AM	7:00 PM	7:00 AM	7:00 PM	
Al_2O_3 (wt. %)	3.64	3.83	4.02	4.11	3.44	3.56	3.77
CaO (wt. %)	52.71	58.08	47.08	51.87	54.76	73.46	56.33
Fe_2O_3 (wt. %)	1.97	2.03	1.96	2.27	1.93	1.88	2.01
K_2O (wt. %)	0.43	0.45	0.44	0.39	0.40	0.46	0.43
MgO (wt. %)	1.77	2.34	1.28	1.67	1.73	2.58	1.90
Na_2O (wt. %)	0.00	0.02	0.02	0.02	0.00	0.00	0.01
P_2O_5 (wt. %)	0.05	0.06	0.08	0.07	0.05	0.05	0.06
SiO_2 (wt. %)	10.64	10.02	11.87	13.94	11.37	10.10	11.32
SO_3 (wt. %)	1.54	2.59	0.53	0.77	0.85	2.32	1.43
TiO_2 (wt. %)	0.21	0.23	0.22	0.25	0.19	0.21	0.22
Moisture (wt. %)	0.06	0.03	0.15	0.09	0.02	0.05	0.07
LOI (wt. %)	27.04	20.36	32.48	24.64	25.28	5.45	22.54
As (ppm)	4	2	6	ND	3	ND	3.70
Ba (ppm)	279	345	257	239	236	314	278.39
Cd (ppm)	ND	ND	ND	ND	ND	ND	NA
Cl (ppm)	286	863	124	1067	233	324	482.83
Co (ppm)	14	12	ND	15	12	22	15.00
Cr (ppm)	45	33	31	38	25	27	32.95
Cu (ppm)	38	66	53	45	49	46	49.35
Hg (ppm)	0.02	ND	0.02	0.01	ND	0.01	0.02
Mn (ppm)	290	243	300	421	365	272	315.07
Mo (ppm)	ND	ND	ND	ND	ND	ND	NA
Ni (ppm)	ND	11	ND	ND	ND	ND	11.00
Pb (ppm)	7	27	10	36	14	28	20.41
Sb (ppm)	57	52	58	47	44	72	55.10
Se (ppm)	2	2	1	ND	1	2	1.31
Sr (ppm)	300	336	301	295	298	394	320.66
V (ppm)	48	59	55	62	48	57	54.85
Zn (ppm)	104	76	74	122	95	78	91.47

Notes:

NA - Not Applicable
ND - Not Detected

B.1.7. CHEMICAL COMPOSITION OF CLINKER

Table B.1.10: CPR - Chemical Composition of Clinker for 4/18/06

Property (wt. %)	4/18/2006							
	8:25 AM	**10:18 AM**	**12:02 PM**	**2:33 PM**	**4:21 PM**	**5:52 PM**	**7:51 PM**	**10:12 PM**
Al_2O_3	5.36	5.17	5.27	5.23	5.34	5.23	5.39	5.38
CaO	64.83	64.76	64.83	64.86	64.64	64.74	64.66	64.64
Fe_2O_3	3.53	3.42	3.53	3.42	3.61	3.74	3.75	3.80
K_2O	0.59	0.62	0.55	0.57	0.57	0.58	0.56	0.55
MgO	2.98	3.00	2.94	3.03	3.04	2.99	3.04	3.03
Na_2O	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.07
Na_2O_{eq}	0.47	0.48	0.44	0.45	0.46	0.46	0.44	0.43
SiO_2	21.47	21.60	21.70	21.60	21.53	21.53	21.62	21.65
SO_3	0.92	0.82	0.59	0.65	0.88	0.78	0.73	0.69
F CaO	0.64	0.54	0.29	0.59	0.78	1.22	0.64	0.59
C_3A	8.20	7.90	8.00	8.10	8.00	7.50	7.90	7.80
C_4AF	10.70	10.40	10.70	10.40	11.00	11.40	11.40	11.60
C_3S	59.70	59.90	58.60	59.90	58.50	59.40	57.30	57.00
C_2S	16.50	16.80	18.00	16.80	17.60	16.90	18.70	19.00

Table B.1.11: CPR - Chemical Composition of Clinker for 4/19/06

Property (wt. %)	4/19/2006													
	12:03 AM	1:49 AM	3:42 AM	5:44 AM	8:40 AM	10:24 AM	11:41 AM	12:31 PM	2:22 PM	4:11 PM	5:39 PM	8:27 PM	10:04 PM	11:49 PM
Al_2O_3	5.37	5.29	5.28	5.28	5.50	5.32	5.47	5.38	5.41	5.47	5.48	5.38	5.50	5.46
CaO	64.49	64.61	64.66	64.81	64.80	65.25	65.04	65.14	64.95	64.86	65.11	65.18	65.00	64.98
Fe_2O_3	3.87	3.91	3.75	3.66	3.62	3.19	3.20	3.12	3.23	3.15	3.14	3.12	3.20	3.27
K_2O	0.57	0.55	0.57	0.56	0.54	0.55	0.56	0.55	0.56	0.60	0.54	0.50	0.53	0.55
MgO	2.99	3.00	2.93	2.94	2.94	2.91	2.94	2.97	2.95	2.94	2.96	2.84	2.87	2.88
Na_2O	0.08	0.07	0.08	0.08	0.07	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.08
Na_2O_{eq}	0.46	0.43	0.46	0.45	0.43	0.43	0.44	0.44	0.44	0.46	0.43	0.40	0.42	0.44
SiO_2	21.62	21.67	21.53	21.43	21.29	21.05	21.22	21.21	21.27	21.29	21.37	21.41	21.37	21.31
SO_3	0.71	0.73	0.78	0.80	0.81	0.86	1.02	0.85	0.95	0.97	0.88	0.82	0.85	0.88
F CaO	0.83	0.73	0.78	0.73	0.93	1.91	1.81	2.06	1.22	1.47	1.03	0.88	1.08	1.13
C_3A	7.70	7.40	7.60	7.80	8.40	8.70	9.10	9.00	8.90	9.20	9.20	9.00	9.20	8.90
C_4AF	11.80	11.90	11.40	11.10	11.00	9.70	9.70	9.50	9.80	9.60	9.60	9.50	9.70	10.00
C_3S	56.60	57.20	58.80	60.30	59.90	65.40	62.20	63.40	61.80	61.00	61.30	62.00	60.70	61.20
C_2S	19.30	19.00	17.40	16.00	15.90	11.00	13.90	13.00	14.40	15.00	15.00	14.60	15.50	14.90

Table B.1.12: CPR - Chemical Composition of Clinker for 4/20/06 and 4/21/06

Property (wt. %)	4/20/2006												4/21/2006			Average	C. V. (%)	Normality P-Value[1]
	2:21 AM	3:53 AM	5:49 AM	8:07 AM	10:11 AM	11:50 AM	2:25 PM	4:00 PM	5:40 PM	7:54 PM	9:53 PM	11:47 PM	2:16 AM	3:59 AM	5:40 AM			
Al_2O_3	5.61	5.35	5.35	5.40	5.30	5.45	5.42	5.22	5.12	4.98	4.94	4.90	5.05	5.11	5.06	5.30	3.2[2]	0.033
CaO	64.83	64.99	64.90	64.89	64.96	65.19	65.27	65.24	65.25	65.23	65.39	65.29	65.23	65.21	65.16	64.97	0.4	0.116
Fe_2O_3	3.41	3.28	3.47	3.45	3.48	3.38	3.41	3.32	3.26	3.23	3.25	3.22	3.30	3.30	3.22	3.41	6.6[2]	0.012
K_2O	0.57	0.56	0.57	0.57	0.55	0.58	0.57	0.54	0.54	0.56	0.51	0.56	0.56	0.57	0.60	0.56	4.1[2]	0.022
MgO	2.87	2.84	2.88	2.93	3.04	2.93	2.96	2.92	2.88	2.88	2.77	2.88	2.80	2.87	2.89	2.93	2.3	0.453
Na_2O	0.07	0.08	0.08	0.08	0.08	0.07	0.08	0.07	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.07	6.8[2]	<0.005
Na_2O_{eq}	0.45	0.45	0.46	0.46	0.44	0.45	0.46	0.43	0.44	0.45	0.41	0.44	0.44	0.45	0.46	0.44	3.7[2]	0.022
SiO_2	21.31	21.47	21.31	21.26	21.32	21.07	21.05	21.21	21.02	21.29	21.50	21.47	21.47	21.34	21.25	21.38	0.9	0.391
SO_3	0.89	0.93	0.95	0.95	0.83	0.95	0.84	0.92	0.95	0.95	0.85	0.93	0.75	0.74	1.02	0.85	12.1	0.323
F CaO	1.27	0.64	1.32	1.13	1.22	1.47	0.98	1.32	1.52	1.52	1.47	1.42	1.08	1.08	1.42	1.10	37.1	0.605
C_3A	9.10	8.60	8.30	8.50	8.20	8.70	8.60	8.20	8.10	7.70	7.60	7.50	7.80	8.00	8.00	8.28	6.8[2]	0.043
C_4AF	10.40	10.00	10.60	10.50	10.60	10.30	10.40	10.10	9.90	9.80	9.90	9.80	10.00	10.00	9.80	10.38	6.7[2]	0.009
C_3S	59.40	60.80	61.30	61.40	61.80	63.80	64.40	64.60	66.80	65.70	65.00	65.10	63.70	64.20	65.20	61.49	4.4	0.362
C_2S	16.30	15.70	14.80	14.60	14.50	12.30	11.70	12.10	9.90	11.50	12.60	12.40	13.50	12.70	11.80	14.91	16.6	0.742

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

Table 13: ELR - Chemical Composition of Clinker

Property	4/18/2006		4/19/2006		4/20/2006		Average
	Comp. 1	Comp. 2	Comp. 1	Comp. 2	Comp. 1	Comp. 2	
Al_2O_3 (wt. %)	5.52	5.37	5.27	5.18	5.29	4.98	5.27
CaO (wt. %)	64.01	64.57	65.68	65.62	65.08	65.94	65.15
Fe_2O_3 (wt. %)	3.55	3.51	3.27	3.16	3.26	3.29	3.34
K_2O (wt. %)	0.64	0.60	0.58	0.59	0.58	0.61	0.60
MgO (wt. %)	2.87	2.89	2.89	2.89	2.85	2.89	2.88
Na_2O (wt. %)	0.05	0.02	0.00	0.01	0.00	0.01	0.01
P_2O_5 (wt. %)	0.09	0.09	0.08	0.08	0.08	0.08	0.08
SiO_2 (wt. %)	21.95	21.64	20.84	20.68	21.53	20.77	21.24
SO_3 (wt. %)	0.89	0.85	1.01	1.19	0.91	0.95	0.97
TiO_2 (wt. %)	0.32	0.31	0.29	0.33	0.28	0.29	0.30
Moisture (wt. %)	0.00	0.00	0.02	0.04	0.01	0.00	0.01
LOI (wt. %)	0.09	0.14	0.09	0.27	0.14	0.19	0.15
As (ppm)	10	8	9	9	7	9	8.65
Ba (ppm)	382	397	365	403	335	313	365.75
Cd (ppm)	ND	ND	ND	ND	ND	ND	NA
Cl (ppm)	265	182	158	315	238	274	238.67
Co (ppm)	15	ND	12	24	12	13	15.19
Cr (ppm)	78	69	63	73	66	84	72.34
Cu (ppm)	50	75	68	69	51	77	65.00
Hg (ppm)	0.03	ND	0.02	ND	0.01	0.01	0.02
Mn (ppm)	985	976	916	924	965	985	958.50
Mo (ppm)	11	ND	ND	16	9	ND	12.00
Ni (ppm)	137	13	14	ND	10	ND	43.36
Pb (ppm)	46	34	70	30	11	26	36.15
Sb (ppm)	47	49	34	57	79	78	57.16
Se (ppm)	1	1	1	1	1	1	1.00
Sr (ppm)	429	401	397	390	394	403	402.31
V (ppm)	68	68	56	70	56	67	64.03
Zn (ppm)	163	146	109	113	147	130	134.69

Notes:

NA - Not Applicable

ND - Not Detected

B.1.8. CHEMICAL COMPOSITION OF CEMENT

Table B.1.14: CPR - Chemical Composition of Cement for 4/18/06 and 4/19/06

Property (wt. %)	**4/18/2006**					**4/19/2006**				
	7:12 AM	**10:25 AM**	**1:17 PM**	**3:11 PM**	**4:21 PM**	**11:31 AM**	**1:24 PM**	**4:18 PM**	**7:02 PM**	**10:00 PM**
Al_2O_3	4.64	4.68	4.92	4.93	4.96	5.17	5.16	5.16	5.08	4.93
CaO	64.03	63.81	63.11	63.13	63.15	62.93	62.98	63.26	63.47	63.52
Fe_2O_3	2.88	2.97	3.17	3.2	3.24	3.26	3.25	3.3	3.09	3.07
K_2O	0.52	0.52	0.51	0.51	0.51	0.52	0.51	0.51	0.52	0.53
MgO	3.16	3.01	2.89	2.88	2.92	2.9	2.91	2.87	2.84	2.93
Na_2O	0.11	0.1	0.09	0.09	0.1	0.09	0.09	0.09	0.1	0.1
Na_2O_{eq}	0.45	0.44	0.43	0.43	0.44	0.43	0.43	0.43	0.44	0.45
SiO_2	20.64	20.72	20.66	20.65	20.75	20.58	20.64	20.69	20.47	20.68
SO_3	2.55	2.72	3.06	2.71	2.65	2.62	2.76	2.57	2.47	2.5
F CaO	0.98	0.98	0.59	NC	0.54	0.69	0.98	1.17	1.08	0.98
LOI	0.99	1.03	1.03	NC	0.79	0.94	1.23	0.97	0.63	0.89
C_3A	7.4	7.4	7.7	7.7	7.7	8.2	8.2	8.1	8.2	7.9
C_4AF	8.8	9	9.6	9.7	9.9	9.9	9.9	10	9.4	9.3
C_3S	61.2	58.8	53.6	54.6	53.9	52.9	52.3	53.6	57.2	56.8
C_2S	13	15	18.8	18	18.9	19.1	19.7	18.9	15.5	16.5
Blaine SSA (m^2/kg)	387	387	400	402	372	391	379	370	366	368

Notes:

NC - Not Collected

Table B.1.15: CPR - Chemical Composition of Cement for 4/20/06 and 4/21/06

Property (wt. %)	4/20/2006									4/21/2006		Average	C. V. (%)	Normality P-Value[1]
	1:07 AM	3:52 AM	5:27 AM	7:04 AM	10:16 AM	12:52 PM	4:00 PM	6:57 PM	9:53 PM	1:28 AM	4:00 AM			
Al_2O_3	4.93	5	5.08	5.02	5.02	5.1	5.06	5.03	4.93	4.88	4.93	4.98	2.8 [2]	0.065
CaO	63.65	63.55	63.6	63.29	63.4	63.31	63.46	63.88	64.03	63.76	63.97	63.49	0.5	0.843
Fe_2O_3	3.09	3.05	3.16	3.06	3.11	3.07	3.04	3.07	3.07	3.06	3.09	3.11	3.2 [2]	0.056
K_2O	0.52	0.53	0.52	0.52	0.52	0.51	0.55	0.53	0.53	0.53	0.53	0.52	1.9 [2]	<0.005
MgO	2.87	2.86	2.88	2.81	2.8	2.82	2.79	2.85	2.81	2.8	2.85	2.88	2.9 [2]	<0.005
Na_2O	0.09	0.09	0.09	0.1	0.1	0.09	0.08	0.09	0.08	0.1	0.09	0.09	7.8 [2]	<0.005
Na_2O_{eq}	0.43	0.44	0.43	0.44	0.44	0.43	0.44	0.44	0.43	0.45	0.44	0.44	1.6 [2]	<0.005
SiO_2	20.6	20.5	20.58	20.41	20.49	20.58	20.54	20.53	20.4	20.39	20.44	20.57	0.5	0.646
SO_3	2.45	2.42	2.41	2.71	2.75	2.73	2.72	2.4	2.66	2.71	2.44	2.62	6.2 [2]	0.075
F CaO	1.13	0.98	NC	0.98	0.59	0.64	1.13	1.03	1.08	1.08	1.27	0.94	23.3 [2]	<0.005
LOI	1.05	1.12	NC	0.96	0.9	1.02	1.1	1.16	1.39	1.3	1.25	1.04	17.4	0.859
C_3A	7.8	8.1	8.1	8.1	8	8.3	8.3	8.1	7.9	7.8	7.8	7.94	3.3	0.118
C_4AF	9.4	9.3	9.6	9.3	9.5	9.3	9.3	9.3	9.3	9.3	9.4	9.45	3.2 [2]	0.016
C_3S	58	58	57	56.7	56.4	54.9	56.1	59	60.5	59.7	60.6	56.75	4.7	0.738
C_2S	15.3	15	16	15.7	16.2	17.6	16.5	14.4	12.8	13.4	12.9	16.15	13.5	0.380
Blaine SSA (m^2/kg)	368	370	NC	373	366	368	372	379	372	370	381	377.05	2.9 [2]	<0.005

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

NC - Not Collected

Table B.1.16: ELR - Chemical Composition of Cement

Property	4/18/2006	4/19/2006	4/20/2006	Average
Al_2O_3 (wt. %)	5.12	5.04	4.99	5.05
CaO (wt. %)	63.64	64.02	64.34	64.00
Fe_2O_3 (wt. %)	3.26	3.21	3.13	3.20
K_2O (wt. %)	0.45	0.53	0.49	0.49
MgO (wt. %)	2.92	2.88	2.87	2.89
Na_2O (wt. %)	0.05	0.00	0.00	0.02
P_2O_5 (wt. %)	0.08	0.08	0.08	0.08
SiO_2 (wt. %)	20.56	20.62	20.42	20.53
SO_3 (wt. %)	2.96	2.65	2.73	2.78
TiO_2 (wt. %)	0.27	0.27	0.26	0.27
Moisture (wt. %)	0.23	0.28	0.35	0.29
LOI (wt. %)	0.68	0.71	0.69	0.69
C_3S (wt. %)	--	--	--	58.07
C_2S (wt. %)	--	--	--	15.06
C_3A (wt. %)	--	--	--	7.96
C_4AF (wt. %)	--	--	--	9.74
TOC (wt. %)	< 0.1	<0.1	<0.1	NA
As (ppm)	9	6	9	8.00
Ba (ppm)	324	316	323	321.10
Cd (ppm)	ND	ND	ND	NA
Cl (ppm)	59	76	105	80.00
Co (ppm)	ND	13	16	14.50
Cr (ppm)	85	81	81	82.36
Cu (ppm)	56	75	61	64.02
Hg (ppm)	0.01	0.01	0.02	0.01
Mn (ppm)	982	955	938	958.30
Mo (ppm)	ND	9	ND	9.00
Ni (ppm)	ND	ND	ND	NA
Pb (ppm)	28	29	43	33.34
Sb (ppm)	35	59	59	51.01
Se (ppm)	1	2	1	1.33
Sr (ppm)	418	401	410	409.79
V (ppm)	73	61	52	62.02
Zn (ppm)	131	125	122	126.04

Notes:

NA - Not Applicable

ND - Not Detected

B.1.9. PHYSICAL PROPERTIES OF CEMENT

Table B.1.17: CPR - Physical Properties of Cement

Property	4/18/2006	4/19/2006	4/20/2006	Average
Air in Mortar (%)	6.5	6.4	7.3	6.73
Blaine Specific Surface Area (m^2/kg)	368.0	361.0	368.0	365.67
Autoclave Expansion (% Exp.)	0.1	0.1	0.1	0.06
Cube Flow (%)	124.0	127.0	126.0	125.67
Comp Str 1day (MPa)	13.5	15.6	16.9	15.33
Comp Str 3day (MPa)	22.3	24.3	26.2	24.27
Comp Str 7day (MPa)	31.7	30.7	33.4	31.93
Comp Str 28day (MPa)	45.8	41.6	40.7	42.70
Normal Consistency (%)	25.7	25.8	25.2	25.57
Gillmore Initial Set (Min)	120.0	105.0	90.0	105.00
Gillmore Final Set (Min)	270.0	315.0	240.0	275.00
Vicat Initial Set (Min)	95.0	79.0	65.0	79.67
Vicat Final Set (Min)	198.0	179.0	163.0	180.00

Notes:

% Exp. - % Expansion

Table B.1.18: AUR - Physical Properties of Cement

Property	Composite
Autoclave Expansion (% Exp.)	0.05
Cube Flow (%)	91.4
Comp Str 1day (MPa)	9.3
Comp Str 3day (MPa)	17.2
Comp Str 7day (MPa)	25.8
Comp Str 28day (MPa)	35.1
Normal Consistency (%)	25.4
Gillmore Initial Set (Min)	150
Gillmore Final Set (Min)	238
Vicat Initial Set (Min)	106
Vicat Final Set (Min)	236
Drying Shrinkage @ 7 days (% LC)	-0.042
Drying Shrinkage @ 14 days (% LC)	-0.068
Drying Shrinkage @ 21 days (% LC)	-0.079
Drying Shrinkage @ 28 days (% LC)	-0.087

Notes:

% LC - Percent Length Change
% Exp. - Percent Expansion

B.1.10. PROPERTIES OF CONCRETE

Table B.1.19: Concrete Properties

Property	**AUR**		**CPR**
	Mix w/c=0.44	**Mix w/c=0.37**	**Mix w/c=0.44**
Total Air Content (%)	4.0	6.0	3.6
Slump (mm)	100	150	30
Unit Weight (kg/m^3)	2394	2374	2450
Initial Set (Min.)	211	318	218
Final Set (Min.)	298	405	322.0
Compressive Strength (MPa)			
1 day	12.3	20.8	15.8
3 days	22.7	31.9	23.3
7 days	25.2	37.7	33.3
28 days	35.0	44.3	43.3
91 days	41.6	51.5	48.2
Splitting Tensile Strength (MPa)			
1 day	1.7	2.5	NC
3 days	2.4	3.3	NC
7 days	2.6	3.7	NC
28 days	3.2	4.1	NC
91 days	3.7	4.3	NC
Drying Shrinkage Development (% Length Change) [1]			
4 days	0.009	0.013	NC
7 days	0.018	0.019	NC
14 days	0.028	0.032	NC
28 days	0.029	0.037	NC
56 days	0.038	0.043	NC
112 days	0.045	0.051	NC
224 days	0.049	0.053	NC
448 days	0.050	0.054	NC
Permeability @ 91 days (Coulombs)	2650	2650	2660

Notes: CIP - Collection in Progress NC - Not Collected [1] Percentage decrease in length

B.1.11. EMISSIONS

Table B.1.20: CPR - Emissions

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
4/18/2006 7:00	9.45E-04	4.38E-06	4.47E-05	9.28E-04
4/18/2006 8:00	8.07E-04	5.05E-06	5.50E-05	1.10E-03
4/18/2006 9:00	7.84E-04	8.88E-07	4.50E-05	9.76E-04
4/18/2006 10:00	8.16E-04	1.88E-07	5.09E-05	8.54E-04
4/18/2006 11:00	7.97E-04	1.31E-07	5.03E-05	8.59E-04
4/18/2006 12:00	8.04E-04	7.85E-08	4.21E-05	8.35E-04
4/18/2006 13:00	8.25E-04	1.36E-07	3.96E-05	8.17E-04
4/18/2006 14:00	8.43E-04	9.76E-08	3.65E-05	7.85E-04
4/18/2006 15:00	8.74E-04	2.57E-08	3.37E-05	8.45E-04
4/18/2006 16:00	8.26E-04	2.05E-08	3.07E-05	8.09E-04
4/18/2006 17:00	9.19E-04	1.08E-07	2.75E-05	7.84E-04
4/18/2006 18:00	9.27E-04	1.18E-07	2.51E-05	8.22E-04
4/18/2006 19:00	8.49E-04	4.63E-08	2.10E-05	8.54E-04
4/18/2006 20:00	8.45E-04	2.58E-08	2.04E-05	8.05E-04
4/18/2006 21:00	8.90E-04	1.64E-07	2.74E-05	7.66E-04
4/18/2006 22:00	8.61E-04	1.08E-07	3.46E-05	8.10E-04
4/18/2006 23:00	8.30E-04	6.69E-08	2.18E-05	7.21E-04
4/19/2006 0:00	8.09E-04	1.79E-07	1.15E-05	7.14E-04
4/19/2006 1:00	8.27E-04	1.80E-07	1.11E-05	7.51E-04
4/19/2006 2:00	8.17E-04	1.23E-07	9.59E-06	7.60E-04
4/19/2006 3:00	8.15E-04	9.82E-08	9.42E-06	7.49E-04
4/19/2006 4:00	7.71E-04	9.74E-08	1.03E-05	7.82E-04
4/19/2006 5:00	8.04E-04	1.70E-07	1.56E-05	8.29E-04
4/19/2006 6:00	8.52E-04	2.11E-07	9.91E-06	7.53E-04
4/19/2006 7:00	7.93E-04	2.21E-07	6.12E-06	7.17E-04
4/19/2006 8:00	7.48E-04	8.24E-08	3.09E-06	7.08E-04
4/19/2006 9:00	7.75E-04	5.65E-08	5.01E-06	7.07E-04
4/19/2006 10:00	8.37E-04	2.82E-06	2.24E-05	6.94E-04
4/19/2006 11:00	7.87E-04	1.30E-07	2.85E-05	7.11E-04
4/19/2006 12:00	7.97E-04	1.23E-07	3.96E-05	7.60E-04
4/19/2006 13:00	8.42E-04	1.42E-07	3.85E-05	7.87E-04
4/19/2006 14:00	8.08E-04	3.53E-08	3.61E-05	7.94E-04
4/19/2006 15:00	7.64E-04	1.16E-08	3.60E-05	7.43E-04
4/19/2006 16:00	7.83E-04	1.34E-07	3.53E-05	7.27E-04
4/19/2006 17:00	7.93E-04	1.18E-07	3.22E-05	7.42E-04
4/19/2006 18:00	8.23E-04	1.24E-07	3.46E-05	7.52E-04
4/19/2006 19:00	7.41E-04	8.24E-08	2.47E-05	7.69E-04
4/19/2006 20:00	7.40E-04	1.34E-07	1.52E-05	8.08E-04
4/19/2006 21:00	8.85E-04	2.18E-06	1.37E-05	7.32E-04
4/19/2006 22:00	8.17E-04	3.63E-07	1.36E-05	7.23E-04
4/19/2006 23:00	7.93E-04	5.41E-07	1.04E-05	7.84E-04
4/20/2006 0:00	7.64E-04	1.09E-06	9.02E-06	7.18E-04
4/20/2006 1:00	9.12E-04	2.28E-07	1.57E-05	7.06E-04
4/20/2006 2:00	9.54E-04	3.74E-07	1.44E-05	7.38E-04
4/20/2006 3:00	8.92E-04	2.35E-07	1.26E-05	6.80E-04
4/20/2006 4:00	9.21E-04	3.86E-07	1.43E-05	6.89E-04
4/20/2006 5:00	7.90E-04	1.83E-07	1.07E-05	7.27E-04
4/20/2006 6:00	8.04E-04	9.03E-08	1.74E-05	7.20E-04

Table B.1.21: CPR - Emission (Continued)

Time	**NO$_x$ (tons/ton clinker)**	**SO$_2$ (tons/ton clinker)**	**VOC (tons/ton clinker)**	**CO (tons/ton clinker)**
4/20/2006 7:00	9.55E-04	2.34E-07	2.40E-05	6.88E-04
4/20/2006 8:00	NC	NC	3.48E-05	7.60E-04
4/20/2006 9:00	NC	NC	3.93E-05	7.58E-04
4/20/2006 10:00	NC	NC	3.87E-05	7.11E-04
4/20/2006 11:00	8.10E-04	NC	4.84E-05	9.65E-04
4/20/2006 12:00	8.40E-04	1.14E-08	2.99E-05	9.15E-04
4/20/2006 13:00	8.44E-04	2.10E-07	4.37E-05	8.30E-04
4/20/2006 14:00	8.81E-04	1.66E-07	4.07E-05	8.42E-04
4/20/2006 15:00	8.85E-04	1.48E-07	1.69E-05	8.40E-04
4/20/2006 16:00	7.68E-04	6.14E-08	1.39E-06	8.86E-04
4/20/2006 17:00	7.64E-04	4.29E-08	NC	8.80E-04
4/20/2006 18:00	8.35E-04	1.84E-07	2.66E-06	8.86E-04
4/20/2006 19:00	8.42E-04	1.96E-07	3.57E-06	7.99E-04
4/20/2006 20:00	7.86E-04	3.59E-07	3.46E-06	7.34E-04
4/20/2006 21:00	6.23E-04	4.59E-07	NC	6.75E-04
4/20/2006 22:00	6.54E-04	2.10E-07	NC	5.96E-04
4/20/2006 23:00	8.01E-04	1.99E-07	2.82E-06	6.28E-04
4/21/2006 0:00	6.70E-04	7.38E-08	NC	6.62E-04
4/21/2006 1:00	7.76E-04	2.28E-07	5.32E-06	6.91E-04
4/21/2006 2:00	6.70E-04	9.68E-08	NC	6.87E-04
4/21/2006 3:00	6.85E-04	3.80E-07	NC	6.78E-04
4/21/2006 4:00	8.83E-04	4.79E-07	5.78E-06	6.95E-04
4/21/2006 5:00	9.00E-04	3.57E-07	5.57E-06	7.05E-04
4/21/2006 6:00	8.69E-04	5.20E-07	5.32E-06	7.53E-04
Average	8.18E-04	4.00E-07	2.31E-05	7.72E-04
C. V. (%)	8.3	218.9	64.5	11.0
Normality P-Value[1]	0.064	<0.006	<0.005	0.007

Notes:

[1] Based on Anderson Darling Normality Test

NC - Not Collected

APPENDIX B.2

RAW DATA FOR *CT1 BURN*

B.2.1. GENERAL COMMENTS

- The raw data from the CT1 burn are presented in this appendix.
- Coal and scrap tires are the fuels used in the burn.
- The burn lasted from 7 AM on July 11, 2006 to 7 AM on July 14, 2006.

