THE UTILIZATION OF ALTERNATIVE FUELS IN THE PRODUCTION OF PORTLAND CEMENT

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THE UTILIZATION OF ALTERNATIVE FUELS IN THE PRODUCTION OF PORTLAND CEMENT

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A Thesis

Submitted to

the Graduate Faculty of

Auburn University

in Partial Fulfillment of the

Requirements for the

Degree of

Master of Science

Auburn, Alabama
August 4, 2007

THE UTILIZATION OF ALTERNATIVE FUELS IN THE PRODUCTION OF PORTLAND CEMENT

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Dustin Wayne Swart is the son of Roger and Marja Swart of Abilene, Texas. He was born in Abilene, Texas on December 27, 1981. He has one younger sister, Julie. Dustin graduated from Abilene Cooper High School in 2000. After high school, he attended Abilene Christian University for three years, before transferring, and ultimately receiving a Bachelor of Science degree in Civil Engineering from Auburn University in May 2005. Dustin immediately began Graduate School at Auburn University. On July 24, 2005 he married Sarah Anne (McCullough) Swart.

THESIS ABSTRACT

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Master of Science, August 4, 2007
(B.S., Auburn University, 2005)

339 Typed Pages

Directed by Anton K. Schindler

The production of portland cement converts many different raw materials into clinker, in the presence of temperatures on the order of 1,500 °C. Historically, nonrenewable fossil fuels have been used to maintain these temperatures; however, the cement industry has started to explore options to supplement nonrenewable fuels with alternative sources. These alternative fuels are generally derived from waste, and their disposal in a cement kiln could benefit the cement industry as well as the environment.

The cement for this study was produced in a full-scale, operational, cement plant, where three different 3-day test burns were conducted using various combinations of alternative fuels. The fuels used in each burn period were: Coal Only; Coal plus Tires; and Coal, Tires, and Plastics.

One objective of this study was to determine if the alternative fuels selected could be successfully burned while maintaining production at the cement plant. Although some minor problems did occur, the energy content, availability, cost, and overall compatibility made both tires and specific waste plastics viable options.

Another objective was to determine if the chemical composition of the fuels directly impacted the chemical composition of the clinker and/or cement. The primary chemical compounds; Al_2O_3, CaO, Fe_2O_3, and SiO_2 showed no practically significant changes. Some changes did occur in other compounds, but based on this study it was not possible to conclude that these changes were a direct result of the fuels that were burned.

The main objective of this study was to determine if the fuels had a direct impact on the properties of the cement and/or concrete produced from the cement. Although the results could not be attributed directly to the fuels, some significantly different results were found relative to the baseline burn, which used Coal plus Tires as fuel. Tests of drying shrinkage development, splitting tensile strength of concrete, and concrete permeability all showed no significant changes. Paste setting times showed an acceleration of 27 percent in the Coal, Tires, and Plastics Burn, and concrete setting times showed a retardation of 40 percent in the Coal Only Burn. Additionally, the compressive strength of concrete made from the Coal Only burn period showed a decrease of as much as 20 percent.

The final objective of this study was to determine if the fuels directly affected the emissions. Based on the averages, the Coal plus Tires burn was the highest, and the Coal Only was the lowest in NO_x, SO_2, and VOC. The CO emissions emitted by the cement plant were the highest for the Coal Only burn. The use of tires and waste plastics appear to be feasible alternative fuels for cement production and their use should be further explored.

ACKNOWLEDGMENTS

The author would like to thank a number of different people and groups. First of all, thanks to Dr. Anton Schindler who has provided instruction and guidance throughout this process. Thanks also to Billy Wilson, who has given an abundance of help, education, and friendship along the trip. The personnel at the cement plant have been a key component to this project, and without their assistance, this research could not have been completed.

Thanks also go out to the McCullough family for their support and encouragement. A tremendous thank you goes out to my family, who have supported me in every way. Finally, to my wife Sarah, who has been there for me every step of the way. Without her, I wouldn’t have been able to maintain the path.

Style Manual Used: Chicago Manual of Style, 14th Edition

Computer Software Used: Microsoft Word XP for Windows; Microsoft Excel XP for Windows; Minitab 14 for Windows

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Chapter 1

Research Introduction

1.1 Project Background

The modern day production of portland cement is an industry composed of countless materials, complex facilities, and closely monitored processes. Each of these entities work closely together 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, and many other structures 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, which leaves the sustainability of the process lacking.

Portland cement is manufactured by taking raw materials, which are generally mined from the earth, and chemically fusing them together in the presence of extremely high temperatures. The new product, known as clinker, is ground down with sulfates to a specific particle size distribution, and this final product is known as portland cement. For a more thorough discussion of the portland cement production process, see Section 2.2.

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 run 24 hours a day for seven days a week. With that amount of production, and 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. One aspect of alternative fuels is that they 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, there are certain situations where 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 a significantly less (or even negative) cost, it could be a particularly worthwhile financial undertaking.

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). Not all cement production facilities can consume this quantity of material, but when one considers that there are thousands of facilities worldwide, the quantities of fuels consumed can be staggering. If only a small portion of the nonrenewable resources used in this process could be replaced in many of these facilities, a significant decrease in use of nonrenewable resources could be seen.

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 may have a profound effect on the emissions. The primary fuel that is being used at any given cement plant may produce more emissions than 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 one (Greco et al. 2004). This 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 product that is being formed. This presents issues associated with the altering of the final chemical composition of the portland cement. In turn, these alterations of chemical composition may lead to changes in the properties of the ultimate product, concrete. For this reason, this study seeks to measure the chemical composition of all of the materials involved in the production process, along with all of the outputs from the process. Perhaps then, the effect on chemical composition due to the alternative fuels can be understood. Ultimately, this study will test the physical properties of the cement and concrete and determine if there have been any effects that can be directly associated with the implementation of the alternative fuels. In spite of all the positive aspects of the utilization of alternative fuels, if the final 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 considered 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 as follows:

1. Determine if the utilization of alternative fuels has an impact on the ability of the cement plant to maintain productive operation,
2. Determine if the implementation of alternative fuels has an impact on the chemical composition of clinker and/or portland cement,
3. Determine if the implementation of alternative fuels directly impacts the physical properties of the portland cement,
4. Determine if the implementation of alternative fuels directly impacts the properties of concrete made from this portland cement, and
5. Determine if the implementation of alternative fuels directly impacts the plant emissions.

The first objective was not given much attention by researchers at Auburn University. It was primarily studied by the personnel at the cement plant itself. However, this objective was no less important to the study. 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 changes in chemical composition in the final product. Many physical properties of cement and concrete were measured, and the differences between the cement from each of the fuels was 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 of particular concern to the cement plant. Because the emissions released by a cement plant are closely monitored and controlled, any effects that the combustion of alternative fuels may have displayed were assessed.

1.3 Research Plan

Based on the objectives listed above, a complex yet thorough sampling and testing plan was developed. Researchers at Auburn University and at a cement production facility, referred to as the cement plant, partnered to complete this research plan. The research was conducted during the full-scale production process using the normal procedures utilized at the cement plant. The only change to the production process was the fuels that were used, as they applied to the study.

The research plan consisted of four burn periods in which unique combinations of fuels were used. The first burn period 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 phase maintained coal as the primary fuel, but replaced a portion of it with whole scrapped tires. This is the fuel combination that the cement plant uses in its everyday operations. Therefore, the second burn period was considered the reference baseline to which each of the other burns were compared. The third burn period used a combination of pulverized coal, whole tires, and recycled industrial plastics. The plastics were considered to be the first alternative fuel used. The final burn phase used coal, tires, and broiler litter. Broiler litter is a byproduct of the broiler farming industry. The broiler litter was considered to be the second alternative fuel.

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. Due to the amount of work and time necessary to install all of this equipment, the fourth burn phase had not been completed at the time this document was developed. Therefore there will be no results presented here. However, discussion of the broiler litter itself, and the testing associated with this burn will still be included.

Within each of these burn periods, a thorough sampling and testing procedure was used. Each of the materials used to produce the portland cement were sampled and tested for their chemical composition. Additionally, each of the outputs from the production process were collected and tested for their chemical composition. Each of the inputs and outputs were sampled and tested at different frequencies relative to their 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 determined. Many physical properties of the cement were evaluated at the cement plant. Most of the same properties were determined by personnel at Auburn University as well. Moreover, the concrete tests were conducted at both Auburn University and the concrete laboratory of the cement plant. However, the testing conducted at Auburn was more thorough than that conducted at the cement plant. At Auburn University, two different concrete mixtures were produced. The goal of producing two different mixtures was to examine the interaction of the cement with various concrete admixtures.

The final aspect of the research plan was to collect and monitor the emissions during each of the burn periods. The emissions were monitored by the cement plant using a continuous emissions monitoring system. These results were then reported to Auburn University and are 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 procedure that was implemented in satisfying the objectives.

The second chapter of this document is where background research for this study is presented. Literature from other studies pertaining to this research was 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 they 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.

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

Chapter Four includes presentation, analysis, and discussion of results of this study. 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 data presented in the literature cited in Chapter Two.

A summary, several conclusions, and recommendations for this study are presented in the final chapter of this document. There is a summary of the reasons why this study is important, along with the way this study was conducted. The objectives are restated, and conclusions pertaining to each one are given. In some cases definitive conclusions could not be made, but in such cases, reasons for this condition 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 given.

A set of appendices follows Chapter Five. Appendix A presents the sampling and testing plan in tabular form. Chapter Three discusses the plan in more detail.

The final section of this document is Appendix B. This appendix has three parts. Each part serves to present all of the raw data associated with each burn period. For instance, Appendix B.1 presents all of the data for the Coal Only burn. This appendix consists of tabulated data only.

Chapter 2

Literature Review

2.1 Introduction

Modern concrete is made from three primary materials, namely: water, aggregate (gravel and/or sand), and cementitious material, that, when mixed with the water, hardens with time. There are many different types of cementing material, however, the most common is known as portland cement. "The invention of portland cement is generally credited to Joseph Aspdin, an English mason. In 1824, he obtained a patent for his product, which he named portland cement because when set, it resembled the color of the natural limestone quarried on the Isle of Portland in the English Channel" (Kosmatka et al. 2002).

The technology of cement production has progressed dramatically from the days of Aspdin. One of the most significant advances was the addition of extremely high temperatures, which causes the raw materials to "melt" together, forming a relatively uniform product. The temperatures required to produce modern cement are on the order of 1500°C, making the production of portland cement an extremely fuel-intensive process (Jackson 1998). In many cases, the costs associated with fuels may be as much as 30 to 40% of the total production costs (Mokrzycki et al. 2003). In an attempt to reduce this cost, many cement production facilities are turning towards the utilization of alternative fuels (Mound and Colbert 2004). The reason for the reduced cost of alternative fuels is that they are typically a byproduct of some other industry. Some examples of alternative fuels are scrap tires, waste wood, biomass, used oils, and spent solvents (Wurst and Prey 2002).

The environment can also benefit from alternative fuel utilization. There are three primary ways in which the use of alternative fuels are beneficial in this way: 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).

Care must be taken, however, to select alternative fuels that do not produce adverse side effects. Increased emissions and changes to product chemistry and performance are the potential negative effects that are of greatest concern (Mokrzycki and Uliasz-Bocheńczyk 2003).

As with any process-related decision, it is necessary to compare the advantages with the disadvantages in order to determine if the implementation of alternative fuels is appropriate for each portland cement facility. The goal of this document is to identify and examine all of the parameters that have significant bearing on the feasibility of introducing alternative fuels to the portland cement industry.

2.2 Portland Cement Production

Simply put, the modern-day production of portland cement occurs when raw materials consisting of appropriate proportions of calcium, silica, alumina, and iron are fused together at approximately 1500°C to form a product known as clinker. Once the clinker is cooled, it is interground 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 the desire to be as economical as possible, the exact process varies from one facility to another (Jackson 1998). One fundamental difference is the choice between a wet or dry process. In the dry process, grinding and blending are done on dry raw materials. The wet process completes these procedures with the raw materials suspended in water to form a slurry. Other than that, both processes are similar (Kosmatka et al. 2002). The dry process is more energy efficient, and is therefore utilized more in modern kilns.

A schematic of a typical dry process is shown in Figure 2.1. The raw materials are first proportioned in the appropriate ratios. They are then sent to a grinder, which reduces each of the materials to a uniform size. From the grinder, the raw materials are sent to a blending silo, where they are thoroughly mixed. If the mixed raw materials are not immediately used, they may be sent to a storage silo. The raw material feed is then sent to the preheater, where it is calcinated before entering the kiln. Once in the kiln, the raw material feed is fused together into clinker. Once the clinker exits the kiln, it is cooled before being stored in silos. Finally, the clinker is mixed with gypsum and ground into cement. The cement is then stored, packaged, or shipped to the consumer. Throughout the process, dust is removed and collected at various locations.

2.2.1 Raw Materials

The selection and processing of raw materials is a major component of the portland cement manufacturing process. In fact, raw material processing accounts for 10 percent of the energy cost in an average facility (Chatterjee 1979).

The raw materials used in the manufacture of portland cement primarily consist of a combination of a calcareous (high $CaCO_3$ content) material and an argillaceous (high silica and alumina content) material (Kosmatka et al. 2002). Table 2.1 shows the wide variety of sources from which raw materials may be acquired. Because the calcareous material is the one used in the greatest quantities, and the fact that approximately one third of the carbon mass is lost as CO_2 during the process, portland cement plants are typically located near a calcareous raw material source (EPA 1995). This helps keep transportation costs down. Due to the variable nature of the chemical composition of the raw materials, it is often necessary to operate a facility in a location where the calcareous and argillaceous materials alone do not provide the appropriate composition. In such cases, as long as one component has a calcium carbonate composition of at least 80 to 85 percent, the correct composition may be achieved by the introduction of other materials, such as those shown in Table 2.1 (Jackson 1998).

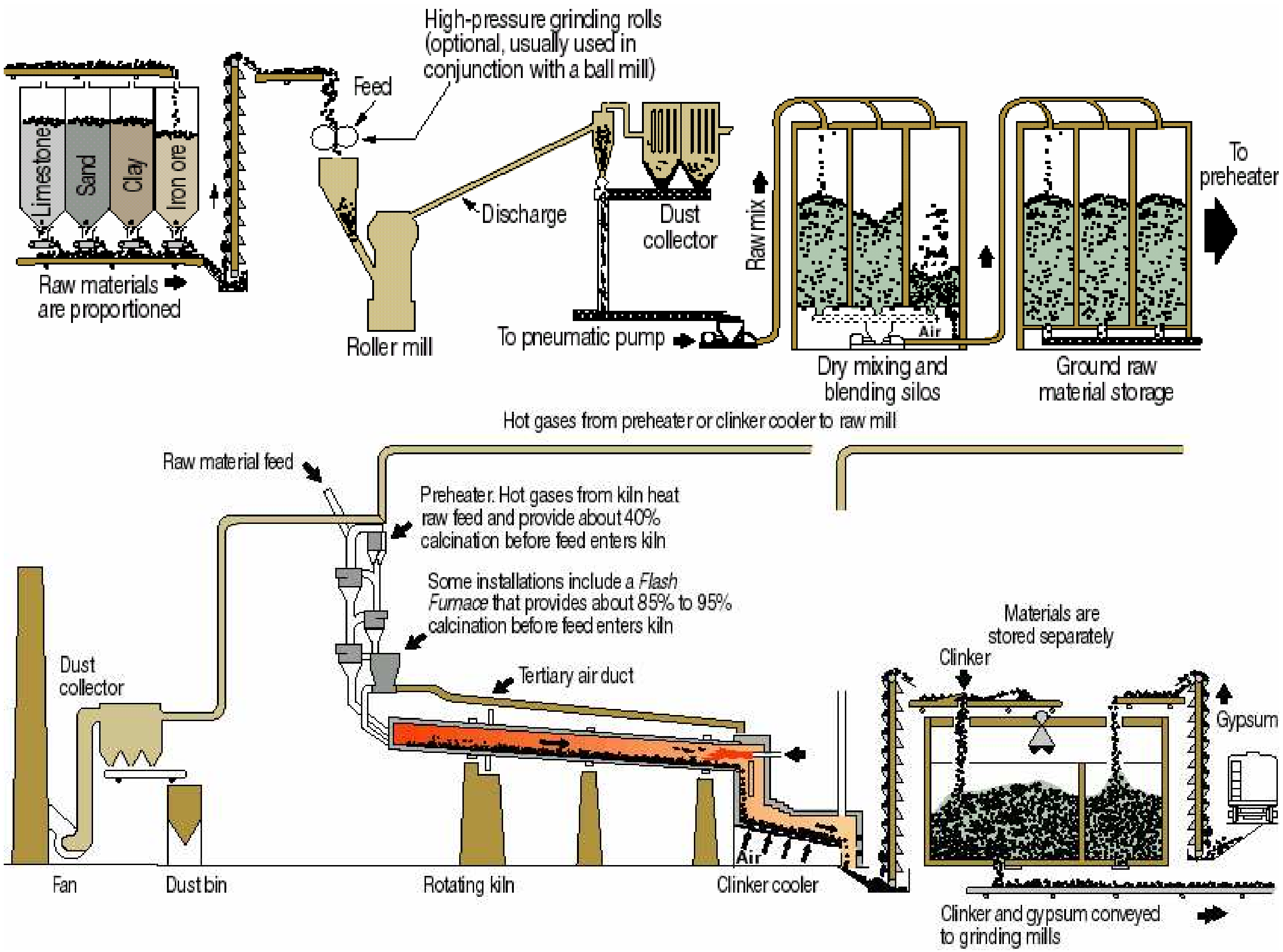


Figure 2.1: Layout of a Typical Dry-Process Portland Cement Production Facility (Kosmatka et al. 2002)

Once the cement plant has obtained all the necessary raw materials, they must be crushed and proportioned so that the appropriate chemical composition of the raw material feed is met (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. In order to achieve the lowest possible temperature in the kiln, and therefore lower fuel consumption, it is imperative that the feedstock is ground to the appropriate fineness (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 utilization of heat to change the chemical composition of a material. Once the raw materials have been proportioned and mixed, they are ready to be fused together on a chemical level. It was mentioned previously that there are two types of processes, wet and dry. While that is fundamentally true, there are actually five types of processes. In the wet process and the long dry process, all of the activity occurs within the kiln itself. The semidry process, the dry process with a preheater, and the dry process with a preheater/precalciner each heat the raw materials before they enter the kiln (EPA 1995). The purpose of a preheater and/or precalciner is to heat the raw material mix from ambient temperature to approximately 850°C before it is fed into the kiln. In the process, some of the carbon is removed as CO_2, which leaves a material with a higher CaO content (Jackson 1998). This process makes clinkerization much more fuel and cost efficient.

Whether or not a preheater and/or precalciner is used, the raw material passes through the kiln at a rate determined by the slope and rotational speed of the kiln (Kosmatka et al. 2002). Although the mechanisms inside the preheater (when present) and kiln are very complex, the progression of activity is basically as follows (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, 700°C-850°C

5. Formation of C_2S, 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 these mechanisms, C_3S (alite), C_2S (belite), C_3A (aluminate), and C_4AF (ferrite) are known as Bogue Compounds, which 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 (dotted line), and the material temperature (solid line) as they progress through the various parts of the kiln system. Additionally, the retention times in each area of the system are shown.