B.2.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.2.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.2.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	22.80	0.30	3.16	6.28	0.76	1.87
CaO	4.38	54.10	40.94	35.10	2.16	29.10
Fe_2O_3	9.27	0.17	1.43	25.00	1.45	0.00
K_2O	2.08	0.01	0.17	0.00	0.16	0.19
MgO	1.09	0.95	3.48	10.40	0.19	1.40
Na_2O	0.40	NR	0.07	NR	NR	0.00
SiO_2	44.90	0.85	14.35	16.50	92.20	8.14
SO_3	1.21	1.05	0.14	0.60	1.12	41.67
Moisture	19.81	1.80	NC	4.46	4.30	8.70
LOI	11.63	42.47	NC	1.84	1.56	17.63

Notes:

NC - Not Collected

NR - Not Reported

Table B.2.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	24.07	0.07	5.32	3.90	1.92	0.76
CaO (wt. %)	2.74	54.92	36.02	31.68	0.37	30.90
Fe_2O_3 (wt. %)	10.97	0.15	2.75	40.25	1.17	0.25
K_2O (wt. %)	2.25	0.06	0.40	0.03	0.25	0.16
MgO (wt. %)	1.07	0.82	1.18	11.95	0.19	0.62
Na_2O (wt. %)	0.55	0.03	0.08	0.03	0.07	0.06
P_2O_5 (wt. %)	0.56	0.00	0.06	0.61	0.03	0.01
SiO_2 (wt. %)	43.09	0.49	22.11	12.37	94.77	4.58
SO_3 (wt. %)	0.15	0.15	0.25	0.20	0.01	41.90
TiO_2 (wt. %)	1.10	0.00	1.04	0.26	0.28	0.02
Moisture (wt. %)	23.67	0.02	0.34	0.31	4.20	0.80
LOI (wt. %)	13.44	43.32	30.78	ND	0.93	20.74
As (ppm)	137	ND	18	ND	7	ND
Ba (ppm)	1510	88	293	ND	ND	ND
Cd (ppm)	ND	ND	ND	3	ND	ND
Cl (ppm)	125	265	158	238	59	105
Co (ppm)	45	ND	ND	ND	ND	ND
Cr (ppm)	135	ND	40	2672	ND	ND
Cu (ppm)	200	ND	ND	22	30	ND
Hg (ppm)	0.01	0.03	0.03	0.05	0.01	0.09
Mn (ppm)	302	18	96	19571	78	82
Mo (ppm)	ND	ND	ND	72	ND	ND
Ni (ppm)	114	ND	21	11	22	9
Pb (ppm)	67	12	47	13	8	21
Sb (ppm)	ND	80	30	36	ND	ND
Se (ppm)	3	ND	ND	2	1	ND
Sr (ppm)	1373	225	259	169	122	566
V (ppm)	271	ND	103	687	ND	ND
Zn (ppm)	150	24	90	134	13	ND

Notes:

ND - Not Detected

B.2.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.2.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	7/11/2006			7/12/2006				7/13/2006				7/14/2006	Average	C. V. (%)	Normality P-Value[1]
	8:30 AM	2:11 PM	8:36 PM	2:31 AM	8:27 AM	2:38 PM	8:31 PM	2:34 AM	8:09 AM	2:52 PM	8:09 PM	2:13 AM			
Al_2O_3	3.29	3.17	3.09	3.29	3.18	3.27	3.27	3.2	3.27	3.3	3.34	3.09	3.23	2.6 [2]	0.092
CaO	43.2	43.34	42.81	43.33	42.43	42.7	43.44	43.42	42.94	43.34	42.74	42.9	43.05	0.8	0.166
Fe_2O_3	1.9	1.94	1.98	1.99	2.04	2.07	1.97	2	2.06	2.03	2.11	2.1	2.02	3.2	0.965
K_2O	0.28	0.27	0.28	0.28	0.28	0.31	0.31	0.3	0.31	0.31	0.31	0.3	0.30	5.3 [2]	<0.005
MgO	2.77	2.77	2.54	2.71	2.61	2.31	2.34	2.4	2.43	2.43	2.4	2.42	2.51	6.6 [2]	0.064
Na_2O	0.11	0.1	0.13	0.1	0.14	0.12	0.09	0.1	0.1	0.09	0.09	0.07	0.10	18.6	0.238
Na_2O_{eq}	0.29	0.28	0.31	0.28	0.32	0.32	0.29	0.3	0.3	0.29	0.29	0.27	0.30	5.3	0.336
SiO_2	14.47	14.24	13.78	14.37	14.35	14.18	14.45	14.39	14.54	14.52	14.73	14.57	14.38	1.7	0.181
SO_3	0.28	0.29	0.23	0.35	0.29	0.31	0.3	0.24	0.27	0.31	0.31	0.34	0.29	12.1	0.611
LOI	34.71	35.26	35.88	34.22	35.22	34.81	35.3	35.22	34.78	35.11	35.07	35.07	35.05	1.2	0.249

Notes:

NC - Not Collected

NA - Not Applicable

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

Table 2.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	2.75
CaO (wt. %)	40.23
Fe_2O_3 (wt. %)	1.92
K_2O (wt. %)	0.29
MgO (wt. %)	2.08
Na_2O (wt. %)	0.03
P_2O_5 (wt. %)	0.04
SiO_2 (wt. %)	17.00
SO_3 (wt. %)	0.24
TiO_2 (wt. %)	0.21
Moisture (wt. %)	0.19
LOI (wt. %)	35.19
As (ppm)	13
Ba (ppm)	257
Cd (ppm)	ND
Cl (ppm)	76
Co (ppm)	21
Cr (ppm)	60
Cu (ppm)	ND
Hg (ppm)	0.10
Mn (ppm)	317
Mo (ppm)	ND
Ni (ppm)	15
Pb (ppm)	9
Sb (ppm)	88
Se (ppm)	ND
Sr (ppm)	229
V (ppm)	48
Zn (ppm)	106

Notes:

ND - Not Detected

B.2.5. CHEMICAL COMPOSITION OF FUELS

Table B.2.4: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	Ash	17.82
	Fixed Carbon	52.05
	Volatile Matter	30.13
Ultimate Analysis	Carbon	71.17
	Hydrogen	4.34
	Nitrogen	1.45
	Oxygen	3.69
	Sulfur	1.53
Standard Parameters	Al_2O_3	23.45
	CaO	12.74
	Fe_2O_3	6.24
	K_2O	2.16
	MgO	1.49
	Na_2O	0.31
	SiO_2	46.21
	SO_3	7.41
Heat Value [1]		12506

Notes:

[1] Value is Reported as BTU/lb

Table B.2.5: ELR - Proximate, Ultimate, and Combustion Analysis of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	16.74
	Fixed Carbon	54.81
	Volatile Matter	28.45
Ultimate Analysis	**Carbon**	73.09
	Hydrogen	4.66
	Nitrogen	1.22
	Oxygen	3.14
	Sulfur	1.15
Heat Value [1]		12624

Notes:

[1] Value is Reported as BTU/lb

Table B.2.6: ELR - Standard Parameters of Coal

Property	3-Day Composite
Al_2O_3 (wt. %)	25.54
CaO (wt. %)	7.97
Fe_2O_3 (wt. %)	7.35
K_2O (wt. %)	2.67
MgO (wt. %)	1.34
Na_2O (wt. %)	0.43
P_2O_5 (wt. %)	0.20
SiO_2 (wt. %)	46.01
SO_3 (wt. %)	7.33
TiO_2 (wt. %)	1.15
As (ppm)	80
Ba (ppm)	1083
Cd (ppm)	ND
Cl (ppm)	182
Co (ppm)	30
Cr (ppm)	127
Cu (ppm)	116
Hg (ppm)	ND
Mn (ppm)	355
Mo (ppm)	9
Ni (ppm)	100
Pb (ppm)	48
Sb (ppm)	ND
Se (ppm)	8
Sr (ppm)	591
V (ppm)	225
Zn (ppm)	133

Notes:

ND - Not Detected

Table B.2.7: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	13.72
	Fixed Carbon	24.6
	Moisture [1]	0.14
	Volatile Matter	61.68
Ultimate Analysis	**Carbon**	72.34
	Hydrogen	7.05
	Nitrogen	0.36
	Oxygen	4.98
	Sulfur	1.54
Heat Value [2]		14467

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.2.8: ELR - Standard Parameters for Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	1.18
CaO (wt. %)	2.36
Fe_2O_3 (wt. %)	68.64
K_2O (wt. %)	0.33
MgO (wt. %)	0.35
Na_2O (wt. %)	0.31
P_2O_5 (wt. %)	0.21
SiO_2 (wt. %)	16.87
SO_3 (wt. %)	2.64
TiO_2 (wt. %)	0.20
As (ppm)	NR
Ba (ppm)	300
Cd (ppm)	6
Cl (ppm)	405
Co (ppm)	616
Cr (ppm)	118
Cu (ppm)	1398
Hg (ppm)	0.4
Mn (ppm)	4100
Mo (ppm)	28
Ni (ppm)	367
Pb (ppm)	11
Sb (ppm)	NR
Se (ppm)	< 1
Sr (ppm)	200
V (ppm)	37
Zn (ppm)	54000

Notes:

ND - Not Detected
NR - Not Reported

B.2.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table 2.109: CPR - Chemical Composition of Cement Kiln Dust (CKD)

Property (wt. %)	7/11/2006	7/12/2006		7/13/2006			7/14/2006	Average
	7:15 AM	5:26 AM	8:28 AM	1:28 AM	2:53 PM	11:04 PM	6:51 AM	
Al_2O_3	4.05	4.03	3.83	3.93	4.18	3.99	3.97	4.00
CaO	43.92	45.13	47.91	44.65	43.33	43.86	44.03	44.69
Fe_2O_3	2.04	1.99	1.81	2.02	2.12	2.07	2.05	2.01
K_2O	0.38	0.45	0.5	0.4	0.42	0.4	0.39	0.42
MgO	1.66	1.97	2.18	1.36	1.51	1.4	1.5	1.65
Na_2O	0.08	0.1	0.1	0.07	0.08	0.09	0.08	0.09
SiO_2	12.54	12.23	10.37	11.96	12.55	12.32	12.35	12.05
SO_3	0.45	1.57	3.14	0.3	0.64	0.24	0.31	0.95

Table 2.11: ELR - Chemical Composition of Cement Kiln Dust

Property	7/11/2006	7/12/2006		7/13/2006			Average
	7:15 AM	5:26 AM	8:28 AM	1:28 AM	2:53 PM	11:04 PM	
Al_2O_3 (wt. %)	4.08	3.63	3.65	3.53	3.79	3.62	3.72
CaO (wt. %)	43.41	45.38	57.84	44.60	45.03	44.41	46.78
Fe_2O_3 (wt. %)	2.04	2.09	2.11	2.03	2.21	2.11	2.10
K_2O (wt. %)	0.38	1.21	0.60	0.39	0.43	0.40	0.57
MgO (wt. %)	1.61	1.47	2.27	1.26	1.35	1.23	1.53
Na_2O (wt. %)	0.06	0.00	0.00	0.06	0.00	0.00	0.02
P_2O_5 (wt. %)	0.06	0.04	0.03	0.05	0.06	0.05	0.05
SiO_2 (wt. %)	12.13	10.85	9.16	11.21	11.61	11.52	11.08
SO_3 (wt. %)	0.28	1.55	4.43	0.29	0.72	0.28	1.26
TiO_2 (wt. %)	0.24	0.21	0.17	0.24	0.22	0.22	0.22
Moisture (wt. %)	0.23	0.23	0.04	0.28	0.25	0.29	0.22
LOI (wt. %)	35.71	32.90	19.70	36.34	34.53	36.10	32.55
As (ppm)	7	18	25	16	22	20	18
Ba (ppm)	443	294	246	295	278	298	309
Cd (ppm)	ND	ND	ND	ND	ND	ND	NA
Cl (ppm)	23	24	42	114	43	111	60
Co (ppm)	18	13	ND	20	13	19	17
Cr (ppm)	44	36	63	42	43	42	45
Cu (ppm)	14	ND	18	14	13	ND	15
Hg (ppm)	<0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01
Mn (ppm)	222	188	125	153	160	162	168
Mo (ppm)	ND	ND	ND	ND	ND	ND	NA
Ni (ppm)	15	17	17	14	15	11	15
Pb (ppm)	19	22	ND	25	15	11	18
Sb (ppm)	30	73	76	45	74	50	58
Se (ppm)	ND	2	4	ND	2	2	2
Sr (ppm)	310	281	341	276	283	270	293
V (ppm)	58	48	43	52	44	54	50
Zn (ppm)	110	93	61	108	120	114	101

Notes:

NA - Not Applicable
ND - Not Detected

B.2.7. CHEMICAL COMPOSITION OF CLINKER

Table B.2.12.a: CPR - Chemical Composition of Clinker for 7/11/06 and 7/12/06

Property (wt. %)	7/11/2006								7/12/2006										
	8:30 AM	9:51 AM	11:50 AM	2:11 PM	4:00 PM	5:56 PM	8:25 PM	10:26 PM	12:09 AM	2:30 AM	4:32 AM	6:05 AM	8:27 AM	10:27 AM	11:41 AM	2:12 PM	3:48 PM	6:09 PM	8:31 PM
Al_2O_3	5.22	5.12	5.14	4.91	4.97	5.06	5.06	5.00	5.20	5.06	4.95	4.95	5.06	4.88	4.98	5.08	5.28	5.28	5.13
CaO	64.43	64.44	64.29	64.53	64.53	64.35	64.33	64.55	64.51	64.56	64.38	64.53	64.39	64.26	64.39	64.63	64.57	64.58	64.71
Fe_2O_3	3.15	3.18	3.08	3.16	3.09	3.11	3.19	3.23	3.20	3.27	3.28	3.37	3.38	3.45	3.53	3.37	3.43	3.31	3.16
K_2O	0.48	0.46	0.50	0.47	0.47	0.47	0.45	0.46	0.52	0.48	0.50	0.46	0.47	0.51	0.48	0.47	0.50	0.51	0.49
MgO	3.59	3.66	3.75	3.83	3.62	3.70	3.56	3.69	3.61	3.75	3.77	3.73	3.60	3.71	3.75	3.45	3.27	3.22	3.22
Na_2O	0.11	0.11	0.10	0.10	0.10	0.12	0.12	0.10	0.11	0.11	0.11	0.10	0.10	0.11	0.10	0.10	0.09	0.10	0.10
Na_2O_{eq}	0.43	0.41	0.43	0.41	0.41	0.43	0.42	0.40	0.45	0.43	0.44	0.40	0.41	0.45	0.42	0.41	0.42	0.44	0.42
SiO_2	20.98	21.03	21.07	21.03	20.94	20.92	20.74	21.13	21.06	21.10	21.05	21.24	21.14	21.15	21.28	21.18	21.20	21.15	21.37
SO_3	0.69	0.65	0.70	0.80	0.65	0.67	0.66	0.62	0.78	0.71	0.86	0.63	0.70	0.79	0.73	0.68	0.64	0.89	0.71
F CaO	1.09	0.76	1.04	0.93	0.93	1.42	1.74	1.74	1.74	1.64	1.80	0.65	0.60	1.04	0.87	1.47	1.04	1.14	0.82
C_3A	8.50	8.20	8.40	7.70	7.90	8.10	8.00	7.80	8.40	7.90	7.60	7.40	7.70	7.10	7.20	7.80	8.20	8.40	8.20
C_4AF	9.60	9.70	9.40	9.60	9.40	9.50	9.70	9.80	9.70	10.00	10.00	10.30	10.30	10.50	10.70	10.30	10.40	10.10	9.60
C_3S	63.27	63.56	62.66	65.37	65.75	64.54	65.71	63.99	63.05	63.79	64.17	63.20	62.64	63.15	61.90	63.19	61.37	61.96	62.04
C_2S	12.42	12.34	13.14	10.98	10.43	11.29	9.89	12.31	12.81	12.37	11.94	13.21	13.35	13.00	14.31	13.05	14.48	13.89	14.46

Table B.2.12.b: CPR - Chemical Composition of Clinker for 7/13/06 and 7/14/06

Property (wt. %)	7/13/2006												7/14/2006				Average	C. V. (%)	Normality P-Value[1]
	1:05 AM	2:34 AM	4:08 AM	5:44 AM	8:09 AM	10:18 AM	12:04 PM	2:52 PM	4:06 PM	5:54 PM	8:09 PM	10:08 PM	12:21 AM	2:12 AM	4:01 AM	5:44 AM			
Al_2O_3	4.96	5.09	5.12	5.03	5.07	5.16	5.17	5.09	5.07	5.14	5.17	5.10	5.20	5.04	5.07	4.99	5.08	2.0	0.840
CaO	64.65	64.68	64.50	64.48	64.51	64.56	64.58	64.49	64.54	64.45	64.47	64.41	64.35	64.45	64.36	64.48	64.48	0.2	0.908
Fe_2O_3	3.26	3.29	3.34	3.39	3.39	3.44	3.43	3.46	3.64	3.55	3.59	3.56	3.49	3.54	3.57	3.55	3.36	4.7	0.289
K_2O	0.50	0.49	0.51	0.45	0.48	0.50	0.50	0.48	0.48	0.45	0.46	0.49	0.50	0.47	0.49	0.49	0.48	3.8	0.118
MgO	3.35	3.22	3.32	3.45	3.35	3.32	3.33	3.39	3.33	3.37	3.36	3.38	3.31	3.42	3.36	3.44	3.49	5.4[2]	<0.005
Na_2O	0.11	0.09	0.10	0.12	0.10	0.10	0.10	0.09	0.08	0.09	0.10	0.10	0.10	0.08	0.11	0.09	0.10	9.6[2]	<0.005
Na_2O_{eq}	0.44	0.41	0.44	0.42	0.42	0.43	0.43	0.41	0.40	0.39	0.40	0.42	0.43	0.39	0.43	0.41	0.42	3.7[2]	0.069
SiO_2	21.27	21.22	21.32	21.35	21.30	21.29	21.32	21.41	21.31	21.30	21.51	21.54	21.40	21.57	21.46	21.50	21.22	0.9	0.869
SO_3	0.60	0.61	0.64	0.54	0.66	0.72	0.67	0.61	0.65	0.57	0.58	0.73	0.55	0.59	0.64	0.61	0.67	12.1	0.117
F CaO	2.13	0.87	1.14	0.71	1.14	0.87	0.71	1.09	1.36	0.71	0.93	0.60	0.55	0.60	0.71	0.60	1.06	38.8[2]	<0.005
C_3A	7.60	7.90	7.90	7.60	7.70	7.90	7.90	7.60	7.30	7.60	7.60	7.50	7.90	7.40	7.40	7.20	7.79	4.9	0.416
C_4AF	9.90	10.00	10.20	10.30	10.30	10.50	10.40	10.50	11.10	10.80	10.90	10.80	10.60	10.80	10.90	10.80	10.21	4.7	0.206
C_3S	63.56	63.14	61.38	61.60	61.83	61.44	61.24	60.68	61.52	60.89	59.12	59.16	59.40	59.52	59.75	60.50	62.29	2.8	0.544
C_2S	13.04	13.20	14.82	14.74	14.42	14.69	14.93	15.61	14.68	15.13	17.07	17.13	16.54	16.94	16.45	16.00	13.86	13.2	0.602

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

Table B.2.13: ELR - Chemical Composition of Clinker

Property	4/18/2006	4/19/2006	4/20/2006	Average
Al_2O_3 (wt. %)	4.91	5.27	4.93	5.04
CaO (wt. %)	64.72	63.53	64.57	64.27
Fe_2O_3 (wt. %)	3.15	3.35	3.29	3.26
K_2O (wt. %)	0.48	0.57	0.49	0.51
MgO (wt. %)	3.85	3.47	3.28	3.53
Na_2O (wt. %)	0.00	0.09	0.06	0.05
P_2O_5 (wt. %)	0.06	0.07	0.08	0.07
SiO_2 (wt. %)	21.36	22.20	22.07	21.88
SO_3 (wt. %)	0.67	0.82	0.62	0.71
TiO_2 (wt. %)	0.25	0.27	0.28	0.27
Moisture (wt. %)	0.04	0.01	0.04	0.03
LOI (wt. %)	0.47	0.36	0.33	0.39
As (ppm)	19	23	22	21
Ba (ppm)	186	200	224	203
Cd (ppm)	ND	ND	3	3
Cl (ppm)	286	863	124	424
Co (ppm)	ND	ND	ND	NA
Cr (ppm)	75	81	78	78
Cu (ppm)	19	29	29	26
Hg (ppm)	0.03	0.04	0.02	0.03
Mn (ppm)	619	513	450	527
Mo (ppm)	ND	ND	ND	NA
Ni (ppm)	15	23	16	18
Pb (ppm)	30	ND	38	34
Sb (ppm)	60	53	35	49
Se (ppm)	ND	ND	2	2
Sr (ppm)	389	403	398	397
V (ppm)	60	66	69	65
Zn (ppm)	168	190	204	187

Notes:

NA - Not Applicable

ND - Not Detected

B.2.8. CHEMICAL COMPOSITION OF CEMENT

Table B.2.14.a: CPR - Chemical Composition of Cement for 7/11/06 and 7/12/06

Property (wt. %)	**7/11/2006**						**7/12/2006**									
	7:15 AM	**9:51 AM**	**1:17 PM**	**4:01 PM**	**6:54 PM**	**9:58 PM**	**1:13 AM**	**2:45 AM**	**4:25 AM**	**7:19 AM**	**10:27 AM**	**11:25 AM**	**1:11 PM**	**3:47 PM**	**7:40 PM**	**10:15 PM**
Al_2O_3	4.4	4.61	4.66	4.55	4.6	4.56	4.67	4.71	4.67	4.61	4.48	4.67	4.77	4.78	4.67	4.66
CaO	62.86	62.81	61.92	62.56	61.72	62.62	62.77	62.91	63.16	62.48	63.01	62.53	62.46	62.64	62.43	62.99
Fe_2O_3	3	3	2.89	2.86	2.88	2.91	2.93	2.96	2.97	2.98	3.04	3.1	3.11	3.07	2.95	2.93
K_2O	0.44	0.45	0.42	0.43	0.42	0.43	0.44	0.42	0.42	0.46	0.44	0.45	0.44	0.46	0.44	0.46
MgO	3.12	3.32	3.54	3.49	3.52	3.49	3.56	3.55	3.47	3.24	3.35	3.55	3.49	3.17	3.12	3.05
Na_2O	0.11	0.1	0.17	0.13	0.14	0.12	0.13	0.12	0.11	0.11	0.11	0.13	0.12	0.12	0.13	0.11
Na_2O_{eq}	0.4	0.4	0.45	0.41	0.42	0.4	0.42	0.4	0.39	0.41	0.4	0.43	0.41	0.42	0.42	0.41
SiO_2	19.95	20.36	19.74	19.59	19.47	19.58	19.89	19.94	19.84	19.97	19.46	20.07	20.16	19.85	19.66	19.91
SO_3	2.74	2.44	2.37	2.32	2.78	2.95	2.87	2.26	2.55	2.69	2.23	2.55	2.53	2.63	2.76	2.8
F CaO	1.14	1.2	1.04	0.93	0.93	1.31	1.36	NR	1.09	1.2	0.87	NR	0.93	1.2	1.25	1.04
LOI	1.41	1.48	1.1	1.2	0.92	1.09	1.12	NR	0.97	1.4	0.92	NR	1.4	0.98	1.14	1.31
C_3A	6.6	7.1	7.5	7.2	7.3	7.2	7.4	7.5	7.4	7.2	6.7	7.1	7.4	7.5	7.4	7.4
C_4AF	9.1	9.1	8.8	8.7	8.8	8.9	8.9	9	9	9.1	9.3	9.4	9.5	9.3	9	8.9
C_3S	62.6	58.7	59.8	64.5	60.3	62.9	60.6	62.2	63.4	59.7	67.8	58.9	57.3	60.1	61.3	61.6
C_2S	10	14.1	11.4	7.5	10.3	8.7	11.3	10.2	9	12.2	4.6	13.1	14.5	11.5	10.1	10.6
Blaine SSA (m^2/kg)	379	391	391	389	402	398	389	NR	389	402	389	NR	377	381	381	388

Notes:

NR - Not Reported

Table B.2.14.b: CPR - Chemical Composition of Cement for 7/13/06 and 7/14/06

Property (wt. %)	7/13/2006								7/14/2006				Average	C. V. (%)	Normality P-Value[1]
	1:33 AM	4:01 AM	7:02 AM	10:15 AM	3:18 PM	4:01 PM	6:56 PM	9:52 PM	12:58 AM	3:35 AM	6:50 AM	9:47 AM			
Al_2O_3	4.7	4.61	4.65	4.62	4.73	4.64	4.87	4.83	4.74	4.69	4.71	4.62	4.66	2.1	0.331
CaO	63.03	62.96	62.87	62.56	62.47	62.59	62.87	62.45	61.74	61.47	62.57	62.29	62.56	0.7 [2]	0.008
Fe_2O_3	3	3	3.04	3.04	3.08	3.1	3.14	3.14	3.13	3.13	3.17	3.14	3.02	3.0	0.297
K_2O	0.45	0.45	0.44	0.46	0.45	0.46	0.46	0.46	0.47	0.45	0.47	0.45	0.45	3.4 [2]	0.023
MgO	3.1	3.08	3.12	3.08	3.16	3.09	3.24	3.22	3.18	3.17	3.17	3.13	3.28	5.5 [2]	<0.005
Na_2O	0.12	0.12	0.11	0.12	0.12	0.1	0.11	0.12	0.1	0.11	0.11	0.11	0.12	12.0 [2]	<0.005
Na_2O_{eq}	0.42	0.42	0.4	0.42	0.42	0.4	0.41	0.42	0.41	0.41	0.42	0.41	0.41	2.9 [2]	<0.005
SiO_2	20.06	19.93	20.06	19.76	20.19	19.95	20.44	20.4	20.17	20.22	20.43	20.08	19.97	1.4	0.810
SO_3	2.5	2.53	2.7	2.84	2.62	2.81	2.49	2.64	2.72	2.72	2.71	3	2.63	7.5	0.751
F CaO	0.71	1.04	0.98	1.14	0.76	1.09	0.82	0.6	0.71	0.55	0.87	1.04	0.99	21.5	0.751
LOI	1.3	1.28	1.14	1.21	1.35	1.17	1.29	1.26	1.38	1.4	1.26	1.34	1.22	13.1	0.270
C_3A	7.4	7.1	7.2	7.1	7.3	7.1	7.6	7.5	7.3	7.1	7.1	6.9	7.24	3.3 [2]	0.030
C_4AF	9.1	9.1	9.3	9.3	9.4	9.4	9.6	9.6	9.5	9.5	9.6	9.6	9.21	3.0	0.109
C_3S	61.1	62.4	60.2	61	57.2	59.6	56.3	54.7	54	52.8	55.5	56.9	59.76	5.6	0.623
C_2S	11.4	10.1	12.1	10.6	14.7	12.3	16.1	17.2	17.1	18.1	16.7	14.7	12.15	26.2	0.281
Blaine SSA (m^2/kg)	377	377	364	366	363	372	379	368	370	365	379	374	381	3.0	0.376

Notes:

[1] Based on Anderson-Darling Normality Test

[2] Data not normally distributed

Table B.2.15: ELR - Chemical Composition of Cement

Property	7/11/2006	7/12/2006	7/13/2006	Average
Al_2O_3 (wt. %)	4.85	4.76	4.85	4.82
CaO (wt. %)	62.88	63.34	62.95	63.06
Fe_2O_3 (wt. %)	2.96	3.07	3.18	3.07
K_2O (wt. %)	0.47	0.47	0.49	0.48
MgO (wt. %)	3.61	3.32	3.22	3.39
Na_2O (wt. %)	0.09	0.08	0.06	0.08
P_2O_5 (wt. %)	0.05	0.07	0.06	0.06
SiO_2 (wt. %)	20.99	20.89	21.29	21.06
SO_3 (wt. %)	2.96	2.82	2.94	2.91
TiO_2 (wt. %)	0.25	0.24	0.25	0.25
Moisture (wt. %)	0.39	0.47	0.58	0.48
LOI (wt. %)	0.89	0.94	0.71	0.85
C_3S (wt. %)	51.21	54.70	48.97	51.63
C_2S (wt. %)	21.55	18.63	24.10	21.42
C_3A (wt. %)	7.85	7.42	7.46	7.58
C_4AF (wt. %)	8.99	9.34	9.68	9.34
TOC (wt. %)	<0.1	<0.1	<0.1	<0.1
As (ppm)	19	17	19	18
Ba (ppm)	71	171	171	138
Cd (ppm)	3	ND	ND	3
Cl (ppm)	1067	233	324	541
Co (ppm)	ND	ND	ND	NA
Cr (ppm)	82	80	76	80
Cu (ppm)	22	43	29	31
Hg (ppm)	0.02	0.02	0.02	0.02
Mn (ppm)	596	467	441	502
Mo (ppm)	ND	ND	ND	NA
Ni (ppm)	22	20	16	19
Pb (ppm)	7	44	61	37
Sb (ppm)	72	64	53	63
Se (ppm)	1	ND	2	2
Sr (ppm)	404	403	399	402
V (ppm)	39	57	62	53
Zn (ppm)	152	193	203	183

Notes:

NA - Not Applicable
ND - Not Detected

B.2.9. PHYSICAL PROPERTIES OF CEMENT

Table B.2.16: CPR - Physical Properties of Cement

Property	7/11/2006	7/12/2006	7/13/2006	Average
Air in Mortar (%)	5.1	5.8	6.5	5.8
Blaine Specific Surface Area (m^2/kg)	385	391	368	381
Autoclave Expansion (% Exp.)	0.10	0.12	0.08	0.10
Cube Flow (%)	119.0	123.0	128.0	123.3
Comp Str 1day (MPa)	16.7	14.9	14.5	15.4
Comp Str 3day (MPa)	26.5	24.6	24.0	25.0
Comp Str 7day (MPa)	33.5	32.6	31.6	32.6
Comp Str 28day (MPa)	45.9	43.7	42.4	44.0
Normal Consistency (%)	25.7	25.8	25.7	25.7
Gillmore Initial Set (Min)	120	105	120	115
Gillmore Final Set (Min)	225	255	320	267
Vicat Initial Set (Min)	80	61	78	73
Vicat Final Set (Min)	210	240	255	235

Notes:

% Exp. - % Expansion

Table B.2.17: AUR - Physical Properties of Cement

Property	Composite
Autoclave Expansion (% Exp.)	0.03
Cube Flow (%)	98
Comp Str 1day (MPa)	11
Comp Str 3day (MPa)	23.1
Comp Str 7day (MPa)	29.8
Comp Str 28day (MPa)	39.5
Normal Consistency (%)	26.2
Gillmore Initial Set (Min)	72
Gillmore Final Set (Min)	145
Vicat Initial Set (Min)	69
Vicat Final Set (Min)	137
Drying Shrinkage @ 7 days (% LC)	-0.051
Drying Shrinkage @ 14 days (% LC)	-0.072
Drying Shrinkage @ 21 days (% LC)	-0.083
Drying Shrinkage @ 28 days (% LC)	-0.094

Notes:

% LC - Percent Length Change

% Exp. - Percent Expansion

B.2.10. PROPERTIES OF CONCRETE

Table B.2.18: Concrete Properties

Property	AUR		CPR
	Mix w/c=0.44	Mix w/c=0.37	Mix w/c=0.44
Total Air Content (%)	4.25	4.0	3.2
Slump (mm)	90	160	30
Unit Weight (kg/m^3)	2439	2427	2448
Initial Set (Min.)	218	239	247
Final Set (Min.)	273	290	NC
Compressive Strength (MPa)			
1 day	13.9	25.9	15.1
3 days	20.7	36.1	21.9
7 days	28.4	40.0	32.8
28 days	37.1	49.7	42.2
91 days	41.4	59.1	49.6
Splitting Tensile Strength (MPa)			
1 day	2.0	3.0	NC
3 days	2.3	3.7	NC
7 days	2.8	3.9	NC
28 days	3.3	4.3	NC
91 days	4.0	4.9	NC
Drying Shrinkage Development (% Length Change) [1]			
4 days	0.018	0.011	NC
7 days	0.027	0.020	NC
14 days	0.034	0.025	NC
28 days	0.035	0.030	NC
56 days	0.036	0.039	NC
112 days	0.044	0.040	NC
224 days	0.047	0.045	NC
448 days	0.049	0.047	NC
Permeability @ 91 days (Coulombs)	2930	2550	2660

Notes: CIP - Collection in Progress NC - Not Collected [1] Percentage decrease in length

B.2.11. EMISSIONS

Table B.2.19: CPR - Emissions

Time	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/11/2006 7:00	1.45E-03	1.03E-05	2.35E-05	6.20E-04
7/11/2006 8:00	1.36E-03	8.88E-06	2.82E-05	5.83E-04
7/11/2006 9:00	1.32E-03	9.61E-06	3.72E-05	5.93E-04
7/11/2006 10:00	9.53E-04	8.59E-06	2.18E-05	3.67E-04
7/11/2006 11:00	8.24E-04	1.30E-05	1.21E-05	3.39E-04
7/11/2006 12:00	1.07E-03	8.63E-06	3.14E-05	4.71E-04
7/11/2006 13:00	1.22E-03	7.61E-06	3.31E-05	4.48E-04
7/11/2006 14:00	1.22E-03	9.65E-06	3.86E-05	4.71E-04
7/11/2006 15:00	1.29E-03	8.22E-06	3.93E-05	4.99E-04
7/11/2006 16:00	1.27E-03	9.87E-06	4.12E-05	4.99E-04
7/11/2006 17:00	1.33E-03	1.14E-05	4.12E-05	5.54E-04
7/11/2006 18:00	1.37E-03	1.02E-05	4.50E-05	5.62E-04
7/11/2006 19:00	1.42E-03	1.16E-05	4.43E-05	5.82E-04
7/11/2006 20:00	1.40E-03	9.13E-06	4.89E-05	5.46E-04
7/11/2006 21:00	1.27E-03	4.88E-06	5.86E-05	5.63E-04
7/11/2006 22:00	1.31E-03	7.59E-06	7.40E-05	5.44E-04
7/11/2006 23:00	1.37E-03	1.01E-05	7.55E-05	5.18E-04
7/12/2006 0:00	1.46E-03	1.27E-05	4.23E-05	5.29E-04
7/12/2006 1:00	1.30E-03	8.17E-06	3.49E-05	5.86E-04
7/12/2006 2:00	1.27E-03	1.37E-05	3.30E-05	6.33E-04
7/12/2006 3:00	1.23E-03	1.19E-05	3.00E-05	5.93E-04
7/12/2006 4:00	1.34E-03	1.39E-05	3.10E-05	6.00E-04
7/12/2006 5:00	1.33E-03	2.03E-05	2.22E-05	6.83E-04
7/12/2006 6:00	1.25E-03	1.26E-05	2.93E-05	6.98E-04
7/12/2006 7:00	1.33E-03	1.59E-05	2.05E-05	6.47E-04
7/12/2006 8:00	1.19E-03	1.75E-05	1.53E-05	5.99E-04
7/12/2006 9:00	1.19E-03	1.68E-05	1.64E-05	5.55E-04
7/12/2006 10:00	1.15E-03	1.90E-05	1.96E-05	5.11E-04
7/12/2006 11:00	1.19E-03	2.02E-05	2.34E-05	5.59E-04
7/12/2006 12:00	1.24E-03	1.07E-05	2.55E-05	5.71E-04
7/12/2006 13:00	1.10E-03	8.74E-06	3.22E-05	5.84E-04
7/12/2006 14:00	1.09E-03	5.53E-06	4.72E-05	5.97E-04
7/12/2006 15:00	1.12E-03	5.55E-06	4.32E-05	5.90E-04
7/12/2006 16:00	1.21E-03	4.89E-06	4.27E-05	5.69E-04
7/12/2006 17:00	1.17E-03	5.52E-06	4.15E-05	5.42E-04
7/12/2006 18:00	1.14E-03	5.73E-06	4.10E-05	5.53E-04
7/12/2006 19:00	1.13E-03	5.61E-06	3.90E-05	5.91E-04
7/12/2006 20:00	1.18E-03	5.22E-06	3.67E-05	5.73E-04
7/12/2006 21:00	1.18E-03	5.05E-06	3.57E-05	5.44E-04
7/12/2006 22:00	1.15E-03	6.43E-06	2.88E-05	4.73E-04
7/12/2006 23:00	1.15E-03	6.90E-06	2.83E-05	4.95E-04
7/13/2006 0:00	1.17E-03	7.77E-06	2.76E-05	5.78E-04
7/13/2006 1:00	1.20E-03	6.61E-06	2.65E-05	5.39E-04
7/13/2006 2:00	1.21E-03	6.57E-06	2.63E-05	5.47E-04
7/13/2006 3:00	1.20E-03	5.74E-06	2.62E-05	5.43E-04
7/13/2006 4:00	1.14E-03	6.52E-06	2.57E-05	5.74E-04
7/13/2006 5:00	1.22E-03	5.75E-06	2.43E-05	5.14E-04
7/13/2006 6:00	1.25E-03	1.00E-05	2.10E-05	4.75E-04

Table B.2.20: CPR - Emissions

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/13/2006 7:00	1.23E-03	5.89E-05	1.15E-05	5.63E-04
7/13/2006 8:00	1.08E-03	3.68E-06	2.67E-05	5.87E-04
7/13/2006 9:00	1.10E-03	3.40E-06	3.20E-05	5.18E-04
7/13/2006 10:00	1.19E-03	2.13E-05	3.35E-05	6.10E-04
7/13/2006 11:00	1.23E-03	1.14E-04	2.62E-05	6.37E-04
7/13/2006 12:00	1.15E-03	7.42E-05	3.57E-05	5.66E-04
7/13/2006 13:00	1.15E-03	3.13E-06	4.87E-05	5.60E-04
7/13/2006 14:00	1.20E-03	3.24E-06	4.91E-05	5.02E-04
7/13/2006 15:00	1.20E-03	3.59E-06	4.50E-05	5.09E-04
7/13/2006 16:00	1.12E-03	3.17E-06	4.64E-05	5.13E-04
7/13/2006 17:00	1.10E-03	2.75E-06	4.61E-05	5.12E-04
7/13/2006 18:00	1.10E-03	3.66E-06	4.52E-05	5.02E-04
7/13/2006 19:00	1.14E-03	3.61E-06	4.47E-05	4.81E-04
7/13/2006 20:00	1.13E-03	2.68E-06	4.69E-05	4.84E-04
7/13/2006 21:00	1.11E-03	3.34E-06	5.42E-05	4.66E-04
7/13/2006 22:00	1.12E-03	3.65E-06	3.08E-05	4.64E-04
7/13/2006 23:00	1.12E-03	3.82E-06	2.77E-05	4.91E-04
7/14/2006 0:00	1.15E-03	3.62E-06	2.98E-05	5.30E-04
7/14/2006 1:00	1.12E-03	3.86E-06	2.73E-05	4.83E-04
7/14/2006 2:00	1.21E-03	4.57E-06	2.64E-05	5.07E-04
7/14/2006 3:00	1.20E-03	4.90E-06	2.62E-05	4.79E-04
7/14/2006 4:00	1.21E-03	4.51E-06	2.47E-05	4.74E-04
7/14/2006 5:00	1.22E-03	4.58E-06	2.47E-05	4.61E-04
7/14/2006 6:00	1.21E-03	3.95E-06	2.51E-05	4.69E-04
Average	1.20E-03	1.12E-05	3.42E-05	5.39E-04
C. V. (%)	8.8	145.6	35.8	11.7
Normality P-Value[1]	0.017	<0.005	0.008	0.22

Notes:

[1] Based on Anderson Darling Normality Test

NC - Not Collected

APPENDIX B.4

RAW DATA FOR *CT2 BURN*

B.4.1. GENERAL COMMENTS

- The raw data from the CT2 burn are presented in this appendix.
- Coal and scrap tires are the fuels used in the burn.
- The burn lasted from 9 AM on May 16, 2007 to 9 AM on May 19, 2007.
- Cement and concrete results not collected for the burn.

B.4.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.4.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.4.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	23.90	0.69	NR	10.60	1.54	0.74
CaO	3.02	53.00	NR	31.70	5.02	43.20
Fe_2O_3	2.14	NR	NR	16.80	NR	0.49
K_2O	2.34	0.08	NR	0.10	0.19	0.09
MgO	0.97	1.20	NR	12.80	0.92	0.51
Na_2O	0.30	NR	NR	NR	NR	NR
SiO_2	57.70	1.83	NR	23.80	87.70	3.41
SO_3	0.93	0.16	NR	0.92	3.95	47.60
Moisture	30.10	3.10	NR	NR	4.90	25.00
LOI	6.90	43.00	NR	NR	0.43	3.90

Notes: NR - Not Reported

Table B.4.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	26.84	1.86	3.19	4.50	1.37	0.55
CaO (wt. %)	2.82	90.04	71.72	34.88	4.08	43.11
Fe_2O_3 (wt. %)	12.35	1.02	2.25	30.69	3.45	0.35
K_2O (wt. %)	2.81	0.30	0.51	0.03	0.12	0.15
MgO (wt. %)	1.46	1.77	2.43	12.82	1.56	0.53
Na_2O (wt. %)	0.49	0.06	0.04	0.05	0.02	0.06
P_2O_5 (wt. %)	0.57	0.05	0.01	0.48	0.04	0.00
SiO_2 (wt. %)	50.61	4.53	19.36	11.57	88.40	4.39
SO_3 (wt. %)	0.17	0.20	0.14	0.30	0.04	50.73
TiO_2 (wt. %)	1.39	0.06	0.24	0.24	0.18	0.02
Moisture (wt. %)	21.56	2.26	0.77	2.42	3.41	19.36
LOI (wt. %)	7.35	40.66	34.34	0.55	0.41	7.34
As (ppm)	163	3	5	10	5	2
Ba (ppm)	2300	500	253	290	200	200
Cd (ppm)	ND	ND	ND	ND	ND	ND
Cl (ppm)	76	39	30	30	42	16
Co (ppm)	67	15	14	11	5	2
Cr (ppm)	159	18	29	2078	220	ND
Cu (ppm)	184	5	15	12	ND	ND
Hg (ppm)	ND	ND	ND	ND	ND	ND
Mn (ppm)	500	200	253	43970	6900	200
Mo (ppm)	18	ND	ND	114	ND	ND
Ni (ppm)	121	ND	ND	35	ND	ND
Pb (ppm)	79	ND	ND	ND	5	7
Sb (ppm)	NR	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	4	ND
Sr (ppm)	2000	600	400	300	100	800
V (ppm)	326	26	35	680	170	11
Zn (ppm)	157	8	8	82	0	ND

Notes: ND - Not Detected

B.4.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.4.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	5/16/2007	5/17/2007		5/18/2007		5/19/2007		5/20/2007		Average	C. V. (%)
	1:49 PM	1:36 AM	2:13 PM	2:04 AM	1:55 PM	2:02 AM	11:00 AM	2:15 AM	2:10 PM		
Al_2O_3	3.05	2.98	3.12	3.16	3.04	3.04	2.98	3.13	3.09	3.07	2.1
CaO	43.74	43.94	43.62	43.71	43.70	43.69	43.64	43.80	43.58	43.71	0.2
Fe_2O_3	1.97	1.95	2.06	1.95	1.99	1.97	2.06	2.00	2.14	2.01	3.2
K_2O	0.30	0.32	0.34	0.35	0.34	0.34	0.33	0.30	0.29	0.32	6.7
MgO	2.11	2.04	2.06	1.93	2.00	2.05	2.23	2.18	2.17	2.09	4.6
Na_2O	0.03	0.04	0.03	0.04	0.03	0.04	0.03	0.03	0.03	0.03	15.0
Na_2O_{eq}	0.23	0.25	0.25	0.27	0.25	0.26	0.25	0.23	0.22	0.25	6.5
SiO_2	13.42	13.02	13.33	13.03	12.99	13.30	13.46	13.06	12.97	13.18	1.5
SO_3	0.22	0.19	0.16	0.15	0.15	0.16	0.18	0.17	0.18	0.17	12.9
LOI	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NA

Notes: NR - Not Reported NA - Not Applicable

Table B.4.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	4.09
CaO (wt. %)	64.08
Fe_2O_3 (wt. %)	3.11
K_2O (wt. %)	0.46
MgO (wt. %)	3.18
Na_2O (wt. %)	0.08
P_2O_5 (wt. %)	0.05
SiO_2 (wt. %)	24.18
SO_3 (wt. %)	0.26
TiO_2 (wt. %)	0.26
Moisture (wt. %)	0.31
LOI (wt. %)	33.30
As (ppm)	23
Ba (ppm)	200
Cd (ppm)	ND
Cl (ppm)	97
Co (ppm)	14
Cr (ppm)	96
Cu (ppm)	28
Hg (ppm)	ND
Mn (ppm)	1800
Mo (ppm)	ND
Ni (ppm)	5
Pb (ppm)	ND
Sb (ppm)	NR
Se (ppm)	3
Sr (ppm)	500
V (ppm)	61
Zn (ppm)	21

Notes: NR - Not Reported
ND - Not Detected

B.4.5. CHEMICAL COMPOSITION OF FUELS

Table B.4.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	Ash	16.17
	Fixed Carbon	54.88
	Volatile Matter	28.95
Ultimate Analysis	Carbon	72.63
	Hydrogen	4.38
	Nitrogen	1.39
	Oxygen	3.56
	Sulfur	2.72
Standard Parameters	Al_2O_3	21.60
	CaO	7.83
	Fe_2O_3	15.74
	K_2O	2.05
	MgO	1.03
	Na_2O	0.15
	SiO_2	43.35
	SO_3	6.80
Heat Value [1]		12864

Notes: [1] Value is Reported as BTU/lb

Table B.4.6: ELR - Proximate, Ultimate, and Combustion Analysis of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	14.51
	Fixed Carbon	30.19
	Volatile Matter	55.3
Ultimate Analysis	**Carbon**	72.24
	Hydrogen	3.71
	Nitrogen	0.5
	Oxygen	7.49
	Sulfur	1.55
Heat Value [1]		12864

Notes: [1] Value is Reported as BTU/lb

Table B.4.7: ELR - Standard Parameters of Coal

Property	3-Day Composite
Al_2O_3 (wt. %)	22.86
CaO (wt. %)	5.63
Fe_2O_3 (wt. %)	18.66
K_2O (wt. %)	1.78
MgO (wt. %)	1.01
Na_2O (wt. %)	0.25
P_2O_5 (wt. %)	0.35
SiO_2 (wt. %)	42.36
SO_3 (wt. %)	5.54
TiO_2 (wt. %)	1.02
As (ppm)	200
Ba (ppm)	1500
Cd (ppm)	ND
Cl (ppm)	94
Co (ppm)	61
Cr (ppm)	107
Cu (ppm)	116
Hg (ppm)	0.130
Mn (ppm)	2900
Mo (ppm)	37
Ni (ppm)	107
Pb (ppm)	39
Sb (ppm)	NR
Se (ppm)	7
Sr (ppm)	900
V (ppm)	210
Zn (ppm)	179

Notes: NR - Not Reported
ND - Not Detected

Table B.4.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	14.54
	Fixed Carbon	46.91
	Moisture [1]	0.09
	Volatile Matter	38.46
Ultimate Analysis	**Carbon**	77.85
	Hydrogen	5.57
	Nitrogen	0.07
	Oxygen	0.65
	Sulfur	1.31
Heat Value [2]		15456

Notes: [1] As Received

[2] Value is Reported as BTU/lb

Table B.4.9: ELR - Standard Parameters for Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	0.78
CaO (wt. %)	3.82
Fe_2O_3 (wt. %)	57.42
K_2O (wt. %)	0.29
MgO (wt. %)	0.04
Na_2O (wt. %)	0.47
P_2O_5 (wt. %)	0.22
SiO_2 (wt. %)	25.12
SO_3 (wt. %)	0.85
TiO_2 (wt. %)	0.40
As (ppm)	ND
Ba (ppm)	1135
Cd (ppm)	ND
Cl (ppm)	1174
Co (ppm)	852
Cr (ppm)	94
Cu (ppm)	546
Hg (ppm)	0.2
Mn (ppm)	3600
Mo (ppm)	31
Ni (ppm)	91
Pb (ppm)	17
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	0
V (ppm)	50
Zn (ppm)	0

Notes: NR - Not Reported
ND - Not Detected

B.4.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.4.10: CPR - Chemical Composition of Cement Kiln Dust (CKD)

Property (wt. %)	5/16/2007			5/17/2007		5/18/2007		Average
	8:34 AM	3:08 PM	7:54 PM	2:13 PM	11:07 PM	8:06 AM	7:59 PM	
Al_2O_3	3.61	4.02	3.82	4.08	3.63	3.6	3.24	3.71
CaO	45.48	43.96	44.77	44.31	45.18	45.08	46.66	45.06
Fe_2O_3	1.87	2.12	2.02	2.04	1.97	1.86	1.81	1.96
K_2O	0.43	0.46	0.44	0.48	0.43	0.44	0.41	0.44
MgO	1.28	1.32	1.28	1.28	1.33	1.27	1.32	1.30
Na_2O	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.04
SiO_2	11.85	12.32	12.08	12.62	11.86	12.15	11.06	11.99
SO_3	0.15	0.15	0.16	0.27	0.17	0.13	0.16	0.17

Table B.4.11: ELR - Chemical Composition of Cement Kiln Dust

Property	5/16/2007		5/17/2007		5/18/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	5.71	5.40	5.52	5.23	5.20	5.69	5.46
CaO (wt. %)	69.01	70.00	69.40	70.34	70.23	70.47	69.91
Fe_2O_3 (wt. %)	3.23	2.98	3.10	3.04	2.86	2.69	2.99
K_2O (wt. %)	0.69	0.66	0.69	0.64	0.64	0.60	0.65
MgO (wt. %)	2.20	2.24	2.08	2.18	2.06	2.18	2.16
Na_2O (wt. %)	0.08	0.07	0.07	0.07	0.06	0.06	0.07
P_2O_5 (wt. %)	0.08	0.06	0.07	0.07	0.05	0.05	0.06
SiO_2 (wt. %)	18.13	17.69	18.12	17.66	18.15	17.47	17.87
SO_3 (wt. %)	0.31	0.39	0.40	0.27	0.25	0.31	0.32
TiO_2 (wt. %)	0.35	0.33	0.36	0.33	0.34	0.31	0.34
Moisture (wt. %)	0.28	0.26	0.20	0.29	0.33	0.34	0.28
LOI (wt. %)	35.41	35.04	34.81	35.92	36.07	36.36	35.60
As (ppm)	34	33	27	27	26	19	28
Ba (ppm)	481	489	390	363	503	483	452
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	180	155	561	135	118	83	205
Co (ppm)	10	10	14	15	9	18	13
Cr (ppm)	82	48	60	56	52	48	57
Cu (ppm)	26	13	22	ND	35	8	21
Hg (ppm)	0.49	0.39	1.31	0.25	0.26	0.04	0
Mn (ppm)	842	733	781	848	377	604	697
Mo (ppm)	ND	1	4	5	ND	ND	3
Ni (ppm)	11	9	10	12	9	ND	10
Pb (ppm)	23	ND	7	5	ND	21	14
Sb (ppm)	NR	NR	NR	NR	NR	NR	NA
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	481	489	521	484	503	483	493
V (ppm)	77	83	73	74	67	63	73
Zn (ppm)	34	26	26	28	30	24	28

Notes: ND - Not Detected NR - Not Reported NA - Not Applicable

B.4.7. CHEMICAL COMPOSITION OF CLINKER

Table B.4.12.a: CPR - Chemical Composition of Clinker for 5/16/2007

Property (wt. %)	5/16/2007								
	7:47 AM	9:40 AM	12:06 PM	1:48 PM	4:05 PM	5:45 PM	7:55 PM	10:05 PM	11:27 PM
Al_2O_3	5.00	4.99	5.01	5.08	5.04	5.04	5.10	5.04	5.05
CaO	64.67	64.72	64.80	64.72	64.71	64.53	64.75	64.82	64.78
Fe_2O_3	3.36	3.35	3.36	3.37	3.31	3.41	3.41	3.38	3.36
K_2O	0.45	0.44	0.45	0.45	0.47	0.55	0.47	0.45	0.50
MgO	3.53	3.54	3.53	3.50	3.53	3.51	3.48	3.50	3.52
Na_2O	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	0.06
Na_2O_{eq}	0.35	0.35	0.35	0.35	0.37	0.43	0.38	0.36	0.39
SiO_2	21.80	21.77	21.62	21.77	21.68	21.66	21.64	21.67	21.63
SO_3	0.71	0.68	0.58	0.69	0.72	0.88	0.71	0.62	0.65
F CaO	0.64	0.91	1.50	0.81	0.48	1.40	1.07	1.02	0.59
C_3A	7.60	7.50	7.60	7.80	7.70	7.60	7.70	7.60	7.70
C_4AF	10.20	10.20	10.20	10.30	10.10	10.40	10.40	10.30	10.20
C_3S	59.30	59.70	61.00	59.10	60.10	59.40	60.00	60.40	60.60
C_2S	17.80	17.40	15.90	17.80	16.80	17.30	16.80	16.50	16.30

Table B.4.12.b: CPR - Chemical Composition of Clinker for 5/17/2007

Property (wt. %)	5/17/2007											
	1:46 AM	**4:02 AM**	**5:49 AM**	**8:04 AM**	**10:25 AM**	**11:40 AM**	**2:07 PM**	**3:58 PM**	**6:05 PM**	**8:08 PM**	**10:05 PM**	**11:51 PM**
Al_2O_3	4.94	5.00	4.84	5.24	5.20	5.12	5.17	5.17	5.09	5.16	5.12	5.17
CaO	64.84	64.74	62.78	64.59	64.59	65.03	64.91	64.75	64.83	64.84	64.90	64.79
Fe_2O_3	3.21	3.41	3.45	3.74	3.63	3.38	3.54	3.47	3.45	3.48	3.40	3.39
K_2O	0.52	0.52	0.56	0.49	0.52	0.47	0.54	0.51	0.50	0.52	0.51	0.55
MgO	3.41	3.44	3.00	3.40	3.41	3.37	3.39	3.37	3.35	3.31	3.31	3.34
Na_2O	0.06	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Na_2O_{eq}	0.40	0.40	0.44	0.39	0.41	0.36	0.41	0.39	0.39	0.41	0.39	0.42
SiO_2	21.70	21.60	20.45	21.50	21.54	21.44	21.40	21.48	21.59	21.57	21.54	21.52
SO_3	0.78	0.78	0.98	0.75	0.77	0.52	0.64	0.64	0.64	0.66	0.59	0.75
F CaO	0.38	0.38	0.54	0.81	0.97	1.34	1.45	1.24	0.21	0.59	0.59	0.59
C_3A	7.70	7.50	7.00	7.60	7.60	7.80	7.70	7.80	7.70	7.80	7.80	8.00
C_4AF	9.80	10.40	10.50	11.40	11.00	10.30	10.80	10.60	10.50	10.60	10.30	10.30
C_3S	61.30	60.90	62.70	59.00	59.10	62.50	61.80	60.60	60.70	60.40	61.20	60.60
C_2S	16.00	16.00	11.30	17.10	17.10	14.30	14.70	15.80	16.10	16.30	15.60	15.90

Table B.4.12.c: CPR - Chemical Composition of Clinker for 5/18/2007

Property (wt. %)	5/18/2007										
	2:04 AM	3:55 AM	5:34 AM	8:02 AM	10:02 AM	11:38 AM	1:49 PM	4:05 PM	6:45 PM	7:56 PM	10:34 PM
Al_2O_3	5.15	4.94	5.33	5.39	5.39	5.25	5.33	5.37	5.37	5.21	5.20
CaO	64.84	63.44	64.56	64.49	64.49	64.86	64.54	64.42	64.34	64.64	64.58
Fe_2O_3	3.36	3.18	3.51	3.60	3.62	3.37	3.63	3.76	3.81	3.56	3.56
K_2O	0.52	0.59	0.55	0.56	0.56	0.52	0.56	0.55	0.56	0.54	0.53
MgO	3.29	2.90	3.29	3.30	3.27	3.23	3.30	3.32	3.36	3.33	3.36
Na_2O	0.06	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.07
Na_2O_{eq}	0.40	0.45	0.43	0.43	0.43	0.40	0.42	0.42	0.43	0.42	0.41
SiO_2	21.60	20.77	21.61	21.59	21.59	21.53	21.56	21.58	21.58	21.61	21.69
SO_3	0.67	0.64	0.79	0.82	0.83	0.60	0.70	0.81	0.79	0.79	0.72
F CaO	0.32	0.64	0.32	0.70	0.75	0.81	0.54	0.54	0.91	0.86	0.86
C_3A	8.00	7.70	8.20	8.20	8.20	8.20	8.00	7.90	7.80	7.80	7.80
C_4AF	10.20	9.70	10.70	11.00	11.00	10.20	11.00	11.40	11.60	10.80	10.80
C_3S	60.40	62.70	57.70	57.10	57.10	60.30	57.90	56.80	56.40	58.90	58.00
C_2S	16.30	12.30	18.40	18.80	18.90	16.20	18.20	19.00	19.30	17.50	18.40

Table B.4.12.d: CPR - Chemical Composition of Clinker for 5/19/2007

Property (wt. %)	5/19/2007					Average	C. V. (%)	Normality P-Value[1]
	12:01 AM	1:57 AM	4:21 AM	5:33 AM	7:49 AM			
Al_2O_3	5.17	5.29	5.21	5.18	5.09	5.08	2.1	<0.005
CaO	64.51	64.52	64.51	64.52	64.40	64.62	0.8	0.039
Fe_2O_3	3.51	3.56	3.46	3.50	3.66	3.41	3.4	<0.005
K_2O	0.54	0.53	0.54	0.55	0.55	0.50	8.2	0.077
MgO	3.40	3.40	3.40	3.46	3.45	3.38	4.7	0.589
Na_2O	0.06	0.06	0.06	0.06	0.07	0.06	4.6	<0.005
Na_2O_{eq}	0.42	0.41	0.41	0.42	0.43	0.39	7.6	0.053
SiO_2	21.69	21.70	21.75	21.73	21.80	21.52	1.4	<0.005
SO_3	0.85	0.66	0.73	0.60	0.81	0.70	14.2	<0.005
F CaO	1.13	0.81	0.64	1.34	0.81	0.78	49.6	0.374
C_3A	7.70	8.00	8.00	7.80	7.30	7.70	2.9	0.021
C_4AF	10.70	10.80	10.50	10.70	11.10	10.39	3.4	<0.005
C_3S	58.00	57.10	57.40	57.60	57.10	60.47	2.0	0.033
C_2S	18.40	19.10	19.10	18.80	19.40	16.08	10.1	0.007