2.2.3 Clinker Cooling

Before the clinker can be ground into the final product, it must be cooled. The cooling of clinker takes place in two locations: 1) while it is still in the kiln, but past the burning zone, and 2) in a clinker cooler (Manias 2004). Because the latter is the primary mode of cooling, the former will not be discussed in detail here.

The cooling of clinker halts the further reaction of the raw materials (Jackson 1998). In order for cement to exhibit its best strength-giving properties, the clinker from which it is produced must be cooled rapidly from the temperature at the burning zone to about 1200°C, otherwise some of the clinker phases may further react into a form that inhibits strength gain as well as other cementitious properties (Jackson 1998; Mosci 2004). Once the reactions have been halted, it must be cooled to approximately 93°C so that it may be handled with traditional conveying equipment (EPA 1995).

Clinker coolers are also designed to recover and return to the system as much heat as secondary or tertiary air (Mosci 2004). As much as 30 percent of the heat input to the kiln may be recovered (EPA 1995). The degree to which heat recovery can be made, as well as efficiency in cooling, is based primarily on the type of cooler used. A number of different types of coolers have been implemented over the years, including planetary, rotary, shaft, and traveling grate coolers (Mosci 2004). The latter type is most commonly used today.

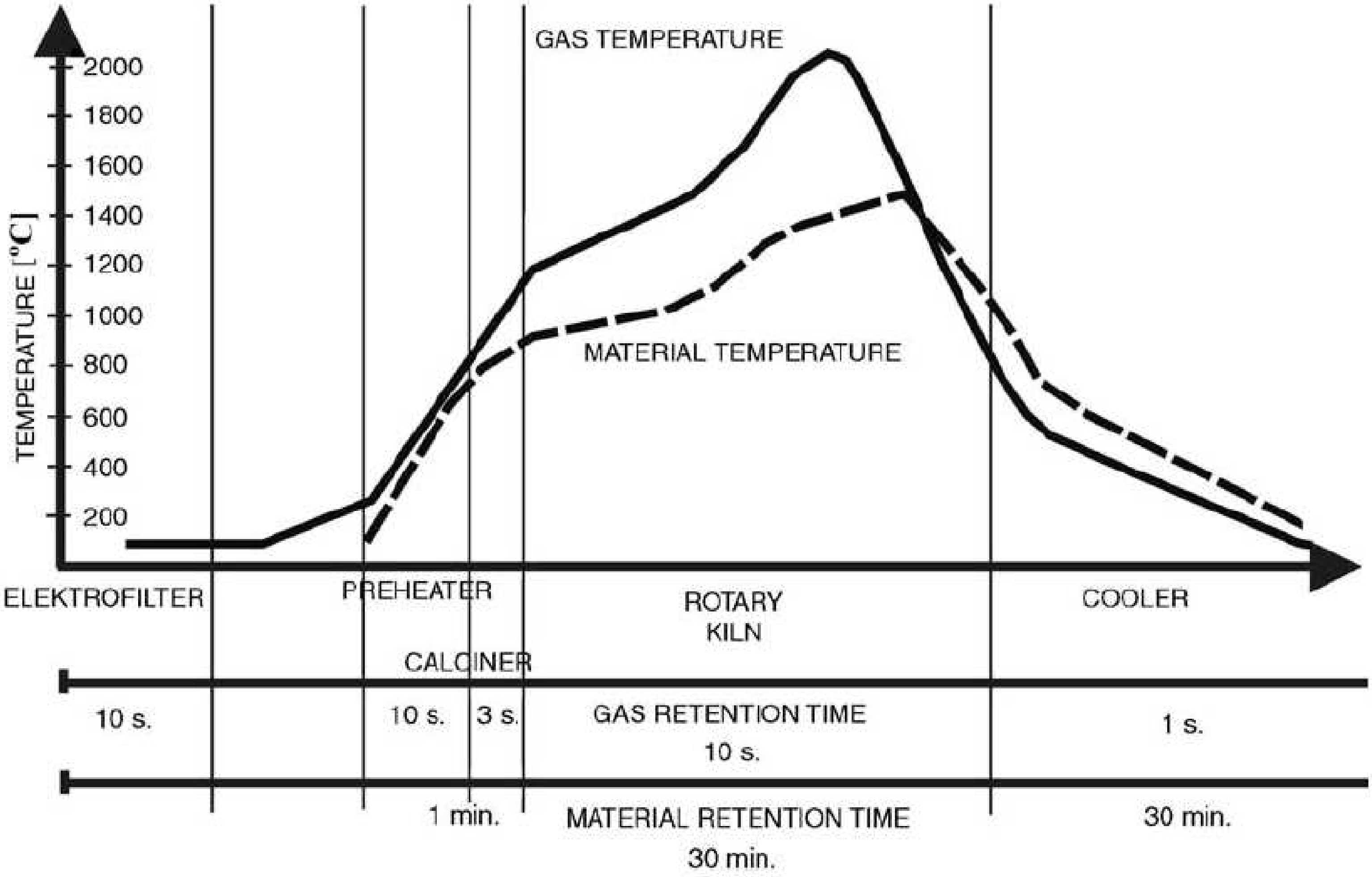


Figure 2.2: Gas and Material Temperature inside a typical cement kiln (Mokrzycki and Uliasz-Bocheńczyk 2003)

2.2.4 Grinding and Finishing

The final step before packaging and shipping is the grinding of clinker and gypsum together. Up to five percent (by weight) gypsum, or other sulfate source, is added to the clinker after it has 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).

There are many types of grinders that may be used in the finishing milling. Typically, the process is accomplished using a ball mill, roller mill, roll press, or a combination of these (Strohman 2004). Today, however, finish milling is done almost exclusively by ball mills (EPA 1995). A ball mill consists of a tube rotating about its horizontal axis, filled with 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). The final size of the cement is determined by its desired application. Typically, the finished product will be ground so that almost every particle will pass through a 45 micrometer sieve (Kosmatka et al. 2002). Whatever the desired fineness, it is imperative that uniformity is maintained as much as possible (Strohman 2004). Once grinding is completed, the finished product is portland cement.

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, selfsustainable, and very rapid." The exothermic component of this reaction is, of course, that with which the cement industry is primarily concerned.

Clinker production is a fuel-intensive process (Jackson 1998). The efficiency with which a facility runs is highly variable. However, an average cement plant burning coal consumes 120 kg of fuel in the process of producing 1 ton of portland cement (Mokrzycki and Uliasz-Bocheńczyk 2003). The least productive plants are typically those that employ the wet kiln process. At these facilities it is possible to produce clinker at a rate of 2,000 tons per day. The most productive plants are generally those utilizing a precalciner system. In a location using this type of kiln, production may be as high as 10,000 tons per day (Manias 2004). At this rate, it is possible to consume as much as 1,200 tons of coal on a daily basis. This amounts to 30 to 40 percent of the total production costs (Mokrzycki et al. 2003).

The significant contribution to operating cost made by fuels, means "the appropriate selection and use of a fuel has always been and still is a matter of great concern for the cement industry" (Greco et al. 2004). Many different types of fuel exist. Figure 2.3 shows some of these fuel types, and the means by which they are derived.

Some of the more traditional fuels commonly used in cement manufacturing today are natural gas, furnace oil, petroleum coke, and miscellaneous coals (Wurst and Prey 2002). However, due to the potentially environmentally friendly aspect, in combination with the possibility of substantial decrease in (or even negative) cost, the cement industry is increasingly turning to alternative fuels (Bhatty 2004). Some typical alternative fuels used are (see Section 3.4): tires, waste wood, used oils, and spent solvents, which may replace some or all of the traditional fuels mentioned above (PCA

2004). 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, alternative fuels will refer to anything used as a substitute for traditional fuels.

2.3.1 Alternative Fuels in Cement Kilns

The unique environment that is present within a cement kiln makes it a very conducive atmosphere for the implementation of alternative fuels (Mokrzycki and Uliasz-Bocheńczyk 2003). The following kiln characteristics render it amenable to alternative fuels (Greco et al. 2004):

- The temperatures in the kiln, upwards of 1500°C, are substantially higher than the threshold above which waste fuels must be incinerated, as established by environmental regulations
- The high alkalinity atmosphere readily absorbs most acidic gases released by the oxidation of sulfur and chlorides.
- Most of the non-fuel compounds, such as metallic oxides, are not deleterious to the production of clinker.
- The majority of the noncombustible products, particularly metals, are either incorporated into the clinker itself, or trapped by and recycled with the cement kiln dust.

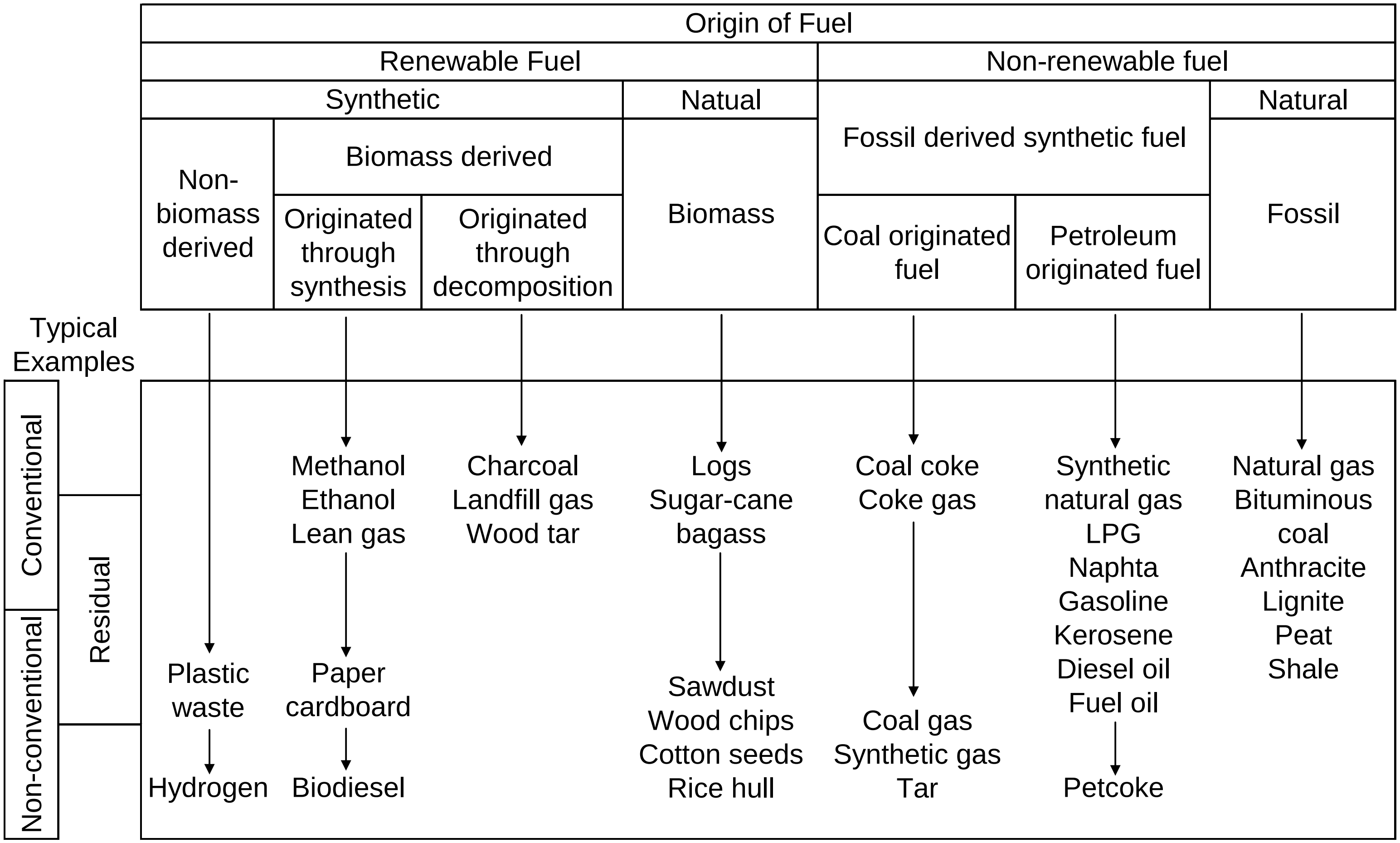


Figure 2.3: Various fuels and their origin (Adapted from Greco et al. 2004)

Because most of the noncombustible products are incorporated into the final product, it is necessary to establish that the performance of the cement is not inhibited by the altered chemical composition. A thorough discussion of the elements and their possible effects on the product can be found in Section 6. Similarly, a discussion of the cement kiln dust and the impact of altered compositions can be found in Section 5.

2.3.2 Advantages of Alternative Fuels

The advantages of using alternative fuels in the cement industry are numerous. According to Greco et al. (2004), the four primary advantages that are simultaneously gained by burning alternative fuels are: reduction of production costs, preservation of fossil fuel resources, reduction in the volume of wastes that must be disposed of by other means, and a decrease in global greenhouse effect. The latter is based on the fact that the emission of CO_2 from what would normally be two separate processes is combined into a single process.

With energy demands in a wet process kiln as substantial as 6 million $BTUs$ per day, it is easy to see that the implementation of low-cost alternative fuels offers significant economic advantages (Barger 1994). Although the unit costs of alternative fuels are less than those of traditional fuels, another aspect of acquisition that must be evaluated in order to accurately estimate the potential for cost savings is availability. A systematic view of the conditions concerning actual fuel availability as well as the short- and medium-term new trends of availability of new fuel types must be conducted (Greco et al. 2004). A substantial portion of the acquisition cost of fuels is intertwined with availability, transportation, and processing costs.

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 product-based life styles, so too do the manufacturing wastes that must be disposed of (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 quantities of land that may become unsightly and environmentally detrimental. Equally strenuous on the environment are waste incinerators, which have only a single purpose. Incinerators burn garbage, but do not use the heat generated; whereas a cement plant does the same thing only it uses the heat generated to manufacture portland cement. Therefore, unlike incinerators, a cement facility serves a dual purpose (Mokrzycki and Uliasz-Bocheńczyk 2003).

Another significant environmental advantage of alternative fuel substitution is the preservation of nonrenewable energy sources (Trezza and Scian 2000). The process of mining coal, for instance, negatively influences 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 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). For instance, 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).

One secondary advantage in the case of some alternative fuels is the reduction in required quantities of certain raw materials. 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 substitution of alternative fuels in the production of portland cement, the disadvantages must be examined and weighed against the advantages. 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, lead, as well as others (Martinez 1996). A detailed discussion of emissions can be found in Section 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 potentially devastating constraint of the implementation of alternative fuels is the final clinker composition (Mound and Colbert 2004). Because the cement clinkering process incorporates the combustion byproducts into the clinker, any undesirable compounds present in the fuels may be deposited into the cement itself. If any of these compounds produces a decrease in quality of the cement, the benefits of alternative fuel substitution could be negated. A detailed discussion of elements that could alter the properties of cement and/or concrete can be found in Section 2.6.

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 as well, and it must be done at a lesser cost than the savings that might be gained from use of cheaper fuels.

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 is 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
- Sulfur content – less than 2.5 percent
- Polychlorinated Biphenyls (*PCBs*) content – less than 50 parts per million (*ppm*)
- Heavy metals content – less than 2500 *ppm*.

It is evident from this list of criteria that the door is wide open for the types of materials that may be considered as a viable alternative fuel. Alternative fuels are categorized by the phase in which they exist. Therefore, the three classifications of fuels are solid, liquid, and gas (Peray 1986). There is a wide variety of fuels that 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, scrap tires, waste plastics, and broiler litter are considered as fuels. All these alternative fuels can be classified as solids. Therefore, liquid and gaseous alternative fuels will not be discussed here. For a comprehensive discussion of these classifications, see Greco et al. (2004).

Solid fuels are the most commonly used, and in terms of particular fuels, 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 with which this study is primarily concerned are: scrap tires, industrial plastics, and broiler litter.

2.3.4.1 Tires as Fuel

Scrap tires first gained notoriety as a serious waste problem 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 of 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 used 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)

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	Municipal waste
	Plastic shavings
	Residual sludge from pulp and paper production
	Rubber shavings
	Sawdust and wood chips
	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 sulfur, 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 sulfur, one to two percent zinc, and an energy value of 26987 to 33472 *kJ/kg* (11602 to 14390 *BTUs/lb*) (Jackson 1998). Wurst and Prey (2002) report average energy values of tires to be 25104 to 29288 *kJ/kg* (10793 to 12592 *BTUs/lb)*, with zinc and sulfur as the primary elements of concern. Table 2.3 shows the energy value of tire derived fuel (TDF) relative to two sources of coal. Sulfur, 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.

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 ($kg \times 10^6/kJ$)	0.35	0.74	0.30
Nitrogen (%)	0.24	1.76	1.76
Nitrogen Production ($kg \times 10^6/kJ$)	0.07	0.65	0.65
Chlorine (%)	0.15	0.08	0.08
Chlorine Production ($kg \times 10^6/kJ$)	0.04	0.03	0.03

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). 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/ton_{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	

The results of the studies shown above show 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.

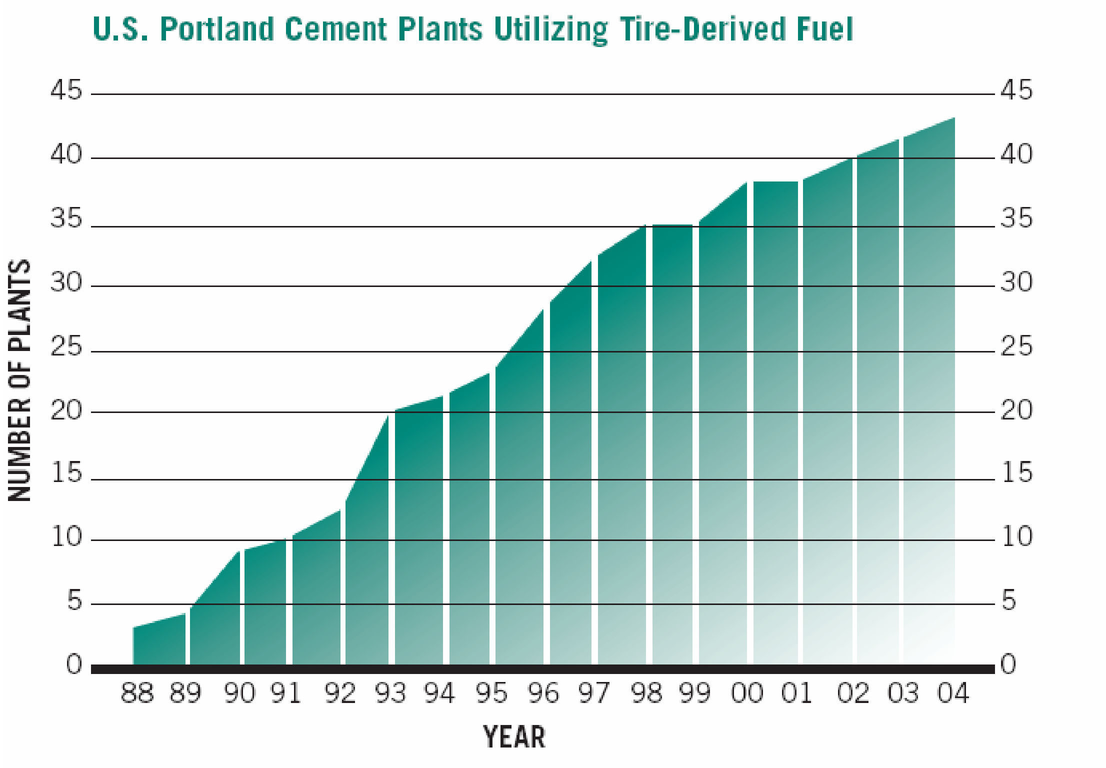


Figure 2.4: Trend of Tire Use as Fuel in Cement Plants in the U.S. (PCA 2005)