Notes: [1] Based on Anderson-Darling Normality Test

Table B.4.13: ELR - Chemical Composition of Clinker

Property	5/16/2007		5/17/2007		5/18/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	4.89	4.93	4.86	4.88	4.99	5.08	4.94
CaO (wt. %)	64.42	64.44	65.08	65.04	64.94	64.76	64.78
Fe_2O_3 (wt. %)	3.23	3.34	3.12	3.25	3.19	3.32	3.24
K_2O (wt. %)	0.52	0.53	0.54	0.54	0.54	0.56	0.54
MgO (wt. %)	3.58	3.61	3.46	3.50	3.36	3.38	3.48
Na_2O (wt. %)	0.07	0.05	0.07	0.06	0.06	0.07	0.06
P_2O_5 (wt. %)	0.06	0.06	0.05	0.06	0.06	0.06	0.06
SiO_2 (wt. %)	21.83	21.57	21.53	21.48	21.68	21.54	21.60
SO_3 (wt. %)	0.87	0.93	0.75	0.68	0.65	0.73	0.77
TiO_2 (wt. %)	0.25	0.26	0.27	0.27	0.28	0.27	0.27
Moisture (wt. %)	0.05	0.03	0.02	0.02	0.03	0.02	0.03
LOI (wt. %)	0.17	0.32	0.26	0.22	0.18	0.20	0.22
As (ppm)	18	24	16	19	26	24	21
Ba (ppm)	391	393	396	393	395	393	393
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	103	119	205	161	155	123	144
Co (ppm)	7	9	12	7	14	11	10
Cr (ppm)	92	89	88	94	80	75	86
Cu (ppm)	27	ND	18	11	20	11	14
Hg (ppm)	ND	ND	ND	ND	ND	ND	ND
Mn (ppm)	1953	1963	1683	1770	1483	1472	1721
Mo (ppm)	10	1	7	3	ND	3	4
Ni (ppm)	6	8	6	11	10	15	9
Pb (ppm)	24	ND	18	21	ND	ND	10
Sb (ppm)	NR	NR	NR	NR	NR	NR	NA
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	488	491	495	492	494	491	492
V (ppm)	58	67	59	66	65	66	63
Zn (ppm)	29	36	33	30	51	43	37

Notes: NA - Not Applicable ND - Not Detected

B.4.8. EMISSIONS

Table B.4.14.a: CPR - Emissions

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
5/16/2007 9:00	1.03E-03	1.00E-06	1.68E-05	3.25E-04
5/16/2007 10:00	1.01E-03	1.74E-06	1.71E-05	3.03E-04
5/16/2007 11:00	9.62E-04	2.55E-07	1.72E-05	3.20E-04
5/16/2007 12:00	1.01E-03	4.89E-07	1.90E-05	3.47E-04
5/16/2007 13:00	1.09E-03	4.79E-07	2.12E-05	3.54E-04
5/16/2007 14:00	1.12E-03	6.10E-07	2.24E-05	3.61E-04
5/16/2007 15:00	1.16E-03	4.77E-07	2.57E-05	3.92E-04
5/16/2007 16:00	1.35E-03	8.58E-07	2.70E-05	4.27E-04
5/16/2007 17:00	1.28E-03	8.36E-07	2.68E-05	3.34E-04
5/16/2007 18:00	1.15E-03	5.81E-07	2.65E-05	3.52E-04
5/16/2007 19:00	1.16E-03	8.61E-07	2.54E-05	3.70E-04
5/16/2007 20:00	1.14E-03	7.48E-07	2.55E-05	3.87E-04
5/16/2007 21:00	1.02E-03	1.19E-06	2.13E-05	3.32E-04
5/16/2007 22:00	1.04E-03	9.90E-07	2.23E-05	3.82E-04
5/16/2007 23:00	1.19E-03	1.77E-06	2.49E-05	3.94E-04
5/17/2007 0:00	1.08E-03	1.07E-06	2.24E-05	3.70E-04
5/17/2007 1:00	1.19E-03	1.18E-06	2.22E-05	3.35E-04
5/17/2007 2:00	1.05E-03	1.29E-06	1.86E-05	3.20E-04
5/17/2007 3:00	1.31E-03	1.68E-06	1.99E-05	3.47E-04
5/17/2007 4:00	1.01E-03	1.76E-06	1.93E-05	3.47E-04
5/17/2007 5:00	9.02E-04	1.22E-06	1.80E-05	3.12E-04
5/17/2007 6:00	9.98E-04	1.54E-06	1.81E-05	3.53E-04
5/17/2007 7:00	1.03E-03	1.01E-06	1.78E-05	3.56E-04
5/17/2007 8:00	1.02E-03	1.56E-06	1.54E-05	2.98E-04
5/17/2007 9:00	1.12E-03	7.15E-07	1.72E-05	2.95E-04
5/17/2007 10:00	1.00E-03	2.47E-07	1.65E-05	3.41E-04
5/17/2007 11:00	1.13E-03	2.15E-07	1.52E-05	3.52E-04
5/17/2007 12:00	1.18E-03	1.37E-07	1.50E-05	2.94E-04
5/17/2007 13:00	1.06E-03	1.46E-07	1.51E-05	3.01E-04
5/17/2007 14:00	1.29E-03	1.68E-07	1.94E-05	3.88E-04
5/17/2007 15:00	1.10E-03	2.20E-07	2.05E-05	3.44E-04
5/17/2007 16:00	1.20E-03	3.15E-07	2.19E-05	3.36E-04
5/17/2007 17:00	1.09E-03	3.80E-07	2.21E-05	3.97E-04
5/17/2007 18:00	1.18E-03	7.25E-07	2.89E-05	5.11E-04
5/17/2007 19:00	9.71E-04	5.81E-07	2.42E-05	3.78E-04
5/17/2007 20:00	1.07E-03	6.11E-07	2.69E-05	3.96E-04
5/17/2007 21:00	1.05E-03	8.08E-07	2.60E-05	4.54E-04
5/17/2007 22:00	9.68E-04	6.94E-07	2.59E-05	4.12E-04
5/17/2007 23:00	9.93E-04	5.74E-07	2.62E-05	4.27E-04

Table B.4.14.b: CPR - Emissions

Time	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
5/18/2007 0:00	1.05E-03	9.66E-07	2.27E-05	4.20E-04
5/18/2007 1:00	1.17E-03	7.19E-07	2.09E-05	4.38E-04
5/18/2007 2:00	1.14E-03	1.15E-06	1.98E-05	4.52E-04
5/18/2007 3:00	1.12E-03	1.02E-06	1.94E-05	4.39E-04
5/18/2007 4:00	1.15E-03	1.20E-06	1.92E-05	4.27E-04
5/18/2007 5:00	9.34E-04	1.34E-06	1.76E-05	4.16E-04
5/18/2007 6:00	1.11E-03	1.99E-06	1.80E-05	4.38E-04
5/18/2007 7:00	1.04E-03	1.14E-06	1.66E-05	4.23E-04
5/18/2007 8:00	1.09E-03	1.42E-06	1.70E-05	4.29E-04
5/18/2007 9:00	1.07E-03	1.33E-06	1.80E-05	4.05E-04
5/18/2007 10:00	1.03E-03	1.05E-06	2.05E-05	3.78E-04
5/18/2007 11:00	1.18E-03	1.24E-06	2.33E-05	4.30E-04
5/18/2007 12:00	1.17E-03	7.49E-07	2.34E-05	4.39E-04
5/18/2007 13:00	1.05E-03	7.20E-07	2.27E-05	4.40E-04
5/18/2007 14:00	1.15E-03	7.20E-07	2.32E-05	4.03E-04
5/18/2007 15:00	1.11E-03	5.69E-07	2.52E-05	3.99E-04
5/18/2007 16:00	1.03E-03	4.73E-07	2.44E-05	3.75E-04
5/18/2007 17:00	1.14E-03	7.42E-07	2.67E-05	4.12E-04
5/18/2007 18:00	1.14E-03	5.49E-07	2.67E-05	3.76E-04
5/18/2007 19:00	1.19E-03	4.01E-07	2.79E-05	3.93E-04
5/18/2007 20:00	1.13E-03	4.71E-07	2.65E-05	3.75E-04
5/18/2007 21:00	1.25E-03	5.36E-07	2.71E-05	4.08E-04
5/18/2007 22:00	1.27E-03	8.87E-07	2.62E-05	3.54E-04
5/18/2007 23:00	1.25E-03	7.51E-07	2.52E-05	3.82E-04
5/19/2007 0:00	1.23E-03	7.20E-07	2.31E-05	3.61E-04
5/19/2007 1:00	1.32E-03	6.87E-07	2.31E-05	3.46E-04
5/19/2007 2:00	1.34E-03	7.42E-07	2.32E-05	3.57E-04
5/19/2007 3:00	NC	NC	NC	3.89E-04
5/19/2007 4:00	1.31E-03	1.03E-06	2.07E-05	3.66E-04
5/19/2007 5:00	1.27E-03	1.05E-06	2.08E-05	3.98E-04
5/19/2007 6:00	1.30E-03	1.28E-06	2.15E-05	4.02E-04
5/19/2007 7:00	1.35E-03	1.19E-06	2.15E-05	4.06E-04
5/19/2007 8:00	1.29E-03	9.39E-07	2.07E-05	4.02E-04
Average	1.13E-03	8.66E-07	2.18E-05	3.79E-04
C. V. (%)	9.8	49.8	17.0	11.6
Normality P-Value[1]	0.015	<0.005	0.008	0.214

Notes: [1] Based on Anderson Darling Normality Test NC - Not Collected

APPENDIX B.5

RAW DATA FOR *CTB BURN*

B.5.1. GENERAL COMMENTS

- The raw data from the CTB burn are presented in this appendix.
- Coal, scrap tires and broiler litter are the fuels used in the burn.
- The burn lasted from 9 AM on May 16, 2007 to 9 AM on May 19, 2007.

B.5.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.5.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.5.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	25.50	0.92	NR	9.43	1.06	0.75
CaO	2.99	51.40	NR	38.50	0.90	43.40
Fe_2O_3	0.50	0.00	NR	13.70	1.21	0.00
K_2O	2.63	0.08	NR	0.12	0.15	0.09
MgO	1.02	1.70	NR	12.00	0.09	0.62
Na_2O	0.38	0.02	NR	1.73	0.00	0.00
SiO_2	56.80	2.25	NR	23.90	95.80	2.92
SO_3	0.73	0.06	NR	0.79	1.40	47.20
Moisture	31.70	3.00	NR	4.60	4.10	26.40
LOI	7.40	43.50	NR	0.30	0.50	5.00

Notes: ND - Not Detected NR - Not Reported

Table B.5.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	27.36	0.59	6.74	5.68	0.66	0.54
CaO (wt. %)	3.03	94.35	48.34	33.12	0.40	42.95
Fe_2O_3 (wt. %)	11.57	0.39	6.58	28.39	0.72	0.32
K_2O (wt. %)	2.76	0.12	0.64	0.06	0.12	0.13
MgO (wt. %)	1.40	2.22	4.23	12.26	0.19	0.52
Na_2O (wt. %)	0.51	0.03	0.21	0.03	0.06	0.06
P_2O_5 (wt. %)	0.60	0.02	0.08	0.46	0.01	0.01
SiO_2 (wt. %)	50.43	2.08	32.12	14.90	97.58	3.78
SO_3 (wt. %)	0.40	0.09	0.20	0.59	0.01	51.54
TiO_2 (wt. %)	1.45	0.00	0.42	0.27	0.17	0.01
Moisture (wt. %)	20.97	0.27	2.40	5.35	2.80	15.93
LOI (wt. %)	8.21	41.46	25.06	5.46	0.29	7.00
As (ppm)	170	3	20	9	5	ND
Ba (ppm)	2400	NR	NR	NR	NR	NR
Cd (ppm)	ND	ND	ND	ND	ND	ND
Cl (ppm)	18	46	42	101	70	23
Co (ppm)	67	12	12	14	4	ND
Cr (ppm)	166	20	143	2152	40	ND
Cu (ppm)	186	31	32	57	24	< 5
Hg (ppm)	ND	ND	ND	ND	ND	ND
Mn (ppm)	400	NR	NR	NR	NR	NR
Mo (ppm)	18	ND	1	48	9	ND
Ni (ppm)	124	ND	21	37	ND	ND
Pb (ppm)	70	ND	23	ND	24	ND
Sb (ppm)	NR	NR	NR	NR	NR	NR
Se (ppm)	4	ND	ND	ND	ND	3
Sr (ppm)	2100	NR	NR	NR	NR	NR
V (ppm)	329	17	89	592	18	16
Zn (ppm)	141	43	42	190	3	ND

Notes: ND - Not Detected NR - Not Reported

B.5.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.5.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	7/11/2006					7/14/2006	Average	C. V. (%)
	2:23 AM	2:10 PM	1:39 AM	2:02 PM	1:59 AM	2:09 PM		
Al_2O_3	3.12	3.08	3.11	3.14	3.15	3.14	3.12	0.8
CaO	43.62	43.64	43.34	43.25	43.21	43.47	43.42	0.4
Fe_2O_3	1.9	1.87	1.86	1.88	1.91	1.88	1.88	1.0
K_2O	0.43	0.4	0.39	0.39	0.39	0.39	0.40	4.0
MgO	2.19	1.93	1.9	1.91	1.91	1.91	1.96	5.8
Na_2O	0.04	0.03	0.05	0.05	0.05	0.05	0.05	18.6
Na_2O_{eq}	0.32	0.29	0.31	0.31	0.31	0.31	0.31	3.2
SiO_2	12.94	12.9	13.04	13.23	13.23	12.88	13.04	1.2
SO_3	0.22	0.21	0.21	0.22	0.23	0.24	0.22	5.3
LOI	36.62	36.35	36.08	36.02	35.99	36.2	36.21	0.7

Table B.5.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	**4.4**
CaO (wt. %)	68
Fe_2O_3 (wt. %)	3.0
K_2O (wt. %)	0.6
MgO (wt. %)	3.1
Na_2O (wt. %)	0.1
P_2O_5 (wt. %)	0.1
SiO_2 (wt. %)	20
SO_3 (wt. %)	0.4
TiO_2 (wt. %)	0.2
Moisture (wt. %)	0.3
LOI (wt. %)	32.7
As (ppm)	22.9
Ba (ppm)	NR
Cd (ppm)	ND
Cl (ppm)	84
Co (ppm)	11.4
Cr (ppm)	108
Cu (ppm)	17.8
Hg (ppm)	ND
Mn (ppm)	NR
Mo (ppm)	ND
Ni (ppm)	7.6
Pb (ppm)	3.8
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	NR
V (ppm)	70
Zn (ppm)	118

Notes: ND - Not Detected
NR - Not Reported

B.5.5. CHEMICAL COMPOSITION OF FUELS

Table B.5.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	Ash	18.78
	Fixed Carbon	53.85
	Volatile Matter	27.37
Ultimate Analysis	Carbon	70.28
	Hydrogen	4.29
	Nitrogen	1.38
	Oxygen	3.61
	Sulfur	2.6
Standard Parameters	Al_2O_3	24.03
	CaO	6.30
	Fe_2O_3	9.86
	K_2O	2.33
	MgO	1.10
	Na_2O	0.17
	SiO_2	48.1
	SO_3	6.51
Heat Value[1]		12169

Notes: [1] Value is Reported as BTU/lb

Table B.5.6: ELR - Proximate, Ultimate, and Combustion of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	17.65
	Fixed Carbon	53.61
	Volatile Matter	28.73
Ultimate Analysis	**Carbon**	69.84
	Hydrogen	3.59
	Nitrogen	0.59
	Oxygen	6.77
	Sulfur	1.55
Heat Value [1]		12431

Notes: [1] Value is Reported as BTU/lb

Table B.5.7: ELR - Standard Parameters of Coal

Property	**3-Day Composite**
Al_2O_3 (wt. %)	24.27
CaO (wt. %)	7.22
Fe_2O_3 (wt. %)	9.04
K_2O (wt. %)	2.40
MgO (wt. %)	1.08
Na_2O (wt. %)	0.17
P_2O_5 (wt. %)	0.18
SiO_2 (wt. %)	47.21
SO_3 (wt. %)	7.21
TiO_2 (wt. %)	1.03
As (ppm)	94
Ba (ppm)	NC
Cd (ppm)	< 3
Cl (ppm)	101
Co (ppm)	41
Cr (ppm)	114
Cu (ppm)	114
Hg (ppm)	0.17
Mn (ppm)	NC
Mo (ppm)	35
Ni (ppm)	86
Pb (ppm)	49
Sb (ppm)	NC
Se (ppm)	5
Sr (ppm)	NC
V (ppm)	213
Zn (ppm)	73

Notes: ND - Not Detected
NR - Not Reported

Table B.5.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	12.21
	Fixed Carbon	49.41
	Moisture [1]	0.09
	Volatile Matter	38.28
Ultimate Analysis	**Carbon**	78.98
	Hydrogen	5.44
	Nitrogen	0.06
	Oxygen	1.84
	Sulfur	1.47
Heat Value [2]		15501

Notes: [1] As Received

[2] Value is Reported as BTU/lb

Table B.5.9: ELR - Standard Parameters of Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	6.17
CaO (wt. %)	3.17
Fe_2O_3 (wt. %)	46.84
K_2O (wt. %)	0.29
MgO (wt. %)	0.03
Na_2O (wt. %)	0.63
P_2O_5 (wt. %)	0.21
SiO_2 (wt. %)	27.09
SO_3 (wt. %)	0.48
TiO_2 (wt. %)	6.82
As (ppm)	ND
Ba (ppm)	NR
Cd (ppm)	ND
Cl (ppm)	568
Co (ppm)	759
Cr (ppm)	56
Cu (ppm)	408
Hg (ppm)	0.2
Mn (ppm)	NR
Mo (ppm)	11
Ni (ppm)	70
Pb (ppm)	ND
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	NR
V (ppm)	214
Zn (ppm)	0

Notes: ND - Not Detected
NR - Not Reported

Table B.5.10: ELR - Proximate, Ultimate, and Combustion Analysis of Broiler Litter

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	20.61
	Fixed Carbon	33.75
	Moisture [1]	29.06
	Volatile Matter	45.64
Ultimate Analysis	**Carbon**	40.89
	Hydrogen	4.86
	Nitrogen	4.30
	Oxygen	28.66
	Sulfur	0.68
Heat Value [2]		6875

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.5.111: ELR - Standard Parameters of Broiler Litter

Property	3-Day Composite
Al_2O_3 (wt. %)	0.84
CaO (wt. %)	23.52
Fe_2O_3 (wt. %)	0.85
K_2O (wt. %)	20.44
MgO (wt. %)	7.73
Na_2O (wt. %)	7.02
P_2O_5 (wt. %)	24.54
SiO_2 (wt. %)	7.44
SO_3 (wt. %)	6.58
TiO_2 (wt. %)	0.07
As (ppm)	13
Ba (ppm)	468
Cd (ppm)	ND
Cl (ppm)	5843
Co (ppm)	3
Cr (ppm)	29
Cu (ppm)	2505
Hg (ppm)	0.2
Mn (ppm)	8870
Mo (ppm)	43
Ni (ppm)	44
Pb (ppm)	32
Sb (ppm)	NA
Se (ppm)	ND
Sr (ppm)	379
V (ppm)	18
Zn (ppm)	2685

Notes: ND - Not Detected
NR - Not Reported

Table B.5.12: AUR - Density of Broiler Litter

Sample #	Density (kg/m^3)
1	682.9
2	693.2
3	663.4
4	699.9
5	692.6
6	670.7
7	723.5
8	658.6
9	672.5
10	662.2
11	647.7
12	681.0
13	677.4
14	613.1
15	656.8
16	661.6
17	641.6
18	668.9
19	645.8
20	708.4
21	636.7
22	637.9
23	651.3
24	683.5
Average	**668.0**

B.5.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.5.13: CPR - Chemical Composition of Cement Kiln Dust

Property (wt. %)	6/19/2007			6/20/2007		6/21/2007		Average
	3:39 AM	9:22 AM	11:23 PM	7:56 AM	10:27 PM	6:47 AM	9:47 PM	
Al_2O_3	3.85	3.91	3.84	3.8	3.84	3.13	4.57	3.85
CaO	45.64	45.53	45.4	45.21	45.12	43.25	43.31	44.78
Fe_2O_3	1.83	1.85	1.86	1.84	1.91	1.9	2	1.88
K_2O	0.52	0.51	0.5	0.5	0.52	0.39	0.63	0.51
MgO	1.27	1.25	1.26	1.28	1.43	1.9	1.33	1.39
Na_2O	0.05	0.05	0.05	0.06	0.05	0.04	0.05	0.05
SiO_2	11.18	11.11	11.03	10.94	11.05	13.08	12.11	11.50
SO_3	0.21	0.23	0.25	0.25	0.27	0.24	0.47	0.27

Table B.5.14: ELR - Chemical Composition of Cement Kiln Dust

Property	6/19/2007		6/20/2007		6/21/2007		Average
	10:00 AM	10:00 PM	10:00 AM	10:00 PM	10:00 AM	10:00 PM	
Al_2O_3 (wt. %)	6.28	5.71	5.73	5.56	6.32	6.39	6.00
CaO (wt. %)	68.45	70.76	70.85	70.81	68.58	68.19	69.60
Fe_2O_3 (wt. %)	3.10	2.95	2.91	2.92	3.02	3.05	2.99
K_2O (wt. %)	0.90	0.76	0.76	0.77	0.91	0.93	0.84
MgO (wt. %)	2.04	2.13	2.15	2.41	2.06	2.14	2.16
Na_2O (wt. %)	0.11	0.08	0.09	0.06	0.07	0.09	0.08
P_2O_5 (wt. %)	0.10	0.08	0.09	0.07	0.09	0.09	0.09
SiO_2 (wt. %)	17.88	16.64	16.53	16.46	17.74	17.90	17.19
SO_3 (wt. %)	0.64	0.43	0.41	0.46	0.72	0.71	0.56
TiO_2 (wt. %)	0.32	0.29	0.31	0.27	0.32	0.33	0.31
Moisture (wt. %)	0.18	0.28	0.28	0.31	0.21	0.19	0.24
LOI (wt. %)	34.94	35.84	36.12	35.88	34.93	34.83	35.42
As (ppm)	36	35	32	23	42	31	33
Ba (ppm)	NR	NR	NR	NR	NR	NR	NA
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	955	198	191	185	1508	1369	734
Co (ppm)	12	13	17	14	14	17	15
Cr (ppm)	54	55	74	64	49	56	59
Cu (ppm)	70	29	42	22	30	17	35
Hg (ppm)	3.22	1.27	0.93	0.86	1.71	1.56	2
Mn (ppm)	NR	NR	NR	NR	NR	NR	NA
Mo (ppm)	4	ND	ND	2	ND	3	2
Ni (ppm)	20	13	13	12	18	13	15
Pb (ppm)	23	11	ND	21	ND	16	12
Sb (ppm)	NR	NR	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	NR	NR	NR	NR	NR	NR	NR
V (ppm)	77	80	76	70	73	77	75
Zn (ppm)	74	59	64	60	68	73	66

Notes: ND - Not Detected NR - Not Reported

B.5.7. CHEMICAL COMPOSITION OF CLINKER

Table B.5.15.a: CPR - Chemical Composition of Clinker for 6/19/2007

Property (wt. %)	6/19/2007							
	9:37 AM	12:05 PM	1:59 PM	4:07 PM	5:37 PM	7:58 PM	10:09 PM	11:39 PM
Al_2O_3	5.18	5.16	5.20	5.17	5.27	5.27	5.22	5.25
CaO	64.77	64.47	64.63	64.65	64.59	64.36	64.27	64.50
Fe_2O_3	3.16	3.13	3.06	3.18	3.18	3.10	3.08	3.23
K_2O	0.57	0.68	0.66	0.64	0.63	0.63	0.68	0.63
MgO	3.29	3.49	3.22	3.21	3.21	3.18	3.10	3.16
Na_2O	0.06	0.08	0.07	0.07	0.07	0.07	0.07	0.07
Na_2O_{eq}	0.44	0.53	0.50	0.49	0.48	0.48	0.52	0.48
SiO_2	21.48	21.25	21.41	21.37	21.46	21.38	21.20	21.41
SO_3	0.79	0.83	0.81	0.80	0.75	0.79	0.83	0.81
F CaO	0.86	1.45	1.50	1.40	1.50	1.24	1.45	0.81
C_3A	8.40	8.40	8.60	8.30	8.60	8.70	8.60	8.40
C_4AF	9.60	9.50	9.30	9.70	9.70	9.40	9.40	9.80
C_3S	61.10	61.80	61.10	61.50	59.90	59.70	61.10	60.00
C_2S	15.50	14.30	15.30	14.90	16.30	16.30	14.70	16.10

Table B.5.15.b: CPR - Chemical Composition of Clinker for 6/20/2007

Property (wt. %)	6/20/2007												
	1:39 AM	3:39 AM	4:55 AM	5:30 AM	7:56 AM	9:57 AM	12:09 PM	2:02 PM	3:55 PM	5:46 PM	7:54 PM	10:02 PM	11:44 PM
Al2O3	5.25	5.30	5.33	5.29	5.38	5.30	5.26	5.30	5.28	5.30	5.25	5.26	5.30
CaO	64.48	64.31	64.31	64.31	64.16	64.27	64.17	64.14	64.03	64.21	64.17	64.32	64.36
Fe2O3	3.11	3.14	3.25	3.04	3.17	3.09	3.21	3.17	3.23	3.06	3.01	3.04	3.10
K2O	0.62	0.68	0.63	0.65	0.65	0.64	0.70	0.70	0.66	0.63	0.59	0.62	0.59
MgO	3.18	3.11	3.15	3.15	3.17	3.17	3.19	3.17	3.10	3.18	3.13	3.19	3.18
Na2O	0.08	0.07	0.08	0.08	0.08	0.08	0.09	0.08	0.12	0.08	0.09	0.08	0.08
Na2Oeq	0.49	0.52	0.49	0.51	0.51	0.50	0.55	0.54	0.55	0.49	0.48	0.49	0.47
SiO2	21.47	21.45	21.48	21.58	21.58	21.68	21.67	21.61	21.49	21.63	21.66	21.69	21.68
SO3	0.84	0.78	0.79	0.78	0.79	0.79	0.74	0.93	0.84	0.81	0.78	0.79	0.73
F CaO	0.97	1.50		1.29	1.18	0.70	0.91	0.64	0.48	0.64	0.70	0.67	
C3A	8.70	8.70	8.60	8.90	8.90	8.80	8.50	8.70	8.50	8.90	8.80	8.80	8.80
C4AF	9.50	9.60	9.90	9.30	9.60	9.40	9.80	9.60	9.80	9.30	9.20	9.30	9.40
C3S	59.60	58.70	58.10	57.90	56.50	56.90	56.60	56.70	57.30	57.00	57.00	57.30	57.20
C2S	16.60	17.20	17.70	18.20	19.20	19.30	19.40	19.20	18.40	19.00	19.10	18.90	19.00

Table B.5.15.c: CPR - Chemical Composition of Clinker for 6/21/2007

Property (wt. %)	6/21/2007											
	3:48 AM	5:44 AM	8:02 AM	10:02 AM	11:36 AM	1:29 PM	2:18 PM	3:51 PM	5:33 PM	7:54 PM	9:46 PM	11:57 PM
Al_2O_3	5.33	5.33	5.34	5.38	4.78	5.34	5.27	5.32	5.39	5.34	5.31	5.3
CaO	64.35	64.34	64.24	64.31	62.23	64.32	64.45	64.41	64.34	64.44	64.4	64.4
Fe_2O_3	3.13	3.12	3.18	3.21	2.79	3.14	3.08	3.11	3.18	3.17	3.15	3.22
K_2O	0.58	0.60	0.64	0.59	0.64	0.62	0.62	0.6	0.58	0.65	0.66	0.63
MgO	3.16	3.17	3.17	3.16	2.62	3.17	3.16	3.18	3.19	3.26	3.21	3.26
Na_2O	0.07	0.08	0.08	0.07	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Na_2O_{eq}	0.45	0.47	0.50	0.46	0.5	0.49	0.49	0.47	0.46	0.51	0.51	0.49
SiO_2	21.61	21.59	21.48	21.55	20.04	21.53	21.58	21.57	21.51	21.48	21.47	21.41
SO_3	0.76	0.73	0.75	0.74	0.82	0.76	0.71	0.78	0.78	0.83	0.87	0.79
FCaO	0.54	0.59	1.03	1.07	0.7		0.75	0.86	1.13	0.97	0.54	0.54
C_3A	8.80	8.80	8.80	8.8	7.9	8.8	8.8	8.8	8.9	8.8	8.7	8.6
C_4AF	9.50	9.50	9.70	9.8	8.5	9.6	9.4	9.5	9.7	9.6	9.6	9.8
C_3S	57.50	57.60	57.90	57.3	64.9	57.9	58.6	58.1	57.7	58.7	58.8	59.2
C_2S	18.60	18.50	17.90	18.6	8.5	18.1	17.7	18	18.1	17.3	17.2	16.7