2.3.4.2 Plastic Waste 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 28870 *kJ/kg (12412 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*. 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 Table 2.6 and Table 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)

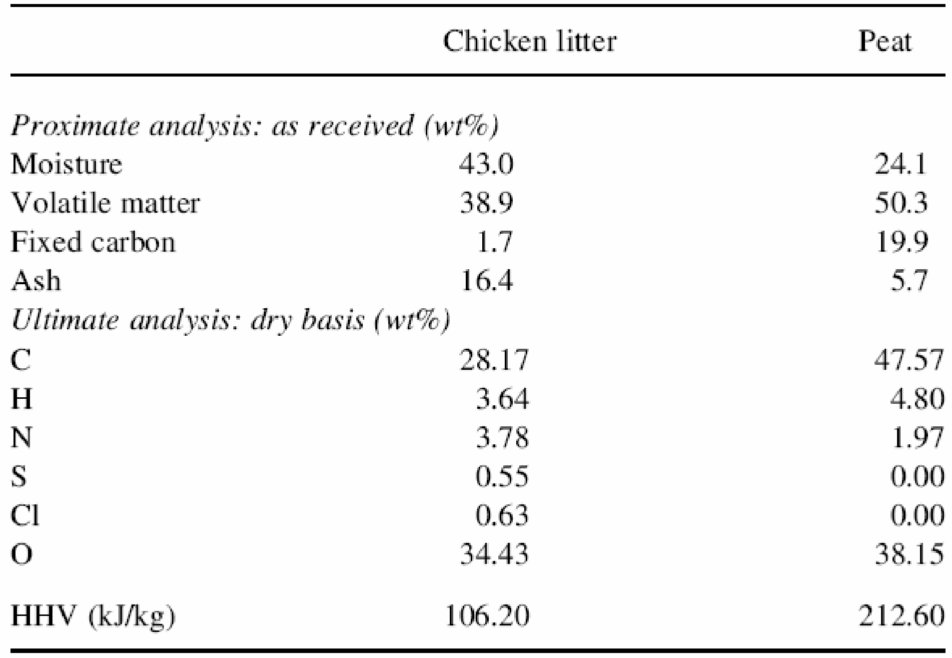
	percentage of trace elements retained in ash				
Fuel	0-20%	21-40%	41-60%	61-80%	81-100%
Colombian coal	Hg, Se	As, Cd		Cr, Mn, Mo, Sb, Sr, Tl	Ba, Be, Pb, Co, Cu, Ni, V, Zn
Polish coal	Hg, Se	Tl	As, Cd, Pb, Sb	Ba, Cr, Cu, Mo, Sr	Be, Co, Mn, Ni, V, Zn
plastic waste	Hg	Cd, Cu, Pb, Tl,	V	Cr, Ba, Mn, Sr	Be,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

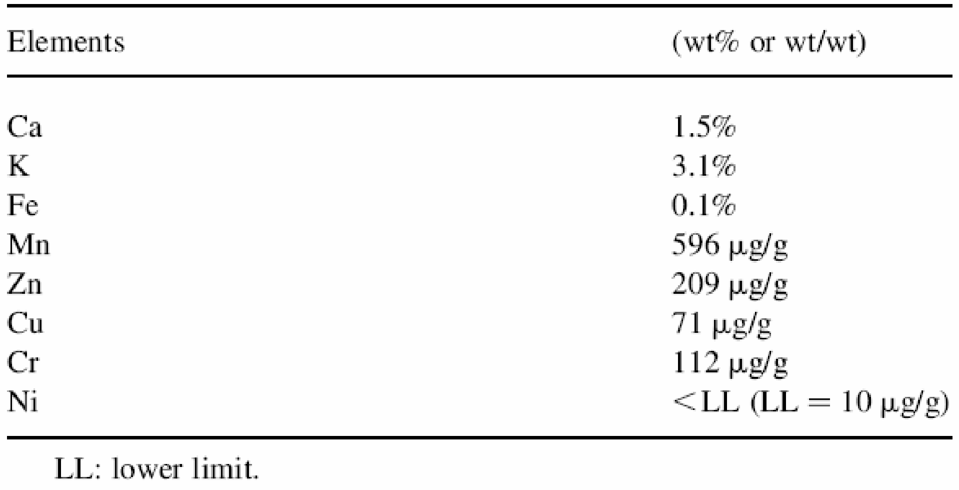
Table 2.8: Proximate and Ultimate Analysis of Chicken Litter and Peat (Abelha et at. 2003)



	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

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)



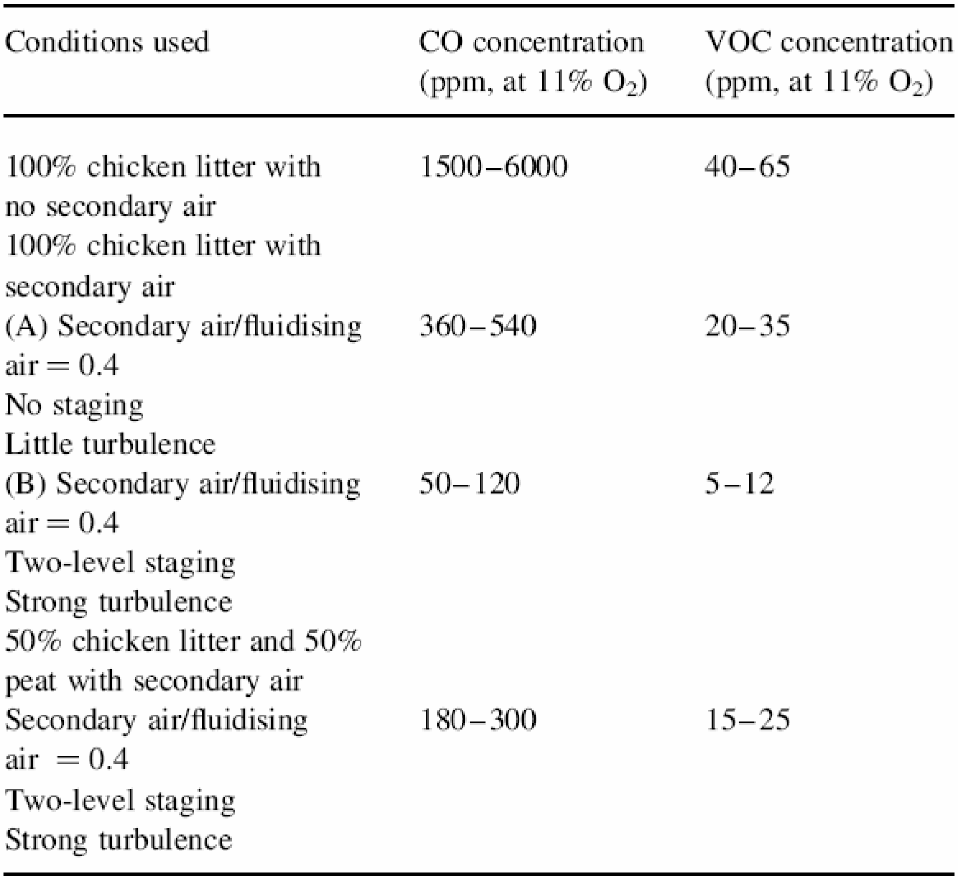
Elements	(wt% or wt/wt)
Ca	1.5%
K	3.1%
Fe	0.1%
Mn	596 μg/g
Zn	209 μg/g
Cu	71 μg/g
Cr	112 μg/g
Ni	<LL (LL = 10 μg/g)

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.

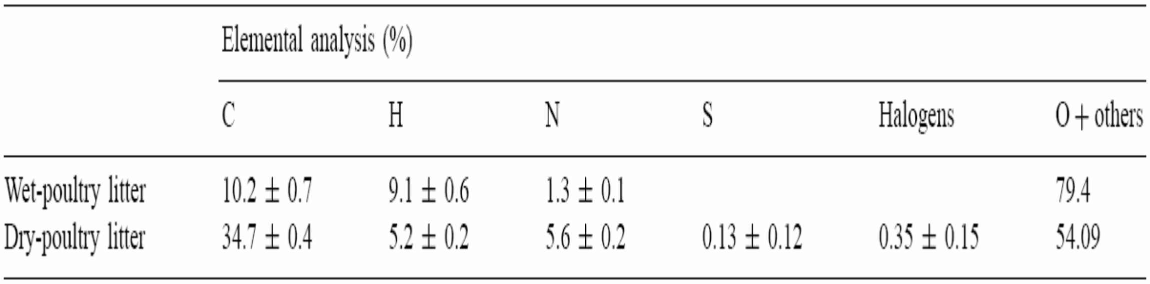
Dávalos et al. (2002) reported on a study in which combustion characteristics of poultry litter were evaluated for various moisture contents. Table 2.11 shows the elemental analysis of a wet sample (approximately 68 percent water content) and a dry sample. Figure 2.5 illustrates the energy content versus 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* (6211 *BTUs/lb*), and a sample has a calorific value of 4,000 *kJ/kg* (1720 *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

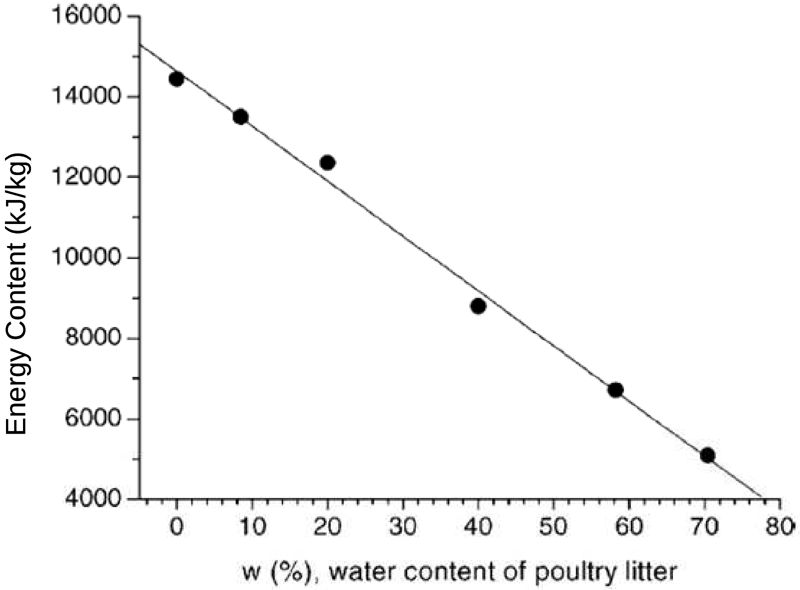


Figure 2.5: Energy Content Relative to Water Content of Poultry Litter (Dávalos et al. 2002)

2.4 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 document, 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 all that year's CO_2 emissions (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.

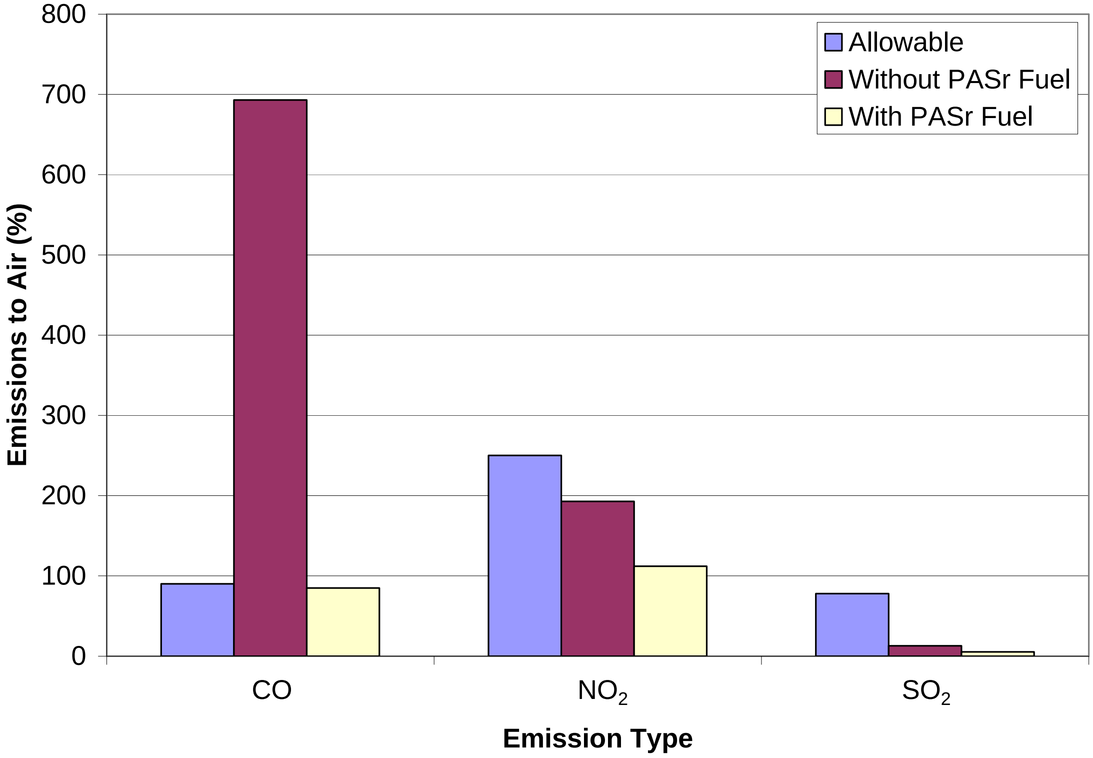


Figure 2.6: Emissions Data from a Plant Burning Alternative Fuels (modified from Mokrzycki et al 2003)

Prisciandaro et al. (2003) have also reported emissions results of tests run 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.

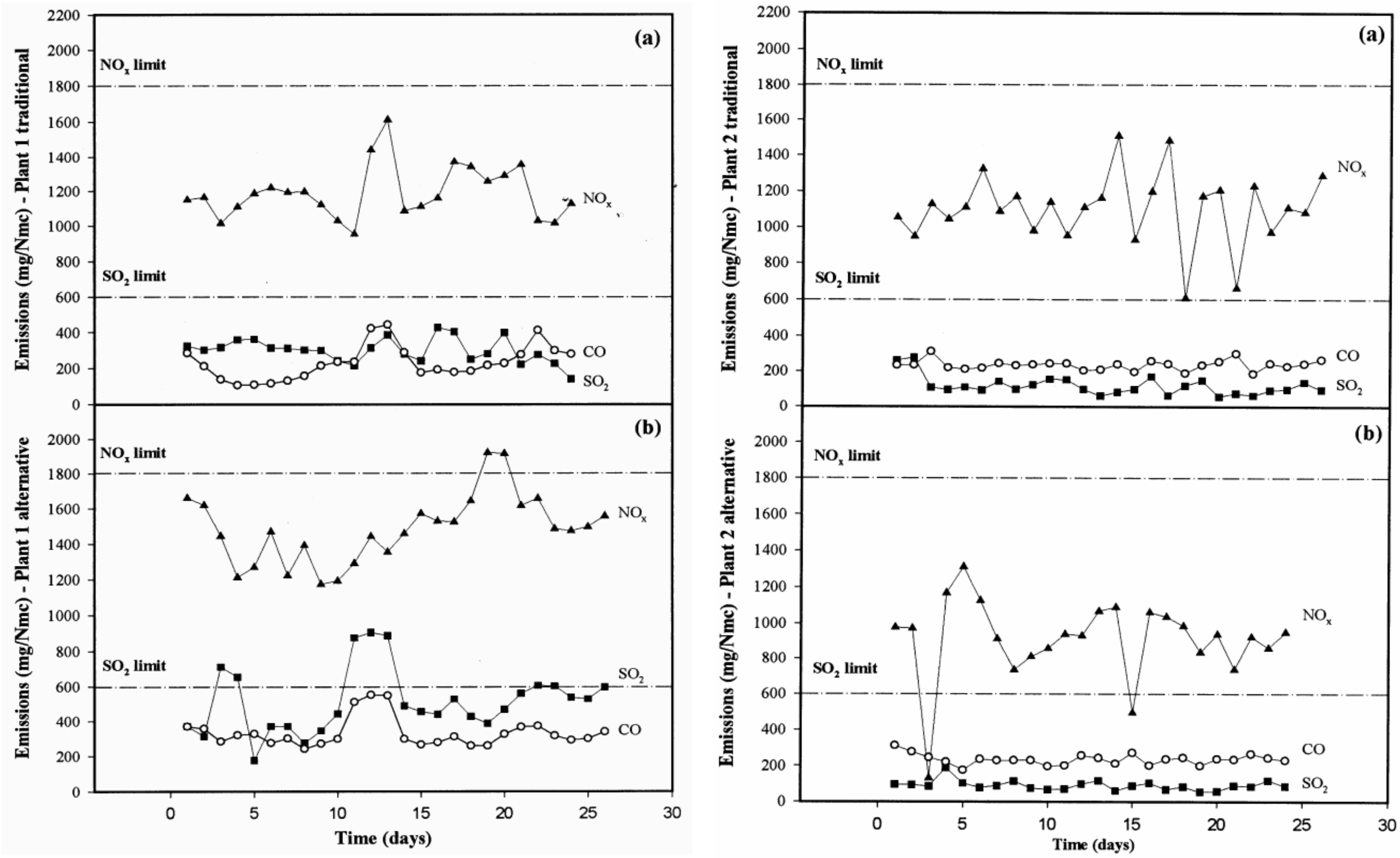


Figure 2.7: Change in Emission Levels due to Changes in Fuel Types (Prisciandaro et al. 2003)

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 generally comprised of 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 300-800°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 (see Figure 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 (see Figure 2.7).

2.4.3 Sulfur Emissions

Sulfur Oxides (SO_x) are a family of sulfur-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 sulfur 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 sulfur are released via emissions, the majority of sulfur 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 sulfur 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 takes one of two forms. SO_2 readily combines with the moisture in the atmosphere to form H_2SO_4, also known as sulfuric 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 (see 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.