Table B.5.15.d: CPR - Chemical Composition of Clinker for 6/22/2007

Property (wt. %)	6/22/2007				Average wt %	C.V. (%)	Normality P-Value[1]
	1:55 AM	4:07 AM	5:28 AM	8:14 AM			
Al_2O_3	5.28	5.28	5.24	5.3	5.27	1.9	0.416
CaO	64.47	64.44	64.51	64.62	64.32	0.6	<0.005
Fe_2O_3	3.18	3.14	3.09	3.08	3.13	2.6	0.542
K_2O	0.62	0.58	0.59	0.63	0.63	5.4	0.077
MgO	3.29	3.23	3.27	3.21	3.18	3.7	0.612
Na_2O	0.08	0.08	0.07	0.08	0.08	11.8	<0.005
Na_2O_{eq}	0.49	0.46	0.46	0.49	0.49	5.3	0.413
SiO_2	21.3	21.36	21.34	21.15	21.45	1.3	0.323
SO_3	0.77	0.8	0.78	0.84	0.79	5.4	0.202
FCaO	1.45	0.81	1.18	1.29	0.98	34.2	0.374
C_3A	8.6	8.7	8.7	8.8	8.67	2.3	0.721
C_4AF	9.7	9.6	9.4	9.4	9.52	2.6	<0.005
C_3S	60.6	60	60.8	62.3	58.94	3.3	0.033
C_2S	15.4	15.9	15.3	13.6	17.03	12.7	0.807

Notes: [1] Based on Anderson-Darling Normality Test

Table B.5.16: ELR - Chemical Composition of Clinker

Property	6/19/2007		620/2007		6/21/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	5.00	5.13	5.05	5.11	5.05	5.06	5.06
CaO (wt. %)	64.73	64.25	64.90	64.65	64.87	65.01	64.73
Fe_2O_3 (wt. %)	2.77	2.96	2.92	3.00	2.96	2.99	2.93
K_2O (wt. %)	0.69	0.70	0.65	0.64	0.67	0.62	0.66
MgO (wt. %)	3.33	3.26	3.42	3.38	3.33	3.34	3.34
Na_2O (wt. %)	0.08	0.07	0.08	0.08	0.10	0.07	0.08
P_2O_5 (wt. %)	0.10	0.10	0.11	0.11	0.11	0.11	0.10
SiO_2 (wt. %)	22.01	22.20	21.57	21.79	21.64	21.59	21.80
SO_3 (wt. %)	0.83	0.86	0.81	0.78	0.82	0.76	0.81
TiO_2 (wt. %)	0.26	0.23	0.25	0.23	0.24	0.23	0.24
Moisture (wt. %)	0.07	0.12	0.04	0.04	0.04	0.03	0.06
LOI (wt. %)	0.35	0.24	0.32	0.29	0.49	0.30	0.33
As (ppm)	19	19	27	21	27	24	23
Ba (ppm)	NR	NR	NR	NR	NR	NR	NA
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	288	266	214	311	455	286	303
Co (ppm)	14	11	14	8	7	8	10
Cr (ppm)	100	89	106	99	85	77	93
Cu (ppm)	16	69	29	16	30	15	29
Hg (ppm)	ND	ND	ND	ND	ND	ND	ND
Mn (ppm)	NR	NR	NR	NR	NR	NR	NR
Mo (ppm)	ND	7	1	6	ND	4	3
Ni (ppm)	19	12	17	9	11	9	13
Pb (ppm)	20	20	ND	11	ND	9	10
Sb (ppm)	NR	NR	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	ND	3	0.5
Sr (ppm)	NR	NR	NR	NR	NR	NR	NA
V (ppm)	71	63	72	69	62	64	67
Zn (ppm)	107	103	100	102	92	90	99

Notes: ND - Not Detected NR - Not Reported

B.5.8. CHEMICAL COMPOSITION OF CEMENT

Table B.5.17: CPR - Chemical Composition of Cement

Property (wt. %)	6/25/2007					6/26/2007				Average	C. V. (%)	Normality P-Value[1]
	10:01 AM	12:32 PM	3:41 PM	6:37 PM	9:48 PM	1:09 AM	2:12 AM	3:58 AM	6:40 AM			
Al_2O_3	4.89	4.89	4.91	4.91	4.86	4.86	4.86	4.86	4.83	4.87	0.6	0.045
CaO	62.31	62.3	62.07	62.44	62.21	62.39	62.28	62.11	61.05	62.13	0.7	0.305
Fe_2O_3	2.92	2.94	2.93	2.97	2.95	2.97	2.94	2.96	2.92	2.94	0.7	0.315
K_2O	0.54	0.51	0.5	0.47	0.47	0.46	0.45	0.46	0.45	0.48	6.5	<0.005
MgO	3.13	3.14	3.19	3.26	3.26	3.28	3.27	3.26	3.21	3.22	1.8	0.025
Na_2O	0.09	0.09	0.1	0.1	0.09	0.1	0.08	0.09	0.08	0.09	8.6	<0.005
Na_2O_{eq}	0.45	0.43	0.43	0.4	0.4	0.4	0.38	0.39	0.38	0.41	6.0	<0.005
SiO_2	20.26	20.2	20.23	20.35	20.38	20.59	20.49	20.54	20.44	20.39	0.7	0.464
SO_3	2.59	2.6	2.54	2.51	2.65	2.55	2.57	2.59	2.52	2.57	1.7	0.065
F CaO	1.56	1.18	1.13	1.02	0.91	0.91		1.02	0.84	1.07	21.3	0.381
LOI	0.79	1.02	1.03	0.85	0.73	0.79		0.94	0.94	0.89	12.7	<0.005
C_3A	8	8	8.1	8	7.9	7.9	7.9	7.9	7.9	7.96	0.9	0.738
C_4AF	8.9	9	8.9	9	9	9	8.9	9	8.9	8.96	0.6	0.380
C_3S	55.3	55.6	54.5	55.1	53.9	53.3	53.6	52.5	49.4	53.69	3.5	0.201
C_2S	16.4	16	16.9	16.8	17.7	18.8	18.3	19.3	21.4	17.96	9.5	0.200
Blaine SSA (m^2/kg)	389	377	385	365	365	338	343	368	366	366	4.7	<0.005

Notes: [1] Based on Anderson-Darling Normality Test

Table B.5.18: ELR - Chemical Composition of Cement

Property	1	2	3	Average
Al_2O_3 (wt. %)	4.99	4.85	4.90	4.92
CaO (wt. %)	63.77	63.99	63.61	63.79
Fe_2O_3 (wt. %)	2.91	2.87	2.79	2.86
K_2O (wt. %)	0.59	0.63	0.62	0.61
MgO (wt. %)	3.35	3.32	3.21	3.29
Na_2O (wt. %)	0.08	0.15	0.12	0.12
P_2O_5 (wt. %)	0.10	0.10	0.10	0.10
SiO_2 (wt. %)	21.10	20.91	21.46	21.16
SO_3 (wt. %)	2.62	2.70	2.75	2.69
TiO_2 (wt. %)	0.22	0.23	0.22	0.22
Moisture (wt. %)	0.00	0.00	0.00	0.00
LOI (wt. %)	0.89	0.98	0.90	0.92
C_3S (wt. %)	54.04	57.20	51.12	54.12
C_2S (wt. %)	19.73	16.80	22.95	19.83
C_3A (wt. %)	8.29	7.99	8.28	8.19
C_4AF (wt. %)	8.87	8.74	8.49	8.70
TOC (wt. %)	ND	ND	ND	ND
As (ppm)	14	20	19	17
Ba (ppm)	400	500	300	400
Cd (ppm)	ND	ND	ND	ND
Cl (ppm)	111	163	140	138
Co (ppm)	13	8	14	12
Cr (ppm)	96	88	87	90
Cu (ppm)	14	5	9	9
Hg (ppm)	2.00	1.10	0.70	1.27
Mn (ppm)	1650	1690	1390	1577
Mo (ppm)	5	ND	3	3.93
Ni (ppm)	12	7	10	10
Pb (ppm)	23	7	15	15
Sb (ppm)	500	500	500	500
Se (ppm)	ND	ND	ND	ND
Sr (ppm)	NR	NR	NR	NR
V (ppm)	69	69	62	66
Zn (ppm)	84	85	97	89

Notes: ND - Not Detected NR - Not Reported

B.5.9. PHYSICAL PROPERTIES OF CEMENT

Table B.5.19: CPR - Physical Properties of Cement

Property	CPR
Air in Mortar (%)	6.6
Blaine Specific Surface Area (m^2/kg)	367
Autoclave Expansion (% Exp.)	0.15
Cube Flow (%)	127.0
Comp Str 1day (MPa)	14.9
Comp Str 3day (MPa)	23.5
Comp Str 7day (MPa)	31.1
Comp Str 28day (MPa)	42.0
Normal Consistency (%)	25.7
Gillmore Initial Set (Min)	131
Gillmore Final Set (Min)	225
Vicat Initial Set (Min)	74
Vicat Final Set (Min)	199

Notes: % Exp. - Percent Expansion

Table B.5.20: AUR - Physical Properties of Cement

Property	AUR
Autoclave Expansion (% Exp.)	0.06
Cube Flow (%)	101
Comp Str 1day (MPa)	12
Comp Str 3day (MPa)	21.5
Comp Str 7day (MPa)	26.5
Comp Str 28day (MPa)	32.9
Normal Consistency (%)	26.2
Gillmore Initial Set (Min)	102
Gillmore Final Set (Min)	202
Vicat Initial Set (Min)	75
Vicat Final Set (Min)	180
Drying Shrinkage @ 7 days (% LC)	-0.035
Drying Shrinkage @ 14 days (% LC)	-0.073
Drying Shrinkage @ 21 days (% LC)	-0.080
Drying Shrinkage @ 28 days (% LC)	-0.082

Notes: % LC - Percent Length Change
% Exp. - Percent Expansion

B.5.10. PROPERTIES OF CONCRETE

Table B.5.21: Concrete Properties

Property	AUR		CPR
	Mix w/c=0.44	Mix w/c=0.37	Mix w/c=0.44
Total Air Content (%)	3.5	5.0	3.4
Slump (mm)	50	130	40
Unit Weight (kg/m^3)	2460	2410	2448
Initial Set (Min.)	154	199	NC
Final Set (Min.)	231	262	273.0
Compressive Strength (MPa)			
1 day	16.8	29.9	6.1
3 days	25.1	34.8	23.1
7 days	34.7	45.2	30.9
28 days	42.5	52.7	43.8
91 days	49.6	59.0	49.8
Splitting Tensile Strength (MPa)			
1 day	2.2	3.0	NC
3 days	2.8	3.1	NC
7 days	3.3	3.4	NC
28 days	3.9	4.0	NC
91 days	4.2	4.3	NC
Drying Shrinkage Development (% Length Change) [1]			
4 days	0.010	0.010	NC
7 days	0.013	0.016	NC
14 days	0.020	0.022	NC
28 days	0.028	0.033	NC
56 days	0.034	0.039	NC
112 days	0.043	0.043	NC
224 days	0.048	0.046	NC
448 days	CIP	CIP	NC
Permeability @ 91 days (Coulombs)	2730	2700	2500

Notes: CIP - Collection in Progress NC - Not Collected [1] Percentage decrease in length

B.5.11. EMISSIONS

Table B.5.22.a: CPR – Emissions for 6/19/2007 – 6/20/2007

Time	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
6/19/2007 9:00	8.41E-04	2.52E-07	2.15E-05	4.28E-04
6/19/2007 10:00	6.85E-04	3.84E-07	2.05E-05	4.02E-04
6/19/2007 11:00	7.45E-04	4.04E-07	2.18E-05	4.49E-04
6/19/2007 12:00	8.79E-04	5.00E-07	2.50E-05	4.69E-04
6/19/2007 13:00	8.31E-04	4.79E-07	3.00E-05	4.45E-04
6/19/2007 14:00	7.69E-04	3.16E-07	2.51E-05	4.48E-04
6/19/2007 15:00	8.71E-04	2.07E-07	2.29E-05	5.14E-04
6/19/2007 16:00	8.13E-04	1.77E-07	2.15E-05	4.48E-04
6/19/2007 17:00	8.78E-04	5.25E-07	2.68E-05	4.82E-04
6/19/2007 18:00	8.15E-04	3.66E-07	2.88E-05	4.92E-04
6/19/2007 19:00	8.13E-04	5.36E-07	3.03E-05	5.12E-04
6/19/2007 20:00	7.09E-04	3.52E-07	3.36E-05	5.87E-04
6/19/2007 21:00	6.82E-04	2.73E-07	2.42E-05	4.72E-04
6/19/2007 22:00	8.01E-04	4.28E-07	2.78E-05	4.78E-04
6/19/2007 23:00	8.77E-04	6.01E-07	3.15E-05	4.79E-04
6/20/2007 0:00	8.32E-04	1.43E-07	3.94E-05	6.31E-04
6/20/2007 1:00	7.44E-04	2.58E-07	3.54E-05	5.15E-04
6/20/2007 2:00	8.03E-04	1.86E-07	3.40E-05	4.30E-04
6/20/2007 3:00	8.47E-04	2.04E-07	3.34E-05	4.12E-04
6/20/2007 4:00	8.06E-04	2.40E-07	3.07E-05	4.17E-04
6/20/2007 5:00	8.11E-04	1.88E-07	2.93E-05	4.54E-04
6/20/2007 6:00	8.56E-04	3.26E-07	2.74E-05	4.54E-04
6/20/2007 7:00	7.41E-04	2.46E-07	2.65E-05	4.74E-04
6/20/2007 8:00	7.49E-04	1.38E-06	2.29E-05	5.13E-04
6/20/2007 9:00	7.02E-04	1.66E-06	2.14E-05	5.17E-04
6/20/2007 10:00	8.07E-04	1.76E-06	2.21E-05	5.62E-04
6/20/2007 11:00	9.02E-04	1.55E-06	2.37E-05	5.61E-04
6/20/2007 12:00	8.24E-04	1.77E-06	2.74E-05	5.35E-04
6/20/2007 13:00	6.86E-04	2.72E-06	3.14E-05	5.04E-04
6/20/2007 14:00	6.64E-04	1.81E-06	3.34E-05	4.80E-04
6/20/2007 15:00	7.25E-04	1.41E-06	3.46E-05	4.83E-04
6/20/2007 16:00	7.95E-04	1.99E-06	3.49E-05	5.36E-04
6/20/2007 17:00	7.45E-04	2.43E-06	3.36E-05	5.24E-04
6/20/2007 18:00	8.83E-04	2.39E-06	3.34E-05	5.70E-04
6/20/2007 19:00	8.27E-04	1.96E-06	2.93E-05	5.01E-04
6/20/2007 20:00	8.05E-04	1.36E-06	2.95E-05	4.73E-04
6/20/2007 21:00	6.98E-04	1.35E-06	2.94E-05	4.64E-04
6/20/2007 22:00	7.77E-04	1.41E-06	3.04E-05	4.97E-04
6/20/2007 23:00	8.06E-04	1.68E-06	2.68E-05	5.48E-04

Table B.5.22.b: CPR – Emissions for 6/21/2007 – 6/22/2007

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
6/21/2007 0:00	7.24E-04	1.43E-06	2.33E-05	4.56E-04
6/21/2007 1:00	7.09E-04	1.30E-06	2.38E-05	5.15E-04
6/21/2007 2:00	7.16E-04	1.12E-06	2.65E-05	5.02E-04
6/21/2007 3:00	7.36E-04	1.82E-06	2.12E-05	5.36E-04
6/21/2007 4:00	6.77E-04	4.47E-06	1.63E-05	5.75E-04
6/21/2007 5:00	6.38E-04	2.74E-06	1.90E-05	4.46E-04
6/21/2007 6:00	7.31E-04	3.41E-06	1.76E-05	4.88E-04
6/21/2007 7:00	7.61E-04	6.58E-06	1.81E-05	4.94E-04
6/21/2007 8:00	8.27E-04	3.98E-06	1.64E-05	5.17E-04
6/21/2007 9:00	9.22E-04	2.18E-05	1.93E-05	5.58E-04
6/21/2007 10:00	1.07E-03	5.03E-05	2.60E-05	5.62E-04
6/21/2007 11:00	8.60E-04	3.35E-05	3.08E-05	5.59E-04
6/21/2007 12:00	8.29E-04	2.63E-05	4.26E-05	5.35E-04
6/21/2007 13:00	7.02E-04	2.04E-05	6.25E-05	6.23E-04
6/21/2007 14:00	9.73E-04	1.84E-05	6.45E-05	5.72E-04
6/21/2007 15:00	9.56E-04	5.72E-05	7.72E-05	5.54E-04
6/21/2007 16:00	7.26E-04	2.81E-05	8.03E-05	5.69E-04
6/21/2007 17:00	8.85E-04	2.40E-05	8.26E-05	5.42E-04
6/21/2007 18:00	8.35E-04	1.35E-05	7.51E-05	5.11E-04
6/21/2007 19:00	9.00E-04	9.63E-06	5.95E-05	5.36E-04
6/21/2007 20:00	9.41E-04	3.67E-05	8.11E-05	5.00E-04
6/21/2007 21:00	8.98E-04	2.72E-05	8.72E-05	4.62E-04
6/21/2007 22:00	9.05E-04	2.19E-06	5.86E-05	5.33E-04
6/21/2007 23:00	8.71E-04	2.06E-06	5.01E-05	4.70E-04
6/22/2007 0:00	7.70E-04	1.73E-06	3.78E-05	4.56E-04
6/22/2007 1:00	7.87E-04	1.70E-06	3.82E-05	4.46E-04
6/22/2007 2:00	8.07E-04	1.13E-06	4.95E-05	4.38E-04
6/22/2007 3:00	7.95E-04	9.00E-07	4.45E-05	4.31E-04
6/22/2007 4:00	8.18E-04	1.54E-06	4.33E-05	4.18E-04
6/22/2007 5:00	9.55E-04	1.98E-06	5.11E-05	4.60E-04
6/22/2007 6:00	9.88E-04	1.37E-06	4.47E-05	5.31E-04
6/22/2007 7:00	9.74E-04	1.60E-06	2.76E-05	5.67E-04
6/22/2007 8:00	9.70E-04	3.92E-06	2.78E-05	5.37E-04
Average	8.13E-04	6.25E-06	3.55E-05	5.01E-04
C. V. (%)	11.0	189.5	48.9	10.2
Normality P-Value[1]	0.269	<0.005	<0.005	0.378

Notes: [1] Based on Anderson Darling Normality Test NC - Not Collected

APPENDIX B.6

RAW DATA FOR *CT3 BURN*

B.6.1. GENERAL COMMENTS

- The raw data from the CT3 burn are presented in this appendix.
- Coal and scrap tires are the fuels used in the burn.
- The burn lasted from 9 AM on August 13, 2007 to 9 AM on August 16, 2007.
- Cement and concrete results not collected for the burn.

B.6.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.6.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.6.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	21.90	0.85	NR	10.60	10.60	0.78
CaO	7.23	52.60	NR	33.90	33.90	41.00
Fe_2O_3	3.79	NR	NR	14.20	14.20	NR
K_2O	1.87	0.10	NR	0.05	0.05	0.12
MgO	1.46	1.80	NR	12.20	12.20	0.58
Na_2O	0.30	NR	NR	NR	NR	NR
SiO_2	52.20	2.12	NR	23.30	23.30	3.21
SO_3	0.65	0.11	NR	0.94	0.94	46.90
Moisture	13.20	3.60	NR	7.20	7.20	25.30
LOI	8.60	42.40	NR	2.20	2.20	7.30

Notes: NR - Not Reported

Table B.6.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	26.84	0.63	4.72	6.77	0.50	0.85
CaO (wt. %)	3.00	94.36	64.97	31.36	0.35	40.41
Fe_2O_3 (wt. %)	12.12	0.27	2.65	29.08	0.42	0.38
K_2O (wt. %)	2.54	0.11	0.46	0.06	0.10	0.15
MgO (wt. %)	1.45	2.02	1.76	13.77	0.16	0.55
Na_2O (wt. %)	0.49	0.12	0.13	0.01	0.02	0.06
P_2O_5 (wt. %)	0.61	0.00	0.05	0.50	0.00	0.01
SiO_2 (wt. %)	50.92	2.27	24.62	13.55	98.21	4.47
SO_3 (wt. %)	0.26	0.14	0.24	0.56	0.00	52.97
TiO_2 (wt. %)	1.31	0.00	0.29	0.30	0.19	0.02
Moisture (wt. %)	15.83	2.37	1.98	4.35	4.33	9.00
LOI (wt. %)	9.41	43.42	35.36	2.59	0.21	13.76
As (ppm)	165	ND	16	7	ND	ND
Ba (ppm)	2095	204	289	191	196	199
Cd (ppm)	ND	ND	ND	ND	ND	ND
Cl (ppm)	91	35	37	133	12	19
Co (ppm)	64	4	8	15	ND	ND
Cr (ppm)	170	24	42	2188	5	10
Cu (ppm)	146	46	39	16	78	14
Hg (ppm)	3.42	1.92	1.31	0.96	0.68	0.52
Mn (ppm)	698	102	289	39916	295	100
Mo (ppm)	17	ND	2	45	ND	ND
Ni (ppm)	114	26	13	53	9	ND
Pb (ppm)	58	ND	10	ND	14	ND
Sb (ppm)	NR	NR	NR	NR	NR	NR
Se (ppm)	2	ND	ND	4	ND	ND
Sr (ppm)	1896	510	481	286	98	1095
V (ppm)	314	34	54	678	16	12
Zn (ppm)	146	9	67	164	13	ND

Notes: ND - Not Detected NR- Not Reported

B.6.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.6.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	8/13/2007		8/14/2007		8/15/2007		8/16/2007	Average	C. V. (%)
	2:05 AM	2:08 PM	1:29 AM	2:00 PM	2:05 AM	1:47 PM	2:06 AM		
Al_2O_3	2.99	2.94	3.04	2.92	2.95	2.88	3.08	2.97	2.4
CaO	43.44	43.53	43.57	43.68	42.91	43.37	43.34	43.41	0.6
Fe_2O_3	1.85	1.93	1.96	2.03	2.01	2.02	2.08	1.98	3.8
K_2O	0.31	0.27	0.29	0.29	0.27	0.27	0.3	0.29	5.7
MgO	1.87	1.91	1.9	1.94	1.89	1.93	2.1	1.93	4.0
Na_2O	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.0
Na_2O_{eq}	0.23	0.21	0.22	0.29	0.21	0.21	0.23	0.23	12.5
SiO_2	13.16	13.32	13.23	13.07	12.96	12.89	13	13.09	1.2
SO_3	0.22	0.25	0.26	0.27	0.26	0.27	0.28	0.26	7.5
LOI	35.31	34.97	35	35	35	35	35	35.04	0.3

Notes: NR - Not Reported NA - Not Applicable

Table B.6.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	4.46
CaO (wt. %)	63.62
Fe_2O_3 (wt. %)	3.03
K_2O (wt. %)	0.42
MgO (wt. %)	3.41
Na_2O (wt. %)	0.08
P_2O_5 (wt. %)	0.07
SiO_2 (wt. %)	23.84
SO_3 (wt. %)	0.53
TiO_2 (wt. %)	0.27
Moisture (wt. %)	0.14
LOI (wt. %)	34.70
As (ppm)	23
Ba (ppm)	295
Cd (ppm)	ND
Cl (ppm)	105
Co (ppm)	10
Cr (ppm)	106
Cu (ppm)	56
Hg (ppm)	0.53
Mn (ppm)	1969
Mo (ppm)	ND
Ni (ppm)	16
Pb (ppm)	17
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	492
V (ppm)	72
Zn (ppm)	300

Notes: NR - Not Reported
ND - Not Detected

B.6.5. CHEMICAL COMPOSITION OF FUELS

Table B.6.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	23.28
	Fixed Carbon	55.74
	Volatile Matter	26.00
Ultimate Analysis	**Carbon**	59.85
	Hydrogen	4.06
	Nitrogen	1.27
	Oxygen	3.32
	Sulfur	2.56
Standard Parameters	**Al_2O_3**	23.26
	CaO	6.94
	Fe_2O_3	7.66
	K_2O	2.81
	MgO	1.12
	Na_2O	0.14
	SiO_2	50.31
	SO_3	6.41
Heat Value [1]		11481

Notes: [1] Value is Reported as BTU/lb

Table B.6.6: ELR - Proximate, Ultimate, and Combustion Analysis of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	26.20
	Fixed Carbon	47.39
	Volatile Matter	26.41
Ultimate Analysis	**Carbon**	63.96
	Hydrogen	3.57
	Nitrogen	1.45
	Oxygen	3.55
	Sulfur	1.27
Heat Value [1]		11,204

Notes: [1] Value is Reported as BTU/lb

Table B.6.7: ELR - Standard Parameters of Coal

Property	**3-Day Composite**
Al_2O_3 (wt. %)	25.24
CaO (wt. %)	4.74
Fe_2O_3 (wt. %)	6.56
K_2O (wt. %)	3.25
MgO (wt. %)	1.34
Na_2O (wt. %)	0.17
P_2O_5 (wt. %)	0.14
SiO_2 (wt. %)	53.36
SO_3 (wt. %)	3.97
TiO_2 (wt. %)	3.97
As (ppm)	72
Ba (ppm)	1100
Cd (ppm)	ND
Cl (ppm)	89
Co (ppm)	29
Cr (ppm)	109
Cu (ppm)	81
Hg (ppm)	0.150
Mn (ppm)	300
Mo (ppm)	24
Ni (ppm)	68
Pb (ppm)	43
Sb (ppm)	NC
Se (ppm)	7
Sr (ppm)	500
V (ppm)	226
Zn (ppm)	81

Notes: NR - Not Reported
ND - Not Detected

Table B.6.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	18.90
	Fixed Carbon	41.88
	Moisture [1]	0.07
	Volatile Matter	39.15
Ultimate Analysis	**Carbon**	69.49
	Hydrogen	4.96
	Nitrogen	1.74
	Oxygen	3.15
	Sulfur	1.77
Heat Value [2]		14972

Notes: [1] As Received

[2] Value is Reported as BTU/lb

Table B.6.9: ELR - Standard Parameters for Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	0.16
CaO (wt. %)	1.61
Fe_2O_3 (wt. %)	85.88
K_2O (wt. %)	0.19
MgO (wt. %)	0.08
Na_2O (wt. %)	0.21
P_2O_5 (wt. %)	0.07
SiO_2 (wt. %)	2.76
SO_3 (wt. %)	0.30
TiO_2 (wt. %)	0.34
As (ppm)	4
Ba (ppm)	0
Cd (ppm)	ND
Cl (ppm)	946
Co (ppm)	1191
Cr (ppm)	260
Cu (ppm)	1068
Hg (ppm)	ND
Mn (ppm)	3900
Mo (ppm)	21
Ni (ppm)	215
Pb (ppm)	10
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	0
V (ppm)	20
Zn (ppm)	0

Notes: NR - Not Reported
ND - Not Detected

B.6.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.6.10: CPR - Chemical Composition of Cement Kiln Dust (CKD)

Property (wt. %)	8/13/07			8/14/07		8/15/07		8/16/07	Average
	8:53 AM	9:34 AM	7:27 PM	7:18 AM	8:33 PM	8:13 AM	6:48 PM	6:33 AM	
Al_2O_3	3.58	3.65	3.93	3.63	3.91	3.73	4	3.76	3.77
CaO	46.3	46.26	44.95	45.61	44.96	45.32	45.03	45.48	45.49
Fe_2O_3	1.8	1.83	1.91	1.81	1.95	1.91	1.97	1.91	1.89
K_2O	0.35	0.35	0.38	0.35	0.41	0.39	0.42	0.41	0.38
MgO	1.17	1.19	1.23	1.22	1.33	1.38	1.37	1.4	1.29
Na_2O	0.07	0.06	0.08	0.08	0.07	0.08	0.06	0.05	0.07
SiO_2	10.62	10.76	11.54	10.68	11.38	11.07	11.38	11.04	11.06
SO_3	0.25	0.25	0.3	0.3	0.27	0.27	0.32	0.39	0.29

Table B.6.11: ELR - Chemical Composition of Cement Kiln Dust

Property	8/13/2007		8/14/2007		8/15/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	5.94	5.44	5.61	6.02	5.71	5.75	5.75
CaO (wt. %)	68.66	69.77	70.12	68.79	69.70	69.69	69.46
Fe_2O_3 (wt. %)	2.89	2.68	2.75	2.95	2.91	2.91	2.85
K_2O (wt. %)	0.55	0.50	0.48	0.60	0.57	0.57	0.55
MgO (wt. %)	2.09	2.06	2.17	2.23	2.31	2.35	2.20
Na_2O (wt. %)	0.08	0.08	0.08	0.10	0.08	0.08	0.08
P_2O_5 (wt. %)	0.10	0.09	0.10	0.09	0.09	0.09	0.09
SiO_2 (wt. %)	18.50	16.69	17.54	18.10	17.56	17.30	17.61
SO_3 (wt. %)	0.63	2.19	0.59	0.58	0.57	0.77	0.89
TiO_2 (wt. %)	0.35	0.32	0.34	0.34	0.32	0.32	0.33
Moisture (wt. %)	0.21	0.17	0.17	0.18	0.15	0.16	0.17
LOI (wt. %)	35.72	36.33	36.19	35.73	36.05	36.33	36.06
As (ppm)	24	28	27	27	27	33	27
Ba (ppm)	494	297	395	394	393	395	394
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	152	164	129	133	168	182	155
Co (ppm)	8	9	13	8	10	13	10
Cr (ppm)	66	64	83	54	70	60	66
Cu (ppm)	43	22	39	19	45	19	31
Hg (ppm)	0.60	0.63	0.53	0.59	0.53	0.62	0.6
Mn (ppm)	987	990	1085	985	982	986	1003
Mo (ppm)	2	ND	ND	ND	3	1	1
Ni (ppm)	14	11	18	16	11	13	14
Pb (ppm)	8	18	18	38	18	4	17
Sb (ppm)	NR	NR	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	592	594	592	591	589	592	592
V (ppm)	75	73	76	78	75	73	75
Zn (ppm)	260	245	237	187	169	192	215