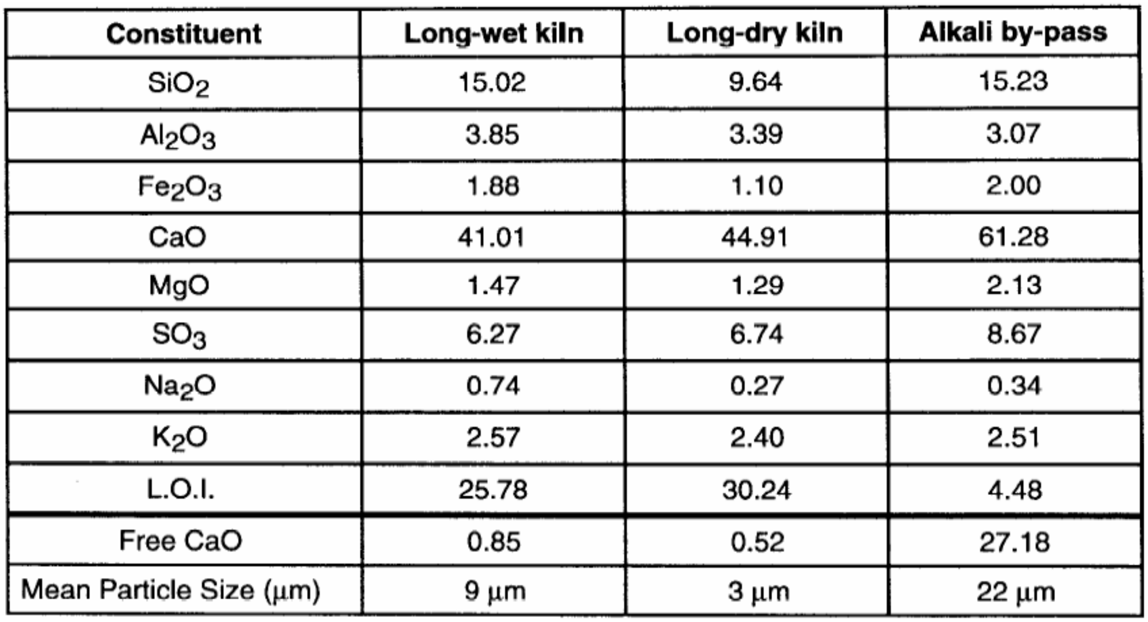
Many portland cement facilities are able to reuse all, or at least a major portion of, the *CKD* they generate as a replacement for some of the raw material feed or the fuels (Taylor 1997). However, due to chemical composition limits related to concrete durability issues, particularly those associated 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), stabilization of soils (Bhatty et al. 1996), and waste stabilization/solidification (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). Table 2.12 shows the chemical composition, as a percentage of total weight, of the *CKD* produced in three different types of kilns (Bhatty et al. 1996). Figure 2.8 shows 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 (Todres et al. 1992).

Table 2.12: 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 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 2.13 provides information about each of the plants, which includes whether it used waste-derived fuels as its primary (P) or alternate (A) fuel source.

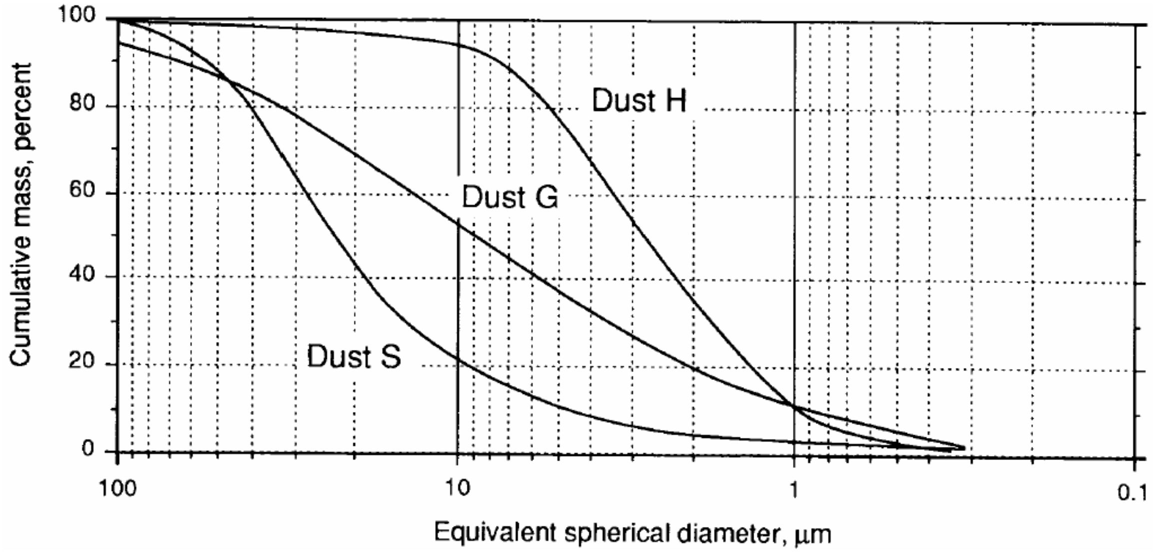


Figure 2.8: Particle Size Distribution of CKD Produced in a S (alkali by-pass kiln), G (long wet kiln), and H (long dry kiln) (Todres et al. 1992)

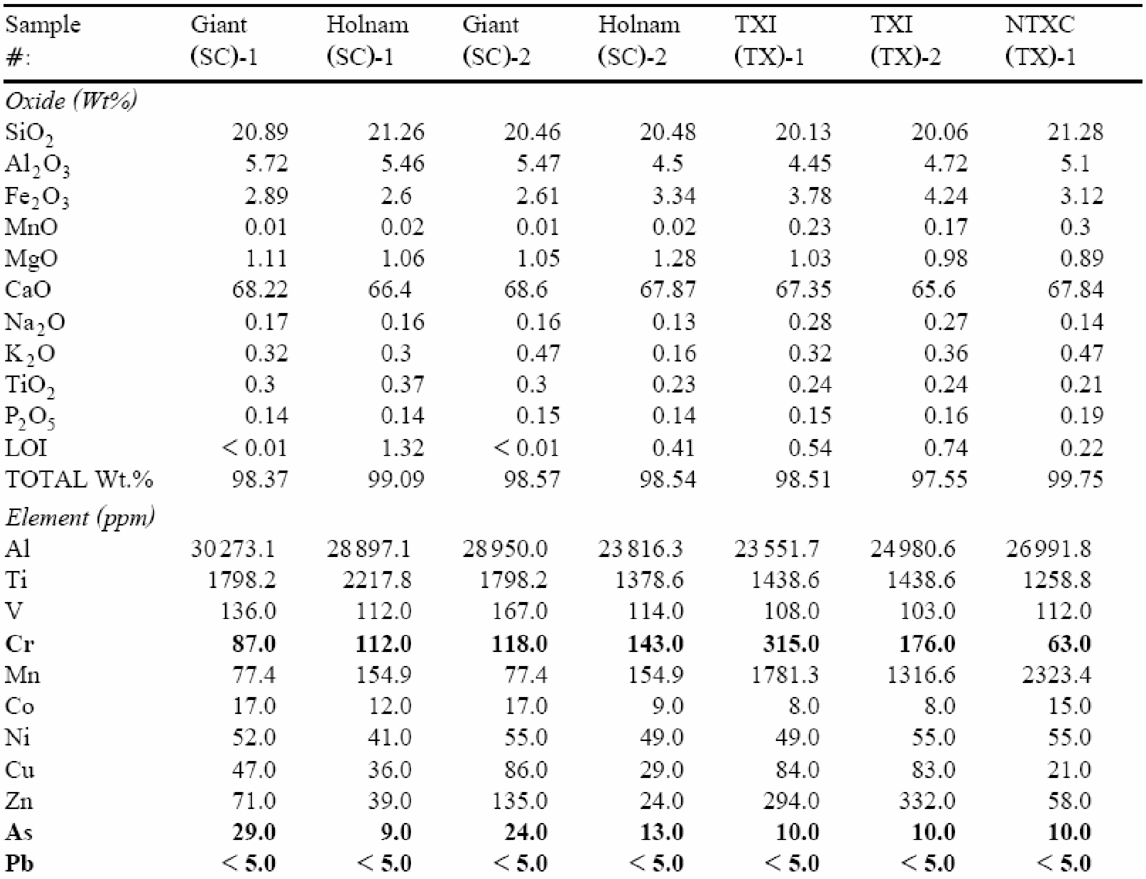
Table 2.14 shows the results for seven of the seventeen kilns studied. Although these results provide only a snapshot of the effects that fuel has on CKD, they do provide some understanding of the link between these two components of portland cement manufacturing.

Table 2.13: 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 2.14: 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

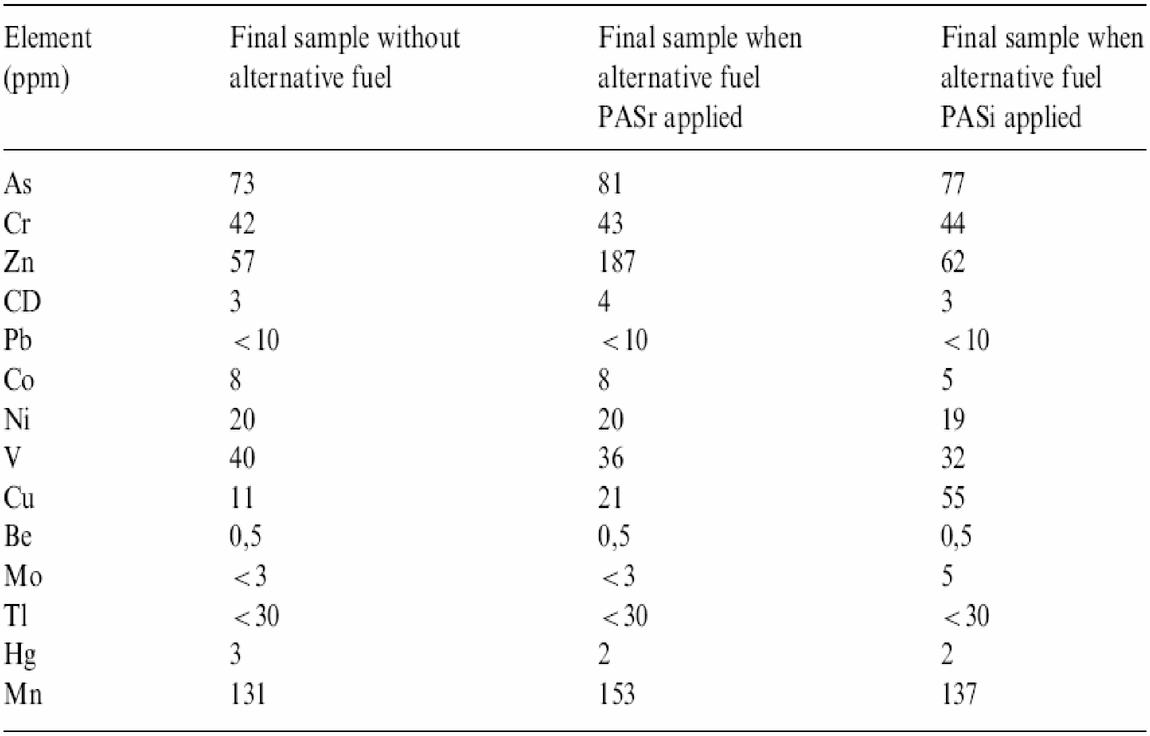
There are many elements that may be incorporated into portland cement throughout the manufacturing process that could alter the performance of the final product. The assimilation of these elements into the cement is highly complex, and depends on the kiln process conditions. The first aspect of their inclusion is the source. It has previously been shown that many materials must be fed into the kiln in order to produce cement. The 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 to 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 separate tests in which two different alternative fuels were used. Table 2.15 shows the change in chemical composition of the clinker based on changes only in fuel types. It is evident from this 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 2.15: 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 2.16 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.