Notes: ND - Not Detected NR - Not Reported NA - Not Applicable

B.6.7. CHEMICAL COMPOSITION OF CLINKER

Table B.6.12.a: CPR - Chemical Composition of Clinker for 8/13/2007

Property (wt. %)	8/13/07												
	2:04 AM	4:08 AM	5:27 AM	8:01 AM	10:05 AM	11:53 AM	1:25 PM	2:08 PM	4:03 PM	5:30 PM	7:28 PM	9:38 PM	11:38 PM
Al_2O_3	5.08	5.36	5.34	4.95	5.25	5.28	5.39	4.98	5.47	5.53	5.33	5.38	5.45
CaO	64.84	64.46	64.65	63.36	64.59	64.50	64.31	63.32	64.27	64.33	64.48	64.52	64.29
Fe_2O_3	3.13	3.17	3.19	2.85	3.20	3.34	3.26	2.91	3.39	3.41	3.31	3.34	3.41
K_2O	0.57	0.52	0.57	0.52	0.50	0.52	0.52	0.50	0.51	0.51	0.52	0.50	0.52
MgO	3.37	3.29	3.40	2.90	3.37	3.36	3.35	2.94	3.42	3.33	3.35	3.31	3.25
Na_2O	0.07	0.07	0.08	0.08	0.07	0.08	0.10	0.09	0.09	0.09	0.08	0.09	0.10
Na_2O_{eq}	0.45	0.42	0.45	0.42	0.41	0.43	0.44	0.42	0.42	0.42	0.42	0.42	0.45
SiO_2	21.40	21.20	21.33	20.80	21.66	21.59	21.55	20.61	21.54	21.47	21.48	21.31	21.32
SO_3	0.78	0.75	0.75	0.78	0.68	0.72	0.78	0.81	0.77	0.72	0.65	0.74	0.76
F CaO	1.21	1.09	1.33	0.36	0.54	1.75	1.39	1.09	0.79	1.27	1.39	1.15	1.15
C_3A	8.20	8.80	8.70	8.30	8.50	8.40	8.80	8.30	8.80	8.90	8.50	8.60	8.70
C_4AF	9.50	9.60	9.70	8.70	9.70	10.10	9.90	8.90	10.30	10.40	10.10	10.10	10.40
C_3S	62.70	60.70	60.70	62.50	58.50	58.20	57.10	63.50	56.30	56.70	58.70	59.80	58.20
C_2S	14.10	15.00	15.40	12.50	17.90	18.00	18.70	11.20	19.30	18.80	17.30	16.00	17.20

Table B.6.12.b: CPR - Chemical Composition of Clinker for 8/14/2007

Property (wt. %)	8/14/07											
	1:33 AM	3:40 AM	5:38 AM	7:53 AM	10:00 AM	11:52 AM	2:01 PM	4:00 PM	5:38 PM	8:03 PM	10:07 PM	11:42 PM
Al_2O_3	5.37	5.35	5.25	5.28	5.20	5.36	5.33	5.23	5.36	5.37	5.39	5.33
CaO	64.59	64.64	64.62	64.59	64.64	64.40	64.46	64.50	64.47	64.44	64.48	64.37
Fe_2O_3	3.35	3.38	3.34	3.42	3.39	3.45	3.49	3.44	3.50	3.49	3.46	3.46
K_2O	0.50	0.49	0.50	0.47	0.51	0.49	0.49	0.49	0.50	0.52	0.52	0.54
MgO	3.30	3.29	3.29	3.22	3.32	3.26	3.24	3.28	3.27	3.28	3.28	3.29
Na_2O	0.08	0.09	0.10	0.10	0.09	0.10	0.09	0.09	0.09	0.09	0.08	0.10
Na_2O_{eq}	0.41	0.41	0.42	0.41	0.43	0.43	0.41	0.41	0.42	0.43	0.43	0.46
SiO_2	21.40	21.32	21.37	21.29	21.40	21.34	21.45	21.45	21.44	21.37	21.35	21.34
SO_3	0.74	0.64	0.71	0.72	0.80	0.72	0.72	0.75	0.78	0.85	0.80	0.82
F CaO	1.03	1.21	1.33	1.21	1.75	1.45	1.09	0.36	0.42	1.33	1.15	0.91
C_3A	8.60	8.50	8.30	8.20	8.00	8.40	8.20	8.00	8.30	8.30	8.40	8.30
C_4AF	10.20	10.30	10.20	10.40	10.30	10.50	10.60	10.50	10.60	10.60	10.50	10.50
C_3S	59.50	60.40	60.60	60.70	60.70	59.00	58.60	59.60	58.50	58.90	59.10	59.10
C_2S	16.50	15.60	15.60	15.20	15.50	16.70	17.30	16.60	17.30	16.90	16.60	16.60

Table B.6.12.c: CPR - Chemical Composition of Clinker for 8/15/2007

Property (wt. %)	8/15/07											
	1:52 AM	**4:03 AM**	**5:30 AM**	**8:09 AM**	**9:53 AM**	**11:39 AM**	**1:52 PM**	**3:39 PM**	**5:35 PM**	**8:18 PM**	**10:13 PM**	**11:52 PM**
Al_2O_3	5.32	5.31	5.26	5.28	5.18	5.33	5.21	5.06	5.35	5.24	5.19	5.34
CaO	64.57	64.43	64.41	64.58	64.53	64.55	64.77	64.94	64.59	64.85	64.73	64.64
Fe_2O_3	3.38	3.48	3.45	3.55	3.47	3.65	3.53	3.33	3.55	3.31	3.43	3.61
K_2O	0.53	0.53	0.59	0.47	0.54	0.53	0.51	0.47	0.52	0.53	0.53	0.53
MgO	3.27	3.31	3.31	3.25	3.32	3.32	3.34	3.25	3.38	3.18	3.40	3.44
Na_2O	0.09	0.09	0.09	0.09	0.10	0.07	0.06	0.07	0.07	0.07	0.07	0.08
Na_2O_{eq}	0.44	0.44	0.48	0.40	0.45	0.42	0.40	0.38	0.41	0.42	0.42	0.43
SiO_2	21.27	21.39	21.32	21.36	21.38	21.31	21.35	21.37	21.36	21.32	21.32	21.28
SO_3	0.86	0.85	0.91	0.74	0.91	0.86	0.80	0.79	0.96	0.83	0.84	0.65
F CaO	1.33	0.85	1.45	0.48	0.60	1.45	1.88	0.91	0.60	0.79	1.15	1.09
C_3A	8.40	8.20	8.10	8.00	7.80	7.90	7.80	7.80	8.20	8.30	8.00	8.10
C_4AF	10.30	10.60	10.50	10.80	10.60	11.10	10.80	10.10	10.80	10.10	10.40	11.00
C_3S	60.70	59.20	59.90	60.00	60.50	59.80	61.30	63.20	59.60	62.10	61.70	60.40
C_2S	15.20	16.70	15.90	16.00	15.70	16.00	14.90	13.60	16.30	14.30	14.50	15.50

Table B.6.12.d: CPR - Chemical Composition of Clinker for 8/16/2007

Property (wt. %)	8/16/07				Average	C. V. (%)	Normality P-Value[1]
	2:06 AM	3:55 AM	5:28 AM	7:46 AM			
Al_2O_3	5.26	5.38	5.28	5.27	5.29	2.2	<0.005
CaO	64.67	64.52	64.70	64.69	64.49	0.5	0.303
Fe_2O_3	3.50	3.59	3.52	3.55	3.39	4.9	0.121
K_2O	0.52	0.54	0.54	0.50	0.52	4.9	0.011
MgO	3.39	3.47	3.46	3.46	3.31	3.4	0.685
Na_2O	0.07	0.07	0.07	0.07	0.08	13.8	<0.005
Na_2O_{eq}	0.41	0.43	0.43	0.40	0.42	4.3	0.035
SiO_2	21.28	21.27	21.35	21.38	21.34	0.8	<0.005
SO_3	0.80	0.97	0.85	0.83	0.79	9.8	0.080
F CaO	1.15	0.97	0.91	0.85	1.08	34.3	0.374
C_3A	8.00	8.20	8.00	8.00	8.29	3.5	0.012
C_4AF	10.70	10.90	10.70	10.80	10.31	4.9	<0.005
C_3S	61.20	59.80	60.60	60.30	59.97	2.7	0.213
C_2S	14.80	15.90	15.50	15.80	15.96	9.9	<0.005

Notes: [1] Based on Anderson-Darling Normality Test

Table B.6.13: ELR - Chemical Composition of Clinker

Property	8/13/2007		8/14/2007		8/15/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	6.01	5.29	5.24	5.31	5.18	5.23	5.38
CaO (wt. %)	63.27	64.21	64.46	64.28	64.47	64.46	64.19
Fe_2O_3 (wt. %)	3.05	3.28	3.29	3.27	3.35	3.35	3.27
K_2O (wt. %)	0.51	0.46	0.45	0.47	0.41	0.45	0.46
MgO (wt. %)	2.98	3.46	3.40	3.41	3.56	3.54	3.39
Na_2O (wt. %)	0.07	0.07	0.09	0.13	0.08	0.07	0.08
P_2O_5 (wt. %)	0.07	0.07	0.08	0.07	0.07	0.07	0.07
SiO_2 (wt. %)	22.79	21.87	21.74	21.78	21.57	21.47	21.87
SO_3 (wt. %)	0.76	0.74	0.68	0.74	0.76	0.81	0.75
TiO_2 (wt. %)	0.26	0.28	0.28	0.27	0.27	0.27	0.27
Moisture (wt. %)	0.07	0.00	0.80	0.00	0.06	0.06	0.17
LOI (wt. %)	0.67	0.16	0.13	0.13	0.16	0.15	0.23
As (ppm)	15	18	20	20	15	18	18
Ba (ppm)	391	397	488	389	294	389	391
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	133	168	114	54	277	172	153
Co (ppm)	11	9	10	7	13	11	10
Cr (ppm)	86	202	106	104	106	107	119
Cu (ppm)	22	34	20	14	41	18	25
Hg (ppm)	0.25	0.22	0.23	0.16	0.22	0.20	0.21
Mn (ppm)	1466	1784	1952	1943	1962	2044	1859
Mo (ppm)	1	ND	ND	2	5	6	2
Ni (ppm)	8	12	11	13	10	15	11
Pb (ppm)	34	15	< 4	15	< 4	18	20
Sb (ppm)	NC	NC	NC	NC	NC	NC	NC
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	489	496	488	486	490	487	489
V (ppm)	65	60	77	69	72	71	69
Zn (ppm)	214	251	367	361	366	357	319

Notes: NA **-** Not Applicable ND **-** Not Detected

B.6.8. EMISSIONS

Table B.6.14.a: CPR - Emissions

Time	**NO_x (tons/ton clinker)**	**SO_2 (tons/ton clinker)**	**VOC (tons/ton clinker)**	**CO (tons/ton clinker)**
5/16/2007 9:00	1.03E-03	1.00E-06	1.68E-05	3.25E-04
5/16/2007 10:00	1.01E-03	1.74E-06	1.71E-05	3.03E-04
5/16/2007 11:00	9.62E-04	2.55E-07	1.72E-05	3.20E-04
5/16/2007 12:00	1.01E-03	4.89E-07	1.90E-05	3.47E-04
5/16/2007 13:00	1.09E-03	4.79E-07	2.12E-05	3.54E-04
5/16/2007 14:00	1.12E-03	6.10E-07	2.24E-05	3.61E-04
5/16/2007 15:00	1.16E-03	4.77E-07	2.57E-05	3.92E-04
5/16/2007 16:00	1.35E-03	8.58E-07	2.70E-05	4.27E-04
5/16/2007 17:00	1.28E-03	8.36E-07	2.68E-05	3.34E-04
5/16/2007 18:00	1.15E-03	5.81E-07	2.65E-05	3.52E-04
5/16/2007 19:00	1.16E-03	8.61E-07	2.54E-05	3.70E-04
5/16/2007 20:00	1.14E-03	7.48E-07	2.55E-05	3.87E-04
5/16/2007 21:00	1.02E-03	1.19E-06	2.13E-05	3.32E-04
5/16/2007 22:00	1.04E-03	9.90E-07	2.23E-05	3.82E-04
5/16/2007 23:00	1.19E-03	1.77E-06	2.49E-05	3.94E-04
5/17/2007 0:00	1.08E-03	1.07E-06	2.24E-05	3.70E-04
5/17/2007 1:00	1.19E-03	1.18E-06	2.22E-05	3.35E-04
5/17/2007 2:00	1.05E-03	1.29E-06	1.86E-05	3.20E-04
5/17/2007 3:00	1.31E-03	1.68E-06	1.99E-05	3.47E-04
5/17/2007 4:00	1.01E-03	1.76E-06	1.93E-05	3.47E-04
5/17/2007 5:00	9.02E-04	1.22E-06	1.80E-05	3.12E-04
5/17/2007 6:00	9.98E-04	1.54E-06	1.81E-05	3.53E-04
5/17/2007 7:00	1.03E-03	1.01E-06	1.78E-05	3.56E-04
5/17/2007 8:00	1.02E-03	1.56E-06	1.54E-05	2.98E-04
5/17/2007 9:00	1.12E-03	7.15E-07	1.72E-05	2.95E-04
5/17/2007 10:00	1.00E-03	2.47E-07	1.65E-05	3.41E-04
5/17/2007 11:00	1.13E-03	2.15E-07	1.52E-05	3.52E-04
5/17/2007 12:00	1.18E-03	1.37E-07	1.50E-05	2.94E-04
5/17/2007 13:00	1.06E-03	1.46E-07	1.51E-05	3.01E-04
5/17/2007 14:00	1.29E-03	1.68E-07	1.94E-05	3.88E-04
5/17/2007 15:00	1.10E-03	2.20E-07	2.05E-05	3.44E-04
5/17/2007 16:00	1.20E-03	3.15E-07	2.19E-05	3.36E-04
5/17/2007 17:00	1.09E-03	3.80E-07	2.21E-05	3.97E-04
5/17/2007 18:00	1.18E-03	7.25E-07	2.89E-05	5.11E-04
5/17/2007 19:00	9.71E-04	5.81E-07	2.42E-05	3.78E-04
5/17/2007 20:00	1.07E-03	6.11E-07	2.69E-05	3.96E-04
5/17/2007 21:00	1.05E-03	8.08E-07	2.60E-05	4.54E-04
5/17/2007 22:00	9.68E-04	6.94E-07	2.59E-05	4.12E-04
5/17/2007 23:00	9.93E-04	5.74E-07	2.62E-05	4.27E-04

Table B.6.14.b: CPR - Emissions

Time	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
5/18/2007 0:00	1.05E-03	9.66E-07	2.27E-05	4.20E-04
5/18/2007 1:00	1.17E-03	7.19E-07	2.09E-05	4.38E-04
5/18/2007 2:00	1.14E-03	1.15E-06	1.98E-05	4.52E-04
5/18/2007 3:00	1.12E-03	1.02E-06	1.94E-05	4.39E-04
5/18/2007 4:00	1.15E-03	1.20E-06	1.92E-05	4.27E-04
5/18/2007 5:00	9.34E-04	1.34E-06	1.76E-05	4.16E-04
5/18/2007 6:00	1.11E-03	1.99E-06	1.80E-05	4.38E-04
5/18/2007 7:00	1.04E-03	1.14E-06	1.66E-05	4.23E-04
5/18/2007 8:00	1.09E-03	1.42E-06	1.70E-05	4.29E-04
5/18/2007 9:00	1.07E-03	1.33E-06	1.80E-05	4.05E-04
5/18/2007 10:00	1.03E-03	1.05E-06	2.05E-05	3.78E-04
5/18/2007 11:00	1.18E-03	1.24E-06	2.33E-05	4.30E-04
5/18/2007 12:00	1.17E-03	7.49E-07	2.34E-05	4.39E-04
5/18/2007 13:00	1.05E-03	7.20E-07	2.27E-05	4.40E-04
5/18/2007 14:00	1.15E-03	7.20E-07	2.32E-05	4.03E-04
5/18/2007 15:00	1.11E-03	5.69E-07	2.52E-05	3.99E-04
5/18/2007 16:00	1.03E-03	4.73E-07	2.44E-05	3.75E-04
5/18/2007 17:00	1.14E-03	7.42E-07	2.67E-05	4.12E-04
5/18/2007 18:00	1.14E-03	5.49E-07	2.67E-05	3.76E-04
5/18/2007 19:00	1.19E-03	4.01E-07	2.79E-05	3.93E-04
5/18/2007 20:00	1.13E-03	4.71E-07	2.65E-05	3.75E-04
5/18/2007 21:00	1.25E-03	5.36E-07	2.71E-05	4.08E-04
5/18/2007 22:00	1.27E-03	8.87E-07	2.62E-05	3.54E-04
5/18/2007 23:00	1.25E-03	7.51E-07	2.52E-05	3.82E-04
5/19/2007 0:00	1.23E-03	7.20E-07	2.31E-05	3.61E-04
5/19/2007 1:00	1.32E-03	6.87E-07	2.31E-05	3.46E-04
5/19/2007 2:00	1.34E-03	7.42E-07	2.32E-05	3.57E-04
5/19/2007 3:00	NC	NC	NC	3.89E-04
5/19/2007 4:00	1.31E-03	1.03E-06	2.07E-05	3.66E-04
5/19/2007 5:00	1.27E-03	1.05E-06	2.08E-05	3.98E-04
5/19/2007 6:00	1.30E-03	1.28E-06	2.15E-05	4.02E-04
5/19/2007 7:00	1.35E-03	1.19E-06	2.15E-05	4.06E-04
5/19/2007 8:00	1.29E-03	9.39E-07	2.07E-05	4.02E-04
Average	1.13E-03	8.66E-07	2.18E-05	3.79E-04
C. V. (%)	9.8	49.8	17.0	11.6
Normality P-Value[1]	0.015	<0.005	0.008	0.214

Notes: [1] Based on Anderson Darling Normality Test NC - Not Collected

APPENDIX B.7

RAW DATA FOR *CTW BURN*

B.7.1. GENERAL COMMENTS

- The raw data from the CTW burn are presented in this appendix.
- Coal, scrap tires and woodchips are the fuels used in the burn.
- The burn lasted from 9 AM on October 16, 2007 to 9 AM on October 19, 2007.

B.7.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.7.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.7.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3	25.50	0.40	0.43	6.16	1.15	2.50
CaO	2.74	51.85	56.13	33.15	1.60	31.47
Fe_2O_3	7.15	0.00	0.00	27.49	1.70	0.30
K_2O	2.26	0.07	0.08	0.02	0.20	0.25
MgO	1.03	0.97	0.89	11.53	0.20	3.25
Na_2O	0.38	0.13	0.06	0.11	NR	0.22
SiO_2	50.10	2.00	2.33	12.92	95.85	13.60
SO_3	0.27	0.13	0.12	0.67	0.20	32.95
Moisture	31.70	3.50	NR	NR	3.50	10.11
LOI	8.80	42.20	41.50	4.33	0.40	11.52

Notes: ND - Not Detected NR - Not Reported

Table B.7.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	23.49	0.30	4.10	5.57	0.63	0.68
CaO (wt. %)	2.95	53.59	39.28	66.01	0.36	32.92
Fe_2O_3 (wt. %)	9.49	0.16	1.88	2.91	0.31	0.47
K_2O (wt. %)	2.34	0.06	0.69	0.64	0.15	0.14
MgO (wt. %)	1.11	1.00	3.29	1.96	0.06	0.86
Na_2O (wt. %)	0.43	0.02	0.04	0.08	0.02	0.12
P_2O_5 (wt. %)	0.52	0.00	0.01	0.04	0.00	0.01
SiO_2 (wt. %)	42.85	1.20	14.56	17.70	97.92	3.97
SO_3 (wt. %)	0.17	0.09	0.28	0.31	0.15	43.53
TiO_2 (wt. %)	1.20	0.00	0.14	0.28	0.19	0.03
Moisture (wt. %)	21.90	2.85	3.91	7.15	2.96	0.00
LOI (wt. %)	15.07	43.53	35.68	4.38	0.18	17.13
As (ppm)	137	ND	10	13	ND	ND
Ba (ppm)	2000	100	200	300	200	200
Cd (ppm)	ND	ND	ND	ND	ND	ND
Cl (ppm)	36	40	62	134	96	11
Co (ppm)	64	2	6	7	4	4
Cr (ppm)	220	76	82	146	58	79
Cu (ppm)	145	ND	ND	ND	ND	ND
Hg (ppm)	0.10	0.10	0.10	0.20	0.10	0.05
Mn (ppm)	400	100	100	800	100	400
Mo (ppm)	30	ND	3	ND	1	ND
Ni (ppm)	113	ND	10	7	ND	ND
Pb (ppm)	73	17	4	22	ND	ND
Sb (ppm)	NR	NR	NR	NR	NR	NR
Se (ppm)	3	ND	ND	ND	ND	ND
Sr (ppm)	1400	300	200	400	0	700
V (ppm)	309	13	50	68	15	22
Zn (ppm)	142	ND	31	37	ND	ND

Notes: ND - Not Detected NR - Not Reported

B.7.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.7.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	10/16/2007		10/17/2007		10/18/2007			Average	C. V. (%)
	1:44 PM	2:04 AM	1:46 PM	1:59 AM	1:41 PM	2:12 AM	1:41 PM		
Al_2O_3	2.96	3.05	2.99	2.94	2.93	2.85	3.08	2.97	2.6
CaO	42.98	42.99	42.93	43.02	43.01	43.09	43.17	43.03	0.2
Fe_2O_3	1.92	1.95	1.83	1.87	1.94	1.92	1.97	1.91	2.5
K_2O	0.31	0.32	0.36	0.36	0.34	0.34	0.38	0.34	7.1
MgO	1.96	1.94	1.91	1.94	1.99	2.04	1.95	1.96	2.2
Na_2O	0.18	0.16	0.16	0.14	0.15	0.16	0.16	0.16	7.7
Na_2O_{eq}	0.38		0.4	0.38	0.37	0.38	0.41	0.39	3.9
SiO_2	13.69	13.62	13.47	13.43	13.27	13.36	13.23	13.44	1.3
SO_3	0.22	0.21	0.21	0.2	0.2	0.21	0.2	0.21	3.6
LOI	35	35	35	35	35	35	35	35.00	0.0

Table B.7.4: ELR - Chemical Composition of Kiln Feed

Property	3-Day Composite
Al_2O_3 (wt. %)	2.96
CaO (wt. %)	41.36
Fe_2O_3 (wt. %)	1.83
K_2O (wt. %)	0.32
MgO (wt. %)	2.04
Na_2O (wt. %)	0.05
P_2O_5 (wt. %)	0.02
SiO_2 (wt. %)	13.26
SO_3 (wt. %)	0.21
TiO_2 (wt. %)	0.15
Moisture (wt. %)	0.23
LOI (wt. %)	38
As (ppm)	17
Ba (ppm)	200
Cd (ppm)	ND
Cl (ppm)	192
Co (ppm)	8
Cr (ppm)	159
Cu (ppm)	ND
Hg (ppm)	0
Mn (ppm)	1100
Mo (ppm)	3
Ni (ppm)	ND
Pb (ppm)	12
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	200
V (ppm)	61
Zn (ppm)	33

Notes: ND - Not Detected
NR - Not Reported

B.7.5. CHEMICAL COMPOSITION OF FUELS

Table B.7.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	18.78
	Fixed Carbon	53.48
	Volatile Matter	27.74
Ultimate Analysis	**Carbon**	53.48
	Hydrogen	4.39
	Nitrogen	1.31
	Oxygen	3.23
	Sulfur	1.41
Standard Parameters	**Al_2O_3**	28.92
	CaO	0.95
	Fe_2O_3	7.48
	K_2O	3.26
	MgO	1.20
	Na_2O	0.43
	SiO_2	55.55
	SO_3	1.01
Heat Value [1]		12321

Notes: [1] Value is Reported as BTU/lb

Table B.7.6: ELR - Proximate, Ultimate, and Combustion of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	17.59
	Fixed Carbon	53.8
	Volatile Matter	28.61
Ultimate Analysis	**Carbon**	71.06
	Hydrogen	4.16
	Nitrogen	1.48
	Oxygen	4.57
	Sulfur	1.14
Heat Value [1]		12445

Notes: [1] Value is Reported as BTU/lb

Table B.7.7: ELR - Standard Parameters of Coal

Property	3-Day Composite
Al_2O_3 (wt. %)	24.6
CaO (wt. %)	9.3
Fe_2O_3 (wt. %)	7.5
K_2O (wt. %)	2.2
MgO (wt. %)	1.1
Na_2O (wt. %)	0.2
P_2O_5 (wt. %)	0.2
SiO_2 (wt. %)	47.2
SO_3 (wt. %)	6.4
TiO_2 (wt. %)	1.2
As (ppm)	86
Ba (ppm)	1096
Cd (ppm)	ND
Cl (ppm)	105
Co (ppm)	54
Cr (ppm)	190
Cu (ppm)	70
Hg (ppm)	0.2
Mn (ppm)	498
Mo (ppm)	31
Ni (ppm)	79
Pb (ppm)	47
Sb (ppm)	NR
Se (ppm)	6
Sr (ppm)	598
V (ppm)	214
Zn (ppm)	63

Notes: ND - Not Detected
NR - Not Reported

Table B.7.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	14.99
	Fixed Carbon	23.56
	Moisture [1]	0.36
	Volatile Matter	61.45
Ultimate Analysis	**Carbon**	77.6
	Hydrogen	5.9
	Nitrogen	0.1
	Oxygen	0.31
	Sulfur	1.10
Heat Value [2]		15098

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.7.9: ELR - Standard Parameters of Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	4.42
CaO (wt. %)	3.00
Fe_2O_3 (wt. %)	57.72
K_2O (wt. %)	0.48
MgO (wt. %)	0.36
Na_2O (wt. %)	1.49
P_2O_5 (wt. %)	0.43
SiO_2 (wt. %)	12.89
SO_3 (wt. %)	4.15
TiO_2 (wt. %)	3.74
As (ppm)	ND
Ba (ppm)	ND
Cd (ppm)	ND
Cl (ppm)	515
Co (ppm)	642
Cr (ppm)	133
Cu (ppm)	3762
Hg (ppm)	0.1
Mn (ppm)	3754
Mo (ppm)	8
Ni (ppm)	8
Pb (ppm)	30
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	36
V (ppm)	117
Zn (ppm)	0

Notes: ND - Not Detected
NR - Not Reported

Table B.7.10: ELR - Proximate, Ultimate, and Combustion Analysis of Woodchips

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	0.82
	Fixed Carbon	16.94
	Moisture [1]	36.46
	Volatile Matter	82.24
Ultimate Analysis	**Carbon**	52.64
	Hydrogen	5.83
	Nitrogen	0.15
	Oxygen	40.53
	Sulfur	0.02
Heat Value [2]		8388

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.7.11: ELR - Standard Parameters of Woodchips

Property	3-Day Composite
Al_2O_3 (wt. %)	0.93
CaO (wt. %)	54.61
Fe_2O_3 (wt. %)	1.79
K_2O (wt. %)	17.28
MgO (wt. %)	9.83
Na_2O (wt. %)	0.38
P_2O_5 (wt. %)	2.80
SiO_2 (wt. %)	3.27
SO_3 (wt. %)	3.33
TiO_2 (wt. %)	0.02
As (ppm)	12
Ba (ppm)	9692
Cd (ppm)	ND
Cl (ppm)	425
Co (ppm)	64
Cr (ppm)	16
Cu (ppm)	126
Hg (ppm)	0.1
Mn (ppm)	43581
Mo (ppm)	65
Ni (ppm)	169
Pb (ppm)	60
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	4230
V (ppm)	172
Zn (ppm)	959

Notes: ND - Not Detected
NR - Not Reported

Table B.7.12: AUR - Density of Woodchips

Sample #	Density (kg/m^3)
1	251.4
2	291.5
3	253.5
4	261.1
5	258.4
6	275.6
7	267.7
8	263.1
9	269.3
10	256.6
11	251.1
12	276.4
13	276.7
14	273.8
15	256.1
16	261.8
17	259.6
18	253.2
19	265.2
20	254.6
21	256.6
22	262.3
23	255.4
24	254.6
Average	**262.7**

B.7.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.7.13: CPR - Chemical Composition of Cement Kiln Dust

Property (wt. %)	**10/16/2007**		**10/17/2007**		**10/18/2007**			**Average**
	9:16 AM	**7:15 PM**	**7:47 AM**	**7:06 PM**	**8:40 AM**	**7:16 PM**	**9:10 AM**	
Al_2O_3	4.02	3.91	3.86	4.01	4.45	4.62	4	4.12
CaO	44.97	45.1	45.43	44.99	43.95	42.96	44.76	44.59
Fe_2O_3	2.04	2.03	2	2.03	2.12	2.21	2.04	2.07
K_2O	0.51	0.51	0.5	0.51	0.57	0.6	0.5	0.53
MgO	1.33	1.35	1.32	1.27	1.35	1.36	1.37	1.34
Na_2O	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04
SiO_2	11.96	12.26	11.89	12.07	12.53	12.71	11.75	12.17
SO_3	0.2	0.22	0.2	0.2	0.42	0.4	0.2	0.26

Table B.7.14: ELR - Chemical Composition of Cement Kiln Dust

Property	10/16/2007		10/17/2007		10/18/2007		Average
	5:16 PM	3.6	3.77	4.02	3.82	4.21	
Al_2O_3 (wt. %)	3.72	3.60	3.77	4.02	3.82	4.21	3.86
CaO (wt. %)	44.12	44.44	43.58	42.85	43.09	43.76	43.64
Fe_2O_3 (wt. %)	1.99	1.96	1.87	1.94	1.98	2.20	1.99
K_2O (wt. %)	0.40	0.42	0.42	0.47	0.41	0.38	0.42
MgO (wt. %)	1.30	1.36	1.30	1.35	1.26	1.33	1.32
Na_2O (wt. %)	0.06	0.04	0.03	0.10	0.04	0.06	0.06
P_2O_5 (wt. %)	0.03	0.03	0.03	0.04	0.04	0.04	0.04
SiO_2 (wt. %)	11.76	11.72	12.24	12.46	11.32	12.22	11.95
SO_3 (wt. %)	0.22	0.20	0.20	0.19	0.34	0.36	0.25
TiO_2 (wt. %)	0.20	0.18	0.17	0.20	0.20	0.23	0.20
Moisture (wt. %)	0.25	0.23	0.30	0.20	0.20	17.83	3.17
LOI (wt. %)	36.10	35.95	36.29	36.28	37.40	35.10	36.19
As (ppm)	14	13	18	12	18	19	16
Ba (ppm)	300	100	200	300	100	300	217
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	167	171	190	171	1173	1354	538
Co (ppm)	9	8	5	14	12	11	10
Cr (ppm)	153	112	71	136	109	102	114
Cu (ppm)	ND	ND	ND	ND	ND	ND	ND
Hg (ppm)	0.60	0.60	0.50	0.40	1.40	1.70	1
Mn (ppm)	500	600	500	400	600	500	517
Mo (ppm)	ND	ND	11	5	5	ND	4
Ni (ppm)	5	9	11	8	10	10	9
Pb (ppm)	< 4	16	18	35	31	9	22
Sb (ppm)	NR	NR	NR	NR	NR	NR	ND
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	300	300	300	300	300	300	300
V (ppm)	65	59	59	73	70	70	66
Zn (ppm)	35	33	36	39	44	42	38

Notes: ND - Not Detected NR - Not Reported

B.7.7. CHEMICAL COMPOSITION OF CLINKER

Table B.7.15.a: CPR - Chemical Composition of Clinker for 10/16/2007

Property (wt. %)	10/16/2007								
	5:47 AM	7:51 AM	9:37 AM	11:47 AM	1:44 PM	3:35 PM	5:43 PM	7:59 PM	10:00 PM
Al_2O_3	5.08	5.24	5.15	5.22	5.32	5.10	5.13	5.07	5.12
CaO	64.39	64.22	64.44	64.47	64.20	64.69	64.38	64.07	64.44
Fe_2O_3	3.50	3.53	3.38	3.40	3.42	3.24	3.27	3.31	3.28
K_2O	0.43	0.45	0.48	0.45	0.47	0.45	0.50	0.46	0.41
MgO	3.27	3.24	3.24	3.25	3.23	3.24	3.19	3.14	3.20
Na_2O	0.07	0.07	0.08	0.07	0.07	0.07	0.08	0.07	0.06
Na_2O_{eq}	0.35	0.37	0.39	0.37	0.38	0.37	0.41	0.37	0.33
SiO_2	21.57	21.43	21.48	21.57	21.45	21.51	21.47	21.30	21.42
SO_3	0.93	0.86	0.98	0.79	0.92	0.58	1.04	1.66	0.49
F CaO	0.33	0.58	1.05	0.75	2.24	1.74	1.68	1.57	0.97
C_3A	7.50	7.90	7.90	8.10	8.30	8.00	8.10	7.80	8.00
C_4AF	10.70	10.70	10.30	10.40	10.40	9.90	9.90	10.10	10.00
C_3S	59.10	58.40	59.70	58.60	57.70	61.00	59.80	60.20	60.40
C_2S	17.30	17.40	16.60	17.70	18.00	15.70	16.50	15.70	15.90

Table B.7.15.b: CPR - Chemical Composition of Clinker for 10/17/2007

Property (wt. %)	10/17/2007											
	12:00 AM	1:07 AM	1:57 AM	3:54 AM	5:29 AM	7:43 AM	9:40 AM	11:32 AM	12:44 PM	1:46 PM	3:44 PM	5:37 PM
Al_2O_3	5.13	5.12	5.00	5.05	5.04	5.01	4.94	4.93	4.86	4.91	4.95	5.01
CaO	64.40	64.69	64.97	64.94	64.72	64.82	65.19	64.54	64.92	64.96	65.01	64.78
Fe_2O_3	3.16	3.17	3.05	3.16	3.09	3.06	3.12	2.94	3.02	3.12	3.26	3.15
K_2O	0.69	0.60	0.59	0.56	0.58	0.57	0.55	0.79	0.57	0.58	0.58	0.67
MgO	3.25	3.34	3.33	3.30	3.29	3.31	3.29	3.23	3.37	3.25	3.30	3.30
Na_2O	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.05
Na_2O_{eq}	0.51	0.45	0.44	0.42	0.43	0.42	0.41	0.58	0.43	0.43	0.43	0.49
SiO_2	20.91	21.51	21.57	21.57	21.75	21.65	21.51	21.37	21.69	21.74	21.58	21.42
SO_3	2.17	1.01	0.69	0.49	0.87	0.81	0.50	1.49	0.75	0.55	0.44	1.00
F CaO	2.40	1.38	1.32	1.44	0.78	0.90	1.44	1.74	0.84	0.78	0.66	1.38
C_3A	8.25	8.20	8.11	8.05	8.11	8.08	7.82	8.09	7.77	7.72	7.61	7.95
C_4AF	9.62	9.65	9.27	9.61	9.41	9.32	9.49	8.95	9.20	9.49	9.91	9.59
C_3S	64.27	61.00	62.55	61.97	59.94	61.30	64.20	63.01	62.48	61.85	62.74	62.77
C_2S	11.46	15.64	14.66	15.09	17.13	15.83	13.24	13.74	15.05	15.67	14.54	14.06

Table B.7.15.c: CPR - Chemical Composition of Clinker for 10/18/2007

Property (wt. %)	10/18/2007											
	11:53 PM	1:51 AM	4:03 AM	5:34 AM	6:35 AM	7:39 AM	8:40 AM	9:49 AM	11:53 AM	1:46 PM	3:23 PM	5:31 PM
Al_2O_3	4.99	5.00	5.04	4.98	5.00	4.97	4.95	4.95	4.93	4.97	4.95	4.89
CaO	65.23	64.94	64.75	64.78	64.85	64.96	64.89	65.01	64.99	64.98	64.76	64.98
Fe_2O_3	3.18	3.25	3.26	3.19	3.27	3.24	3.11	3.15	3.33	3.11	3.09	3.13
K_2O	0.49	0.57	0.60	0.56	0.56	0.58	0.58	0.60	0.56	0.57	0.68	0.61
MgO	3.34	3.34	3.26	3.30	3.30	3.32	3.32	3.33	3.28	3.27	3.26	3.29
Na_2O	0.04	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05	0.05	0.05
Na_2O_{eq}	0.37	0.43	0.44	0.42	0.42	0.43	0.44	0.45	0.42	0.43	0.50	0.45
SiO_2	21.55	21.63	21.59	21.54	21.49	21.47	21.45	21.50	21.56	21.56	21.50	21.62
SO_3	0.35	0.51	0.89	1.04	0.85	0.67	0.89	0.55	0.52	0.82	1.04	0.64
F CaO	1.32	1.32	0.60	0.78	1.20	1.68	1.32	1.62	1.50	0.84	0.78	
C_3A	7.83	7.73	7.82	7.81	7.72	7.69	7.86	7.79	7.42	7.89	7.89	7.66
C_4AF	9.68	9.90	9.93	9.70	9.97	9.85	9.45	9.59	10.13	9.48	9.40	9.52
C_3S	63.73	61.77	61.04	62.00	62.41	63.29	63.42	63.50	62.84	62.83	62.57	62.89
C_2S	13.70	15.41	15.84	14.98	14.53	13.80	13.67	13.73	14.41	14.41	14.44	14.54

Table B.7.15.d: CPR - Chemical Composition of Clinker for 10/19/2007

Property (wt. %)	**10/19/2007**									**Average**	**C. V. (%)**	**Normality P-Value**[1]
	7:15 PM	8:13 PM	10:06 PM	11:52 PM	2:03 AM	3:47 AM	5:32 AM	7:37 AM	10:18 AM			
Al_2O_3	5.00	5.20	5.07	5.04	5.08	5.20	5.05	5.02	5.02	5.04	2.0	0.032
CaO	65.08	64.92	64.91	64.98	65.02	64.82	64.96	65.09	65.03	64.79	0.6	0.311
Fe_2O_3	3.20	3.17	3.11	3.17	3.17	3.23	3.19	3.16	3.20	3.20	6.1	<0.005
K_2O	0.61	0.68	0.66	0.60	0.66	0.65	0.63	0.61	0.61	0.57	4.6	0.177
MgO	3.07	3.16	3.13	3.19	3.22	3.25	3.17	3.24	3.28	3.26	3.3	0.572
Na_2O	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.06	5.8	<0.005
Na_2O_{eq}	0.45	0.50	0.48	0.45	0.48	0.48	0.46	0.45	0.45	0.43	4.4	0.253
SiO_2	21.53	21.39	21.47	21.52	21.35	21.42	21.49	21.48	21.44	21.50	1.2	0.304
SO_3	0.67	0.83	0.83	0.75	0.81	0.77	0.74	0.65	0.69	0.82	21.1	<0.005
F CaO	0.72			0.72					0.60	1.17	41.0	0.374
C_3A	7.84	8.42	8.17	7.99	8.10	8.31	7.99	7.96	7.89	7.93	5.4	0.031
C_4AF	9.74	9.65	9.46	9.65	9.65	9.83	9.71	9.62	9.74	9.75	6.2	0.102
C_3S	63.15	62.26	62.57	62.60	63.78	61.54	62.64	63.49	63.49	61.92	3.9	<0.005
C_2S	14.09	14.36	14.35	14.47	13.10	14.99	14.36	13.69	13.57	14.94	16.4	0.007

Notes: [1] Based on Anderson-Darling Normality Test

Table B.7.16: ELR - Chemical Composition of Clinker

Property	10/16/2007		10/17/2007		10/18/2007		Average
	1	2	1	2	1	2	
Al_2O_3 (wt. %)	4.98	5.09	5.06	5.11	4.97	5.15	5.06
CaO (wt. %)	64.03	64.12	64.51	64.60	64.84	64.45	64.43
Fe_2O_3 (wt. %)	3.07	3.09	3.10	3.11	3.00	3.05	3.07
K_2O (wt. %)	0.61	0.55	0.53	0.51	0.51	0.54	0.54
MgO (wt. %)	3.33	3.29	3.40	3.37	3.35	3.34	3.35
Na_2O (wt. %)	0.06	0.07	0.08	0.05	0.06	0.11	0.07
P_2O_5 (wt. %)	0.06	0.06	0.03	0.05	0.05	0.05	0.05
SiO_2 (wt. %)	22.03	22.28	22.25	22.17	22.15	21.90	22.13
SO_3 (wt. %)	1.12	0.67	0.45	0.43	0.50	0.65	0.64
TiO_2 (wt. %)	0.25	0.26	0.25	0.25	0.24	0.26	0.25
Moisture (wt. %)	0.06	0.04	0.00	0.04	0.00	0.04	0.03
LOI (wt. %)	0.15	0.18	0.09	0.10	0.07	0.25	0.14
As (ppm)	18	21	15	15	21	20	18
Ba (ppm)	300	400	300	300	300	300	317
Cd (ppm)	ND	ND	ND	ND	ND	ND	ND
Cl (ppm)	290	753	21	58	70	557	292
Co (ppm)	9	13	9	9	7	9	9
Cr (ppm)	111	113	98	86	90	89	98
Cu (ppm)	14	22	21	13	14	7	15
Hg (ppm)	0.05	0.16	0.13	0.11	0.14	0.08	0.11
Mn (ppm)	2400	2500	1900	1900	2000	1900	2100
Mo (ppm)	6	6	2	ND	ND	ND	5
Ni (ppm)	8	12	8	6	5	7	8
Pb (ppm)	29	ND	11	ND	ND	12	17
Sb (ppm)	NR	NR	NR	NR	NR	NR	NA
Se (ppm)	ND	ND	ND	ND	ND	ND	ND
Sr (ppm)	400	400	400	400	400	400	400
V (ppm)	72	73	63	61	64	63	66
Zn (ppm)	79	70	82	88	77	51	75

Notes: NA - Not Applicable ND - Not Detected

B.7.8. CHEMICAL COMPOSITION OF CEMENT

Table B.7.17: CPR - Chemical Composition of Cement

Property (wt. %)	10/22/2007								10/23/2007			Average	C. V. (%)	Normality P-Value[1]
	7:07 AM	10:12 AM	11:34 AM	1:09 PM	2:39 PM	4:01 PM	6:43 PM	9:54 PM	1:13 AM	4:12 AM	11:53 AM			
Al_2O_3	4.68	4.67	4.65	4.63	4.64	4.64	4.59	4.6	4.57	4.62	4.71	4.64	0.9	0.216
CaO	63.86	63.44	63.79	63.75	63.37	63.74	63.64	63.66	63.87	63.5	63.63	63.66	0.3	0.150
Fe_2O_3	3.19	3.14	3.13	3.11	3.1	3.13	3.2	3.22	3.21	3.13	3.12	3.15	1.4	<0.005
K_2O	0.52	0.51	0.51	0.5	0.5	0.51	0.5	0.52	0.53	0.52	0.52	0.51	2.0	0.100
MgO	3.13	3.14	3.14	3.13	3.12	3.11	3.16	3.15	3.11	3.11	3.18	3.13	0.7	<0.005
Na_2O	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.07	0.06	5.0	<0.005
Na_2O_{eq}	0.41	0.39	0.39	0.39	0.39	0.39	0.39	0.4	0.41	0.41	0.41	0.40	2.5	<0.005
SiO_2	20.36	20.27	20.48	20.46	20.43	20.55	20.45	20.36	20.38	20.22	20.44	20.40	0.5	0.148
SO_3	2.73	2.62	2.64	2.63	2.57	2.7	2.67	2.71	2.73	2.61	2.57	2.65	2.2	0.126
F CaO	1.08	1.26	1.08	NR	0.9	1.02	0.9	1.2	1.14	1.14	0.96	1.07	11.5	0.139
LOI	0.92	1.3	NR	1.24	1.17	1.21	1.27	1.25	1.22	1.43	0.97	1.20	12.6	<0.005
C_3A	7.01	7.06	7.04	7.01	7.06	7	6.76	6.75	6.69	6.94	7.21	6.96	2.3	0.310
C_4AF	9.72	9.56	9.52	9.45	9.43	9.54	9.74	9.8	9.77	9.54	9.49	9.60	1.4	0.251
C_3S	61.39	60.9	60.82	61.02	59.71	59.91	60.62	61.18	62.04	61.92	60.26	60.89	1.2	0.323
C_2S	12.07	12.17	12.82	12.62	13.54	13.72	12.9	12.22	11.63	11.25	13.13	12.55	6.1	<0.005
Blaine SSA (m^2/kg)	385	387	384	NR	389	385	383	386	379	386	371	384	1.3	0.143

Notes: [1] Based on Anderson-Darling Normality Test NR- Not Reported

Table B.7.18: ELR - Chemical Composition of Cement

Property	1	2	3	Average
Al_2O_3 (wt. %)	4.82	4.75	4.82	4.80
CaO (wt. %)	62.85	62.89	62.81	62.85
Fe_2O_3 (wt. %)	2.94	2.86	2.93	2.91
K_2O (wt. %)	0.50	0.57	0.51	0.53
MgO (wt. %)	3.24	3.31	3.24	3.26
Na_2O (wt. %)	0.06	0.07	0.06	0.06
P_2O_5 (wt. %)	0.05	0.06	0.04	0.05
SiO_2 (wt. %)	21.12	21.07	21.24	21.14
SO_3 (wt. %)	2.97	2.83	2.59	2.80
TiO_2 (wt. %)	0.24	0.23	0.24	0.24
Moisture (wt. %)	0.19	0.18	0.22	0.20
LOI (wt. %)	0.95	1.08	1.25	1.09
C_3S (wt. %)	50.29	51.82	50.32	50.81
C_2S (wt. %)	22.61	21.31	22.94	22.29
C_3A (wt. %)	7.80	7.75	7.82	7.79
C_4AF (wt. %)	8.95	8.70	8.92	8.86
TOC (wt. %)	ND	ND	ND	ND
As (ppm)	17	19	12	16
Ba (ppm)	300	400	300	333
Cd (ppm)	ND	ND	ND	ND
Cl (ppm)	52	105	71	76
Co (ppm)	7	11	9	9
Cr (ppm)	100	96	94	97
Cu (ppm)	ND	ND	ND	ND
Hg (ppm)	0.06	0.09	0.07	0.07
Mn (ppm)	2000	2100	2000	2033
Mo (ppm)	ND	ND	3	1
Ni (ppm)	7	7	7	7
Pb (ppm)	ND	12	13	12
Sb (ppm)	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND
Sr (ppm)	400	400	400	400
V (ppm)	63	68	54	62
Zn (ppm)	84	75	90	83

Notes: ND - Not Detected NR - Not Reported

B.7.9. PHYSICAL PROPERTIES OF CEMENT

Table B.7.19: CPR - Physical Properties of Cement

Property	Average
Air in Mortar (%)	6.4
Blaine Specific Surface Area (m^2/kg)	372
Autoclave Expansion (% Exp.)	0.06
Cube Flow (%)	130.0
Comp Str 1day (MPa)	14.3
Comp Str 3day (MPa)	23.9
Comp Str 7day (MPa)	30.6
Comp Str 28day (MPa)	43.3
Normal Consistency (%)	25.2
Gillmore Initial Set (Min)	NR
Gillmore Final Set (Min)	NR
Vicat Initial Set (Min)	71
Vicat Final Set (Min)	228

Notes: % Exp. - Percent Expansion

Table B.7.20: AUR - Physical Properties of Cement

Property	Composite
Autoclave Expansion (% Exp.)	0.05
Cube Flow (%)	106
Comp Str 1day (MPa)	10.9
Comp Str 3day (MPa)	22.8
Comp Str 7day (MPa)	28.3
Comp Str 28day (MPa)	35.1
Normal Consistency (%)	26.2
Gillmore Initial Set (Min)	108
Gillmore Final Set (Min)	205
Vicat Initial Set (Min)	84
Vicat Final Set (Min)	150
Drying Shrinkage @ 7 days (% LC)	-0.045
Drying Shrinkage @ 14 days (% LC)	-0.070
Drying Shrinkage @ 21 days (% LC)	-0.080
Drying Shrinkage @ 28 days (% LC)	-0.088

Notes: % LC - Percent Length Change
% Exp. - Percent Expansion

B.7.10. PROPERTIES OF CONCRETE

Table B.7.21: Concrete Properties

Property	AUR	
	Mix w/c=0.44	Mix w/c=0.37
Total Air Content (%)	5.00	3.0
Slump (mm)	80	180
Unit Weight (kg/m^3)	2370	2440
Initial Set (Min.)	216	230
Final Set (Min.)	269	288
Compressive Strength (MPa)		
1 day	14.8	23.3
3 days	22.4	32.5
7 days	32.5	37.2
28 days	42.4	48.8
91 days	47.2	53.8
Splitting Tensile Strength (MPa)		
1 day	1.8	2.6
3 days	2.1	3.1
7 days	2.7	3.4
28 days	3.1	3.8
91 days	3.9	4.2
Drying Shrinkage Development (% Length Change) [1]		
4 days	0.010	0.009
7 days	0.018	0.013
14 days	0.025	0.019
28 days	0.032	0.026
56 days	0.038	0.032
112 days	0.045	CIP
224 days	CIP	CIP
448 days	CIP	CIP
Permeability @ 91 days (Coulombs)	2550	2350

Notes: CIP - Collection in Progress NC - Not Collected

[1] Percentage decrease in length

B.7.11. EMISSIONS

Table B.7.22.a: CPR – Emissions for 10/16/2007 – 10/18/2007

Time	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
10/16/2007 9:00	8.70E-04	1.84E-06	2.13E-05	6.93E-04
10/16/2007 10:00	1.03E-03	8.96E-06	2.45E-05	7.54E-04
10/16/2007 11:00	1.02E-03	6.44E-06	2.68E-05	7.43E-04
10/16/2007 12:00	1.07E-03	6.30E-06	3.17E-05	8.52E-04
10/16/2007 13:00	1.10E-03	6.79E-06	2.85E-05	7.20E-04
10/16/2007 14:00	1.07E-03	6.60E-06	3.00E-05	7.91E-04
10/16/2007 15:00	7.42E-04	4.46E-06	3.31E-05	8.41E-04
10/16/2007 16:00	6.58E-04	7.03E-06	2.41E-05	7.26E-04
10/16/2007 17:00	9.26E-04	1.06E-05	2.71E-05	5.81E-04
10/16/2007 18:00	6.69E-04	4.57E-06	3.88E-05	7.75E-04
10/16/2007 19:00	7.60E-04	6.13E-06	3.99E-05	7.57E-04
10/16/2007 20:00	8.32E-04	6.16E-06	3.71E-05	6.71E-04
10/16/2007 21:00	9.27E-04	6.92E-06	3.32E-05	6.24E-04
10/16/2007 22:00	9.56E-04	6.78E-06	3.45E-05	7.08E-04
10/16/2007 23:00	8.32E-04	7.51E-06	3.35E-05	7.00E-04
10/17/2007 0:00	7.42E-04	6.52E-06	3.25E-05	7.12E-04
10/17/2007 1:00	8.69E-04	5.48E-06	2.65E-05	6.16E-04
10/17/2007 2:00	9.92E-04	6.76E-06	2.88E-05	6.22E-04
10/17/2007 3:00	9.53E-04	5.31E-06	3.12E-05	6.42E-04
10/17/2007 4:00	7.96E-04	7.33E-06	3.49E-05	7.14E-04
10/17/2007 5:00	7.53E-04	7.35E-06	3.18E-05	5.52E-04
10/17/2007 6:00	1.05E-03	8.65E-06	3.28E-05	5.73E-04
10/17/2007 7:00	1.09E-03	8.23E-06	3.29E-05	5.66E-04
10/17/2007 8:00	9.28E-04	7.33E-06	2.63E-05	5.23E-04
10/17/2007 9:00	1.01E-03	7.42E-06	2.62E-05	5.39E-04
10/17/2007 10:00	7.16E-04	2.90E-06	2.15E-05	5.53E-04
10/17/2007 11:00	8.03E-04	2.27E-06	2.35E-05	5.71E-04
10/17/2007 12:00	1.02E-03	2.40E-06	2.67E-05	5.85E-04
10/17/2007 13:00	1.16E-03	2.74E-06	3.31E-05	7.58E-04
10/17/2007 14:00	9.76E-04	3.79E-06	3.64E-05	6.80E-04
10/17/2007 15:00	7.50E-04	1.72E-06	3.96E-05	6.61E-04
10/17/2007 16:00	1.16E-03	2.47E-06	4.16E-05	6.46E-04
10/17/2007 17:00	7.06E-04	2.14E-06	3.31E-05	5.84E-04
10/17/2007 18:00	9.74E-04	1.65E-06	3.75E-05	6.41E-04
10/17/2007 19:00	7.47E-04	2.54E-06	2.99E-05	5.60E-04
10/17/2007 20:00	8.86E-04	2.42E-06	2.91E-05	5.43E-04
10/17/2007 21:00	9.89E-04	1.75E-06	3.51E-05	5.75E-04
10/17/2007 22:00	7.12E-04	2.70E-06	3.35E-05	6.56E-04
10/17/2007 23:00	7.79E-04	2.97E-06	2.78E-05	5.46E-04
10/18/2007 0:00	8.53E-04	2.72E-06	2.32E-05	5.07E-04
10/18/2007 1:00	9.51E-04	3.19E-06	2.19E-05	4.87E-04
10/18/2007 2:00	8.11E-04	2.82E-06	2.25E-05	5.92E-04
10/18/2007 3:00	7.16E-04	3.80E-06	2.28E-05	6.84E-04
10/18/2007 4:00	7.44E-04	2.12E-06	2.27E-05	5.61E-04
10/18/2007 5:00	8.09E-04	3.18E-06	2.29E-05	6.09E-04
10/18/2007 6:00	8.03E-04	2.60E-06	1.75E-05	6.07E-04
10/18/2007 7:00	8.09E-04	1.97E-06	1.19E-05	4.49E-04
10/18/2007 8:00	9.29E-04	4.11E-06	1.39E-05	5.57E-04

Table B.7.22.b: CPR – Emissions for 10/18/2007 – 10/19/2007

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
10/18/2007 9:00	7.17E-04	3.61E-06	1.17E-05	5.46E-04
10/18/2007 10:00	9.87E-04	2.52E-06	2.05E-05	5.93E-04
10/18/2007 11:00	1.17E-03	5.20E-06	1.94E-05	5.64E-04
10/18/2007 12:00	1.10E-03	8.51E-06	1.83E-05	4.37E-04
10/18/2007 13:00	9.93E-04	5.27E-06	2.03E-05	4.98E-04
10/18/2007 14:00	1.16E-03	3.76E-06	2.39E-05	5.76E-04
10/18/2007 15:00	1.04E-03	1.91E-06	2.39E-05	5.47E-04
10/18/2007 16:00	8.67E-04	8.77E-07	2.00E-05	4.57E-04
10/18/2007 17:00	1.07E-03	5.78E-07	2.12E-05	5.19E-04
10/18/2007 18:00	1.05E-03	2.93E-07	1.97E-05	4.29E-04
10/18/2007 19:00	1.17E-03	3.64E-07	2.19E-05	5.26E-04
10/18/2007 20:00	1.08E-03	3.65E-07	2.24E-05	4.70E-04
10/18/2007 21:00	1.07E-03	1.78E-07	1.87E-05	5.47E-04
10/18/2007 22:00	1.06E-03	1.75E-07	1.65E-05	4.62E-04
10/18/2007 23:00	1.06E-03	5.11E-07	1.85E-05	5.57E-04
10/19/2007 0:00	1.40E-03	7.52E-07	2.49E-05	6.57E-04
10/19/2007 1:00	9.76E-04	9.66E-07	1.63E-05	3.18E-04
10/19/2007 2:00	8.72E-04	8.99E-07	1.28E-05	2.69E-04
10/19/2007 3:00	8.28E-04	6.36E-07	1.20E-05	2.93E-04
10/19/2007 4:00	9.02E-04	6.32E-07	1.37E-05	4.67E-04
10/19/2007 5:00	1.08E-03	2.85E-07	1.69E-05	6.05E-04
10/19/2007 6:00	1.13E-03	5.98E-07	2.39E-05	5.29E-04
10/19/2007 7:00	1.02E-03	4.20E-07	2.99E-05	4.75E-04
10/19/2007 8:00	1.20E-03	3.95E-07	3.76E-05	4.51E-04
Average	9.37E-04	3.72E-06	2.61E-05	5.89E-04
C. V. (%)	16.7	73.4	29.1	19.7
Normality P-Value[1]	0.011	<0.005	0.065	0.278

Notes: [1] Based on Anderson Darling Normality Test NC - Not Collected

APPENDIX B.8

RAW DATA FOR *CTS BURN*

B.8.1. GENERAL COMMENTS

- The raw data from the CTS burn are presented in this appendix.
- Coal, scrap tires and switchgrass are the fuels used in the burn.
- The burn lasted for only two days from 9 AM on November 27, 2007 to 9 AM on November 29, 2007.

B.8.2. NOTATION

CPR – Cement Plant Results

ELR – External Lab Results

AUR – Auburn University Results

C. V. – Coefficient of Variation

B.8.3. CHEMICAL COMPOSITION OF RAW MATERIALS

Table B.8.1: CPR - Chemical Composition of Raw Materials

Property (wt. %)	**Raw Material One**	**Raw Material Two**	**Raw Material Three**	**Raw Material Four**	**Raw Material Five**	**Raw Material Six**
Al_2O_3	NR	NR	NR	NR	NR	NR
CaO	NR	NR	NR	NR	NR	NR
Fe_2O_3	NR	NR	NR	NR	NR	NR
K_2O	NR	NR	NR	NR	NR	NR
MgO	NR	NR	NR	NR	NR	NR
Na_2O	NR	NR	NR	NR	NR	NR
SiO_2	NR	NR	NR	NR	NR	NR
SO_3	NR	NR	NR	NR	NR	NR
Moisture	NR	NR	NR	NR	NR	NR
LOI	NR	NR	NR	NR	NR	NR

Notes: ND - Not Detected NR - Not Reported

Table B.8.2: ELR - Chemical Composition of Raw Materials

Property	Raw Material One	Raw Material Two	Raw Material Three	Raw Material Four	Raw Material Five	Raw Material Six
Al_2O_3 (wt. %)	25.84	0.26	5.89	3.11	0.85	NR
CaO (wt. %)	2.51	53.71	33.82	35.77	0.16	NR
Fe_2O_3 (wt. %)	10.39	0.10	2.63	30.11	0.15	NR
K_2O (wt. %)	2.40	0.05	0.91	0.01	0.14	NR
MgO (wt. %)	1.23	1.38	1.87	13.04	0.08	NR
Na_2O (wt. %)	0.78	0.11	0.27	0.12	0.37	NR
P_2O_5 (wt. %)	0.54	0.00	0.03	0.65	0.00	NR
SiO_2 (wt. %)	47.69	0.67	23.94	12.65	97.65	NR
SO_3 (wt. %)	0.14	0.11	0.14	0.41	0.08	NR
TiO_2 (wt. %)	1.21	0.00	0.24	0.24	0.20	NR
Moisture (wt. %)	23.10	1.63	6.12	4.35	1.86	NR
LOI (wt. %)	6.88	43.58	30.17	0.38	0.30	NR
As (ppm)	181	4	14	7	ND	NR
Ba (ppm)	2000	100	300	100	200	NR
Cd (ppm)	ND	ND	ND	ND	ND	NR
Cl (ppm)	77	47	45	97	87	NR
Co (ppm)	74	4	17	19	9	NR
Cr (ppm)	157	44	53	2454	25	NR
Cu (ppm)	139	ND	ND	ND	ND	NR
Hg (ppm)	0.05	0.08	0.07	0.31	0.06	NR
Mn (ppm)	600	100	300	34900	100	NR
Mo (ppm)	6	ND	ND	52	ND	NR
Ni (ppm)	129	22	23	6430	< 5	NR
Pb (ppm)	106	6	31	< 4	24	NR
Sb (ppm)	NR	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	ND	NR
Sr (ppm)	1300	200	100	200	0	NR
V (ppm)	332	16	61	772	11	NR
Zn (ppm)	152	ND	35	97	ND	NR

Notes: ND - Not Detected NR - Not Reported

B.8.4. CHEMICAL COMPOSITION OF KILN FEED

Table B.8.3: CPR - Chemical Composition of Kiln Feed

Property (wt. %)	11/27/2008		11/28/2007		Average	C. V. (%)
	2:23 AM	2:10 PM	1:39 AM	2:02 PM		
Al_2O_3	3.12	3.22	3.08	3.03	3.11	2.6
CaO	42.79	42.88	42.57	42.55	42.70	0.4
Fe_2O_3	2.04	2.03	2.03	2	2.03	0.9
K_2O	0.37	0.38	0.38	0.4	0.38	3.3
MgO	1.89	1.87	1.91	1.9	1.89	0.9
Na_2O	0.04	0.05	0.05	0.06	0.05	16.3
Na_2O_{eq}	0.28	0.3	0.3	0.32	0.30	5.4
SiO_2	13.79	13.72	13.63	13.67	13.70	0.5
SO_3	0.2	0.21	0.2	0.21	0.21	2.8
LOI	35	35	35	35	35.00	0.0

Table B.8.4: ELR - Chemical Composition of Kiln Feed

Property	**3-Day Composite**
Al_2O_3 (wt. %)	3.26
CaO (wt. %)	42.69
Fe_2O_3 (wt. %)	2.00
K_2O (wt. %)	0.37
MgO (wt. %)	2.07
Na_2O (wt. %)	0.20
P_2O_5 (wt. %)	0.05
SiO_2 (wt. %)	13.95
SO_3 (wt. %)	0.33
TiO_2 (wt. %)	0.14
Moisture (wt. %)	0.18
LOI (wt. %)	34.81
As (ppm)	26
Ba (ppm)	200
Cd (ppm)	ND
Cl (ppm)	182
Co (ppm)	14
Cr (ppm)	107
Cu (ppm)	ND
Hg (ppm)	0.06
Mn (ppm)	1000
Mo (ppm)	15
Ni (ppm)	1640
Pb (ppm)	ND
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	300
V (ppm)	66
Zn (ppm)	34

Notes: NR - Not Reported
ND- Not Detected

B.8.5. CHEMICAL COMPOSITION OF FUELS

Table B.8.5: CPR - Chemical Composition of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	17.78
	Fixed Carbon	54.51
	Volatile Matter	27.71
Ultimate Analysis	**Carbon**	72.51
	Hydrogen	4.37
	Nitrogen	1.33
	Oxygen	2.65
	Sulfur	1.36
Standard Parameters	Al_2O_3	22.74
	CaO	8.16
	Fe_2O_3	7.94
	K_2O	2.66
	MgO	1.07
	Na_2O	0.16
	SiO_2	48.84
	SO_3	7.02
Heat Value [1]		12495

Notes: [1] Value is Reported as BTU/lb

Table B.8.6: ELR - Proximate, Ultimate, and Combustion of Coal

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	16.45
	Fixed Carbon	55.19
	Volatile Matter	28.36
Ultimate Analysis	**Carbon**	71.33
	Hydrogen	3.75
	Nitrogen	0.96
	Oxygen	6.41
	Sulfur	1.1
Heat Value [1]		12664

Notes: [1] Value is Reported as BTU/lb

Table B.8.7: ELR - Standard Parameters of Coal

Property	3-Day Composite
Al_2O_3 (wt. %)	23.87
CaO (wt. %)	12.81
Fe_2O_3 (wt. %)	7.77
K_2O (wt. %)	2.56
MgO (wt. %)	1.31
Na_2O (wt. %)	0.57
P_2O_5 (wt. %)	0.12
SiO_2 (wt. %)	49.44
SO_3 (wt. %)	0.33
TiO_2 (wt. %)	1.04
As (ppm)	114
Ba (ppm)	1100
Cd (ppm)	ND
Cl (ppm)	236
Co (ppm)	43
Cr (ppm)	132
Cu (ppm)	103
Hg (ppm)	0.076
Mn (ppm)	500
Mo (ppm)	29
Ni (ppm)	78
Pb (ppm)	ND
Sb (ppm)	NR
Se (ppm)	7
Sr (ppm)	400
V (ppm)	228
Zn (ppm)	9

Notes: NR - Not Reported
ND- Not Detected

Table B.8.8: ELR - Proximate, Ultimate, and Combustion Analysis of Tires

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	24.40
	Fixed Carbon	19.82
	Moisture [1]	1.00
	Volatile Matter	55.78
Ultimate Analysis	**Carbon**	72.63
	Hydrogen	0.23
	Nitrogen	0.39
	Oxygen	1.06
	Sulfur	1.29
Heat Value [2]		13239

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.8.9: ELR - Standard Parameters of Tires

Property	3-Day Composite
Al_2O_3 (wt. %)	0.53
CaO (wt. %)	2.94
Fe_2O_3 (wt. %)	77.06
K_2O (wt. %)	0.25
MgO (wt. %)	0.20
Na_2O (wt. %)	0.13
P_2O_5 (wt. %)	0.20
SiO_2 (wt. %)	5.38
SO_3 (wt. %)	2.25
TiO_2 (wt. %)	0.10
As (ppm)	ND
Ba (ppm)	0
Cd (ppm)	ND
Cl (ppm)	1696
Co (ppm)	724
Cr (ppm)	129
Cu (ppm)	0
Hg (ppm)	NR
Mn (ppm)	4300
Mo (ppm)	11
Ni (ppm)	332
Pb (ppm)	8
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	20
V (ppm)	10
Zn (ppm)	0

Notes: NR - Not Reported
ND- Not Detected

Table B.8.10: ELR - Proximate, Ultimate, and Combustion Analysis of Switchgrass

Test	Parameter	Value (wt. %)
Proximate Analysis	**Ash**	5.27
	Fixed Carbon	17.02
	Moisture [1]	9.87
	Volatile Matter	77.72
Ultimate Analysis	**Carbon**	50.25
	Hydrogen	5.70
	Nitrogen	1.22
	Oxygen	37.37
	Sulfur	0.19
Heat Value [2]		8162

Notes:

[1] As Received

[2] Value is Reported as BTU/lb

Table B.8.11: ELR - Standard Parameters of Switchgrass

Property	3-Day Composite
Al_2O_3 (wt. %)	1.57
CaO (wt. %)	13.99
Fe_2O_3 (wt. %)	1.06
K_2O (wt. %)	24.72
MgO (wt. %)	9.02
Na_2O (wt. %)	0.96
P_2O_5 (wt. %)	8.49
SiO_2 (wt. %)	34.86
SO_3 (wt. %)	4.53
TiO_2 (wt. %)	0.14
As (ppm)	11
Ba (ppm)	739
Cd (ppm)	ND
Cl (ppm)	819
Co (ppm)	6
Cr (ppm)	22
Cu (ppm)	56
Hg (ppm)	0.1
Mn (ppm)	5511
Mo (ppm)	146
Ni (ppm)	145
Pb (ppm)	47
Sb (ppm)	NR
Se (ppm)	ND
Sr (ppm)	267
V (ppm)	82
Zn (ppm)	1118

Notes: NR - Not Reported
ND- Not Detected

Table B.8.12: AUR - Density of Switchgrass

Sample #	Density (kg/m3)
1	70.2
2	76.8
3	76.1
4	70.0
5	73.0
6	77.3
7	70.5
8	68.7
9	69.1
10	72.4
11	75.3
12	76.0
13	78.0
14	74.2
15	76.3
16	68.5
Average	73.3

B.8.6. CHEMICAL COMPOSITION OF CEMENT KILN DUST (CKD)

Table B.8.13: CPR - Chemical Composition of Cement Kiln Dust

Property (wt. %)	11/27/2007	11/28/2007		11/29/2007	Average
	6:47 PM	9:23 AM	6:48 PM	9:11 AM	
Al_2O_3	3.9	3.8	4.05	4.11	3.97
CaO	44.49	44.77	44.08	44.07	44.35
Fe_2O_3	1.96	1.96	2.05	2.02	2.00
K_2O	0.58	0.56	0.58	0.6	0.58
MgO	1.3	1.32	1.36	1.34	1.33
Na_2O	0.05	0.05	0.05	0.05	0.05
SiO_2	12.11	11.89	12.36	12.24	12.15
SO_3	0.19	0.13	0.23	0.26	0.20

Table B.8.14: ELR - Chemical Composition of Cement Kiln Dust

Property	**11/27/2007**		**11/28/2007**		**Average**
	10:00 AM	10:00 PM	10:00 AM	10:00 PM	
Al_2O_3 (wt. %)	3.49	4.42	3.72	3.94	3.89
CaO (wt. %)	44.65	43.07	44.20	44.16	44.02
Fe_2O_3 (wt. %)	2.04	2.13	1.86	1.97	2.00
K_2O (wt. %)	0.76	0.57	0.49	0.50	0.58
MgO (wt. %)	1.35	1.33	1.37	1.42	1.37
Na_2O (wt. %)	0.04	0.08	0.09	0.15	0.09
P_2O_5 (wt. %)	0.11	0.05	0.05	0.06	0.07
SiO_2 (wt. %)	10.57	12.82	11.25	11.66	11.58
SO_3 (wt. %)	0.23	0.36	0.27	0.30	0.29
TiO_2 (wt. %)	0.15	0.20	0.15	0.16	0.17
Moisture (wt. %)	0.28	0.21	0.22	0.23	0.24
LOI (wt. %)	36.50	34.86	36.45	35.59	35.85
As (ppm)	19	19	19	29	22
Ba (ppm)	300	300	200	200	250
Cd (ppm)	ND	ND	ND	ND	ND
Cl (ppm)	172	602	224	214	303
Co (ppm)	19	16	14	15	16
Cr (ppm)	51	65	60	102	70
Cu (ppm)	19	ND	ND	ND	5
Hg (ppm)	0.48	0.30	0.12	0.10	0
Mn (ppm)	600	500	500	600	550
Mo (ppm)	22	5	ND	5	8
Ni (ppm)	28	1336	8	971	586
Pb (ppm)	12	27	11	ND	13
Sb (ppm)	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	ND
Sr (ppm)	300	300	300	300	300
V (ppm)	47	72	66	81	67
Zn (ppm)	38	34	33	30	34

Notes: ND - Not Detected NR - Not Reported

B.8.7. CHEMICAL COMPOSITION OF CLINKER

Table B.8.15.a: CPR - Chemical Composition of Clinker for 11/27/2007

Property (wt. %)	**11/27/2007**							
	9:59 AM	11:41 AM	2:05 PM	3:51 PM	5:24 PM	7:51 PM	9:47 PM	11:50 PM
Al_2O_3	5.28	5.20	5.18	5.25	5.19	5.17	5.31	5.20
CaO	64.77	64.82	64.65	64.62	64.59	64.62	64.64	64.48
Fe_2O_3	3.44	3.43	3.45	3.44	3.43	3.36	3.44	3.41
K_2O	0.61	0.52	0.64	0.65	0.64	0.64	0.63	0.60
MgO	3.04	2.98	2.98	3.07	3.09	3.13	3.16	3.15
Na_2O	0.09	0.09	0.10	0.10	0.10	0.09	0.09	0.09
Na_2O_{eq}	0.49	0.43	0.52	0.53	0.52	0.51	0.50	0.48
SiO_2	21.52	21.64	21.61	21.59	21.55	21.46	21.45	21.36
SO_3	0.66	0.50	0.74	0.75	0.81	0.71	0.59	0.62
F CaO	0.84	0.24	0.30	0.36	0.42	1.20	1.50	1.80
C_3A	8.17	7.98	7.89	8.09	7.95	8.02	8.25	8.01
C_4AF	10.47	10.44	10.50	10.47	10.44	10.22	10.47	10.38
C_3S	59.74	59.56	59.22	58.80	59.39	60.44	59.54	60.35
C_2S	16.63	17.11	17.28	17.54	16.98	15.93	16.58	15.71

Table B.8.15.b: CPR - Chemical Composition of Clinker for 11/28/2007

Property (wt. %)	10/28/2007											
	1:43 AM	4:01 AM	5:38 AM	8:01 AM	10:03 AM	11:41 AM	1:58 PM	3:50 PM	5:38 PM	7:52 PM	9:01 PM	11:00 PM
Al_2O_3	5.16	5.15	5.15	5.17	5.13	5.10	5.07	4.99	5.08	5.04	5.06	4.97
CaO	64.61	64.69	64.58	64.72	64.85	64.75	64.86	64.76	64.58	64.80	64.83	64.92
Fe_2O_3	3.36	3.50	3.48	3.29	3.35	3.42	3.40	3.43	3.40	3.33	3.34	3.43
K_2O	0.60	0.62	0.65	0.71	0.61	0.65	0.60	0.64	0.64	0.67	0.65	0.58
MgO	3.18	3.20	3.15	3.14	3.15	3.14	3.18	3.18	3.17	3.22	3.24	3.22
Na_2O	0.10	0.09	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10	0.09
Na_2O_{eq}	0.49	0.50	0.53	0.56	0.49	0.52	0.48	0.51	0.51	0.54	0.53	0.47
SiO_2	21.54	21.53	21.48	21.36	21.50	21.54	21.56	21.55	21.34	21.39	21.36	21.48
SO_3	0.75	0.52	0.73	0.66	0.45	0.55	0.48	0.54	0.58	0.74	0.74	0.49
F CaO	0.96	0.84	0.78	2.58	1.14	0.72	0.54	0.60	0.90	1.80	1.98	0.90
C_3A	7.99	7.73	7.76	8.13	7.93	7.73	7.68	7.42	7.71	7.72	7.76	7.37
C_4AF	10.22	10.65	10.59	10.01	10.19	10.41	10.35	10.44	10.35	10.13	10.16	10.44
C_3S	59.85	60.12	60.08	61.70	61.35	60.74	61.27	61.43	61.73	62.62	62.82	62.75
C_2S	16.60	16.37	16.26	14.69	15.36	15.93	15.59	15.44	14.61	14.09	13.85	14.25

Table B.8.15.c: CPR - Chemical Composition of Clinker for 11/29/2007

Property (wt. %)	**11/29/2007**						**Average**	**C. V. (%)**	**Normality P-Value[1]**
	12:05 AM	**1:48 AM**	**3:58 AM**	**5:41 AM**	**7:48 AM**	**9:40 AM**			
Al_2O_3	4.90	4.83	4.94	5.02	5.01	4.88	5.09	2.4	<0.005
CaO	64.95	64.60	64.82	64.92	64.87	64.99	64.74	0.2	0.093
Fe_2O_3	3.36	3.27	3.31	3.32	3.32	3.30	3.39	1.8	0.177
K_2O	0.56	0.70	0.70	0.70	0.67	0.69	0.64	7.1	0.412
MgO	3.13	3.16	3.17	3.21	3.20	3.20	3.15	2.1	0.625
Na_2O	0.09	0.10	0.10	0.10	0.09	0.09	0.09	5.3	0.179
Na_2O_{eq}	0.46	0.56	0.56	0.56	0.53	0.54	0.51	6.4	<0.005
SiO_2	21.58	21.38	21.30	21.35	21.54	21.50	21.48	0.4	0.226
SO_3	0.53	0.74	0.91	0.68	0.61	0.56	0.64	18.3	<0.005
F CaO	0.48	0.96	1.44	1.68	0.60	0.66	1.01	58.3	<0.005
C_3A	7.30	7.27	7.49	7.69	7.66	7.35	7.77	3.6	0.021
C_4AF	10.22	9.95	10.07	10.10	10.10	10.04	10.30	1.9	<0.005
C_3S	62.68	63.37	64.08	63.56	61.98	63.67	61.26	2.6	0.143
C_2S	14.58	13.49	12.72	13.26	15.00	13.61	15.36	8.9	0.107

Notes: [1] Based on Anderson-Darling Normality Test

Table B.8.16: ELR - Chemical Composition of Clinker

Property	10/27/2007		10/28/2007		Average
	1	2	1	2	
Al_2O_3 (wt. %)	4.64	5.10	5.15	4.41	4.83
CaO (wt. %)	65.95	64.31	64.44	66.65	65.34
Fe_2O_3 (wt. %)	3.57	3.11	3.18	3.50	3.34
K_2O (wt. %)	0.60	0.67	0.56	0.54	0.59
MgO (wt. %)	3.42	3.25	3.27	3.44	3.35
Na_2O (wt. %)	0.09	0.16	0.10	0.12	0.12
P_2O_5 (wt. %)	0.07	0.09	0.07	0.06	0.07
SiO_2 (wt. %)	20.47	21.94	21.71	19.98	21.03
SO_3 (wt. %)	0.58	0.80	0.84	0.60	0.71
TiO_2 (wt. %)	0.23	0.20	0.22	0.21	0.22
Moisture (wt. %)	0.00	0.00	0.00	0.00	0.00
LOI (wt. %)	0.16	0.16	0.24	0.26	0.21
As (ppm)	20	32	27	23	26
Ba (ppm)	300	300	400	300	325
Cd (ppm)	ND	ND	ND	ND	ND
Cl (ppm)	166	388	829	212	399
Co (ppm)	18	17	12	17	16
Cr (ppm)	108	104	97	108	104
Cu (ppm)	94	49	57	68	67
Hg (ppm)	0.05	0.05	0.08	0.04	0.05
Mn (ppm)	1600	1400	1500	1600	1525
Mo (ppm)	17	25	ND	11	13
Ni (ppm)	62	418	15	52	137
Pb (ppm)	ND	ND	18	ND	5
Sb (ppm)	NR	NR	NR	NR	NR
Se (ppm)	ND	ND	ND	ND	NA
Sr (ppm)	400	400	400	400	400
V (ppm)	72	78	70	64	71
Zn (ppm)	83	97	61	81	81

Notes: NA - Not Applicable ND - Not Detected

B.8.8. CHEMICAL COMPOSITION OF CEMENT

Table B.8.17: CPR - Chemical Composition of Cement

Property (wt. %)	12/12/2007			12/13/2007			Average	C. V. (%)	Normality P-Value[1]
	5:35 PM	7:36 PM	10:05 PM	12:54 AM	4:01 AM	6:53 AM			
Al_2O_3	4.79	4.79	4.77	4.77	4.81	4.82	4.79	0.4	0.123
CaO	63.25	63.31	63.12	63.01	63.29	63.22	63.20	0.2	0.100
Fe_2O_3	3.18	3.19	3.17	3.17	3.17	3.18	3.18	0.3	0.165
K_2O	0.56	0.56	0.56	0.55	0.56	0.57	0.56	1.1 [1]	0.052
MgO	3.24	3.26	3.23	3.24	3.26	3.29	3.25	0.7	0.352
Na_2O	0.08	0.08	0.07	0.07	0.07	0.08	0.08	7.3 [1]	<0.005
Na_2O_{eq}	0.45	0.45	0.44	0.43	0.44	0.46	0.45	2.4 [1]	<0.005
SiO_2	20.46	20.4	20.2	20.2	20.31	20.28	20.31	0.5	0.192
SO_3	2.58	2.66	2.64	2.6	2.66	2.69	2.64	1.6	0.224
F CaO	1.2	1.14	1.02	1.02	1.08	1.2	1.11	7.5	0.341
LOI	1.18	0.84	1.12	1.3	1.12	1.02	1.10	14.2 [1]	<0.005
C_3A	7.3	7.3	7.28	7.29	7.39	7.4	58.67	0.7	0.412
C_4AF	9.69	9.71	9.65	9.65	9.66	9.68	13.96	0.3	0.278
C_3S	57.89	58.36	59.32	58.98	58.86	58.63	7.33	0.9	0.524
C_2S	14.99	14.46	13.16	13.42	13.81	13.91	9.67	4.8 [1]	<0.005
Blaine SSA (m^2/kg)	373	381	387	376	374	361	375.33	2.3	0.729

Notes: [1] Based on Anderson-Darling Normality Test [2] Data not normally distributed

Table B.8.18: ELR - Chemical Composition of Cement

Property	11/27/2007	11/28/2007	Average
Al_2O_3 (wt. %)	3.99	4.93	4.46
CaO (wt. %)	65.78	62.98	64.38
Fe_2O_3 (wt. %)	3.35	3.05	3.20
K_2O (wt. %)	0.58	0.58	0.58
MgO (wt. %)	3.14	3.18	3.16
Na_2O (wt. %)	0.10	0.13	0.12
P_2O_5 (wt. %)	0.06	0.07	0.07
SiO_2 (wt. %)	18.86	20.99	19.93
SO_3 (wt. %)	2.51	2.99	2.75
TiO_2 (wt. %)	0.21	0.20	0.21
Moisture (wt. %)	0.06	0.39	0.23
LOI (wt. %)	1.20	0.70	0.95
C_3S (wt. %)	85.70	50.86	48.40
C_2S (wt. %)	-10.58	21.81	25.17
C_3A (wt. %)	4.91	7.90	7.80
C_4AF (wt. %)	10.19	9.28	9.46
TOC (wt. %)	0.1	2.29	1.20
As (ppm)	13	31	22
Ba (ppm)	300	400	350
Cd (ppm)	ND	ND	ND
Cl (ppm)	73	91	82
Co (ppm)	21	8	15
Cr (ppm)	104	103	104
Cu (ppm)	22	33	28
Hg (ppm)	0.03	0.07	0.05
Mn (ppm)	1500	1400	1450
Mo (ppm)	29	30	30
Ni (ppm)	32	315	174
Pb (ppm)	13	ND	7
Sb (ppm)	NR	NR	NR
Se (ppm)	ND	ND	ND
Sr (ppm)	400	400	400
V (ppm)	68	68	68
Zn (ppm)	83	66	75

Notes: ND - Not Detected NR - Not Reported

B.8.9. PHYSICAL PROPERTIES OF CEMENT

Table B.8.19: CPR - Physical Properties of Cement

Property	**Value**
Air in Mortar (%)	5.2
Blaine Specific Surface Area (m^2/kg)	373
Autoclave Expansion (% Exp.)	0.06
Cube Flow (%)	105.0
Comp Str 1day (MPa)	15.4
Comp Str 3day (MPa)	24.6
Comp Str 7day (MPa)	31.6
Comp Str 28day (MPa)	41.3
Normal Consistency (%)	25.0
Gillmore Initial Set (Min)	120
Gillmore Final Set (Min)	240
Vicat Initial Set (Min)	66
Vicat Final Set (Min)	225

Notes: % Exp. - Percent Expansion

Table B.8.20: AUR - Physical Properties of Cement

Property	**Composite**
Autoclave Expansion (% Exp.)	0.05
Cube Flow (%)	106
Comp Str 1day (MPa)	10.5
Comp Str 3day (MPa)	21.3
Comp Str 7day (MPa)	26.3
Comp Str 28day (MPa)	32.7
Normal Consistency (%)	26.2
Gillmore Initial Set (Min)	110
Gillmore Final Set (Min)	210
Vicat Initial Set (Min)	94
Vicat Final Set (Min)	180
Drying Shrinkage @ 7 days (% LC)	-0.047
Drying Shrinkage @ 14 days (% LC)	-0.071
Drying Shrinkage @ 21 days (% LC)	-0.082
Drying Shrinkage @ 28 days (% LC)	-0.090

Notes: % LC - Percent Length Change
% Exp. - Percent Expansion

B.8.10. PROPERTIES OF CONCRETE

Table B.8.21: Concrete Properties

Property	AUR	
	Mix w/c=0.44	Mix w/c=0.37
Total Air Content (%)	4.00	5.0
Slump (mm)	60	150
Unit Weight (kg/m^3)	2441	2395
Initial Set (Min.)	154	200
Final Set (Min.)	227	259
Compressive Strength (MPa)		
1 day	16.5	23.0
3 days	20.9	31.2
7 days	30.1	38.2
28 days	40.1	49.8
91 days	48.5	CIP
Splitting Tensile Strength (MPa)		
1 day	1.7	2.8
3 days	2.0	3.3
7 days	2.5	3.8
28 days	3.4	4.2
91 days	4.0	CIP
Drying Shrinkage Development (% Length Change) [1]		
4 days	0.009	0.010
7 days	0.012	0.018
14 days	0.019	0.022
28 days	0.024	0.030
56 days	0.032	0.036
112 days	CIP	CIP
224 days	CIP	CIP
448 days	CIP	CIP
Permeability @ 91 days (Coulombs)	2750	CIP

Notes: CIP - Collection in Progress [1] Percentage decrease in length

TABLE B.8.22: CPR – EMISSIONS FOR 11/27/2007 – 11/29/2007

Time	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
11/27/2007 9:00	1.31E-03	8.81E-06	1.87E-05	4.29E-04
11/27/2007 10:00	1.54E-03	7.30E-06	2.24E-05	4.48E-04
11/27/2007 11:00	1.81E-03	7.12E-06	2.30E-05	3.56E-04
11/27/2007 12:00	1.77E-03	7.53E-06	2.42E-05	3.85E-04
11/27/2007 13:00	1.61E-03	5.58E-06	2.32E-05	3.83E-04
11/27/2007 14:00	1.43E-03	4.67E-06	2.27E-05	3.70E-04
11/27/2007 15:00	1.27E-03	4.74E-06	2.15E-05	3.37E-04
11/27/2007 16:00	1.44E-03	4.69E-06	2.38E-05	3.70E-04
11/27/2007 17:00	1.55E-03	6.05E-06	2.30E-05	3.59E-04
11/27/2007 18:00	1.65E-03	7.36E-06	2.24E-05	4.20E-04
11/27/2007 19:00	1.46E-03	6.85E-06	2.07E-05	3.96E-04
11/27/2007 20:00	1.23E-03	7.03E-06	1.85E-05	3.92E-04
11/27/2007 21:00	1.27E-03	7.69E-06	2.16E-05	3.75E-04
11/27/2007 22:00	1.28E-03	8.87E-06	2.28E-05	4.01E-04
11/27/2007 23:00	1.13E-03	6.02E-06	2.06E-05	3.88E-04
11/28/2007 0:00	2.06E-03	7.80E-06	2.03E-05	4.26E-04
11/28/2007 1:00	1.56E-03	8.37E-06	1.94E-05	4.08E-04
11/28/2007 2:00	1.67E-03	9.35E-06	2.14E-05	3.78E-04
11/28/2007 3:00	1.51E-03	8.72E-06	2.04E-05	3.48E-04
11/28/2007 4:00	1.53E-03	6.96E-06	2.06E-05	3.28E-04
11/28/2007 5:00	1.55E-03	6.64E-06	2.12E-05	3.36E-04
11/28/2007 6:00	1.61E-03	8.84E-06	2.33E-05	3.56E-04
11/28/2007 7:00	1.42E-03	5.26E-06	2.48E-05	4.28E-04
11/28/2007 8:00	1.18E-03	8.55E-06	1.76E-05	3.56E-04
11/28/2007 9:00	1.16E-03	6.32E-06	1.88E-05	3.38E-04
11/28/2007 10:00	1.17E-03	4.71E-06	1.94E-05	3.59E-04
11/28/2007 11:00	1.03E-03	4.82E-06	1.93E-05	3.46E-04
11/28/2007 12:00	1.47E-03	4.93E-06	2.13E-05	4.01E-04
11/28/2007 13:00	1.36E-03	3.85E-06	2.12E-05	3.60E-04
11/28/2007 14:00	1.31E-03	4.01E-06	2.20E-05	3.43E-04
11/28/2007 15:00	1.26E-03	2.79E-06	2.20E-05	3.75E-04
11/28/2007 16:00	1.32E-03	4.29E-06	2.14E-05	3.61E-04
11/28/2007 17:00	1.36E-03	5.16E-06	1.85E-05	3.81E-04
11/28/2007 18:00	1.08E-03	6.17E-06	1.71E-05	3.42E-04
11/28/2007 19:00	1.20E-03	6.25E-06	1.71E-05	3.43E-04
11/28/2007 20:00	1.25E-03	7.34E-06	1.82E-05	3.45E-04
11/28/2007 21:00	1.16E-03	8.03E-06	1.65E-05	3.41E-04
11/28/2007 22:00	1.44E-03	8.71E-06	1.83E-05	3.44E-04
11/28/2007 23:00	1.84E-03	8.40E-06	1.72E-05	3.26E-04
11/29/2007 0:00	1.56E-03	6.41E-06	1.77E-05	3.02E-04
11/29/2007 1:00	1.44E-03	3.35E-06	1.98E-05	3.25E-04
11/29/2007 2:00	1.32E-03	3.97E-06	2.07E-05	3.32E-04
11/29/2007 3:00	1.45E-03	5.35E-06	2.07E-05	3.22E-04
11/29/2007 4:00	1.36E-03	3.43E-06	1.84E-05	3.45E-04
11/29/2007 5:00	1.39E-03	5.33E-06	2.04E-05	3.78E-04
11/29/2007 6:00	1.63E-03	4.36E-06	2.19E-05	4.15E-04
11/29/2007 7:00	1.58E-03	3.64E-06	2.33E-05	3.33E-04
11/29/2007 8:00	1.59E-03	4.46E-06	2.06E-05	3.50E-04
Average	1.43E-03	6.18E-06	2.06E-05	3.66E-04
C. V. (%)	14.9	29.0	10.1	9.1
Normality P-Value[1]	0.169	<0.005	0.09	0.314

Notes: [1] Based on Anderson Darling Normality Test