The following sections discuss the source, resulting destination, and effect on the properties of the product for many selected elements.

Table 2.16: Effects of Elements on Concrete Properties

Element	Property								
	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?	Other
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	↑↑	↑	↓↓	↓

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 typical 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 sulfur 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 sulfur. 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 condense in the cooler parts (Jackson 1998). This produces clogs in the preheater (when present) and rings in the kiln (Gartner 1980). 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 sulfur, 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 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 2.17 and 2.18 as reported by Lawrence (1998). Table 2.17 shows the initial and final setting times, in minutes, for concrete with various concentrations of alkalis. 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.

Table 2.18 shows the variation in compressive strength, at four ages, for the same concrete specimens as in Table 2.17. 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 with 1.48 percent K_2O was decreased at 1 and 3 days, and increased at 7 and 28 days relative to the concrete with 0.88 percent K_2O. This is consistent with what Gartner (1980) and Taylor (1997) reported.

Table 2.17: 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 2.18: 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 possible 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, it is something that anyone placing concrete high in cadmium levels should be aware of its consequences.

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 don’t 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 a decrease in 28-day strength (Bhatty 2004; Gartner 1980; Miller 197;, 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 2.19. 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 2.19: 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.

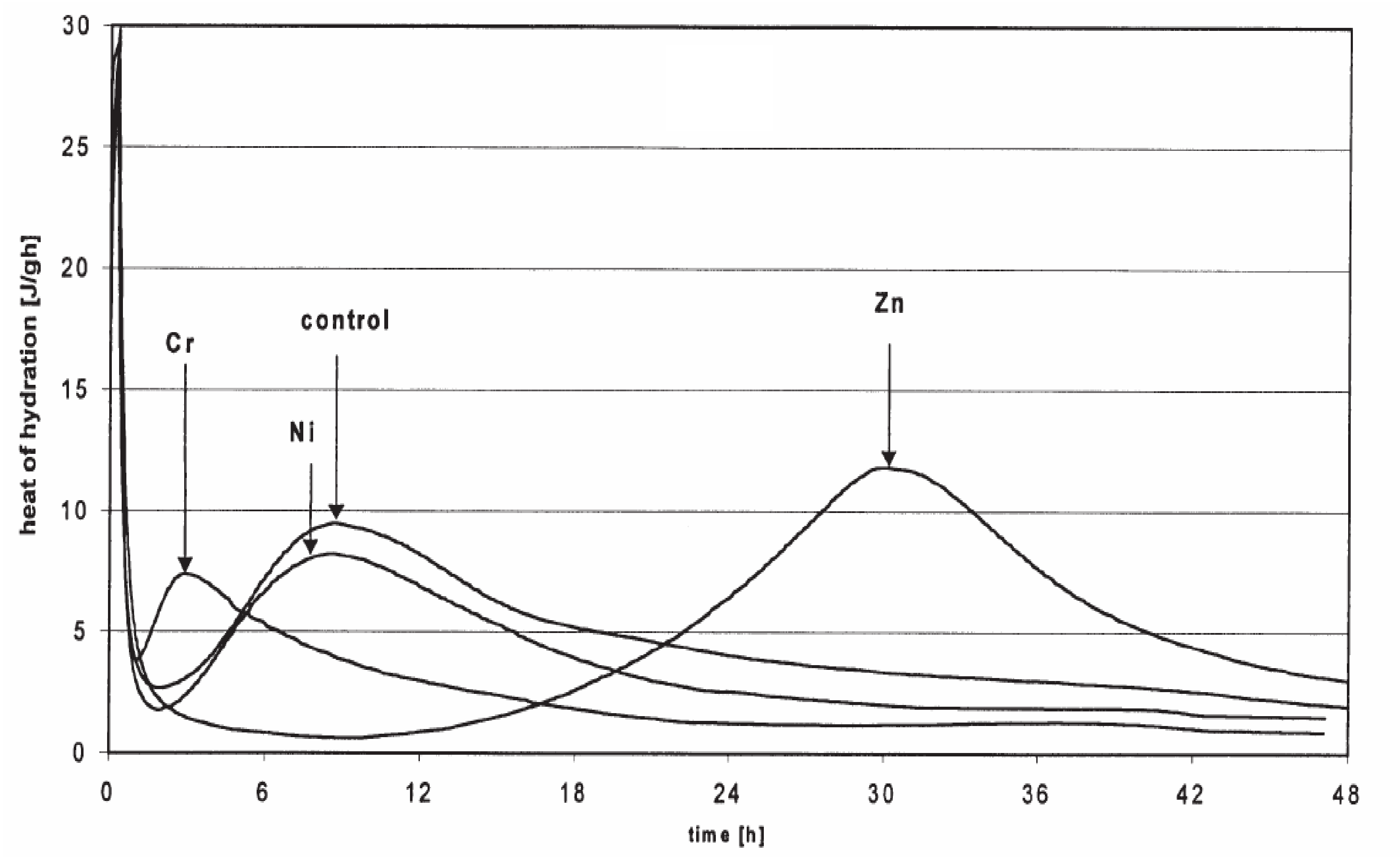


Figure 2.9: Heat of Hydration for Cement with Various Concentrations of Cr, Ni, and Zn (Stephan et al. 2000)

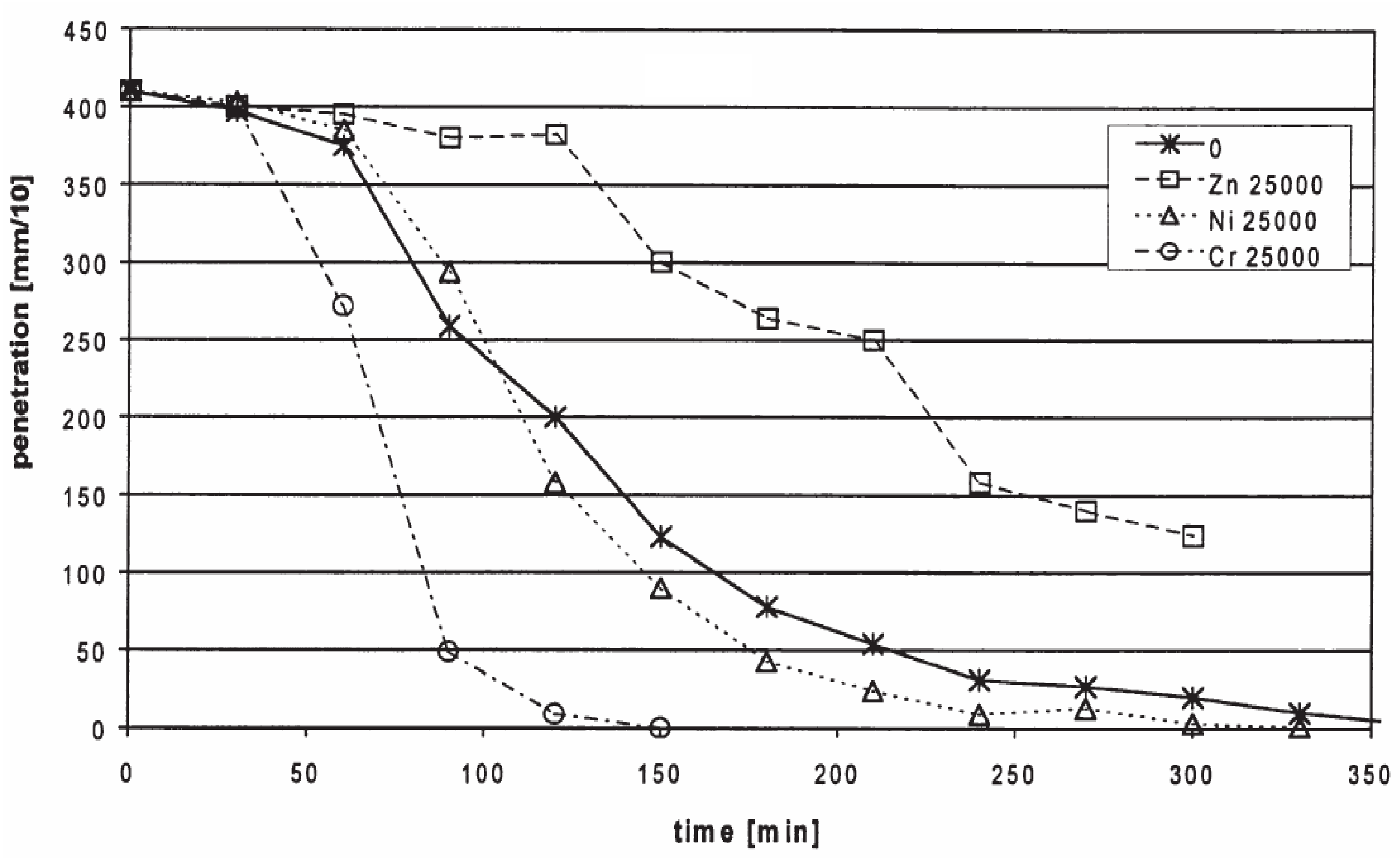


Figure 2.10: Penetration of Cements Dosed with 25,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

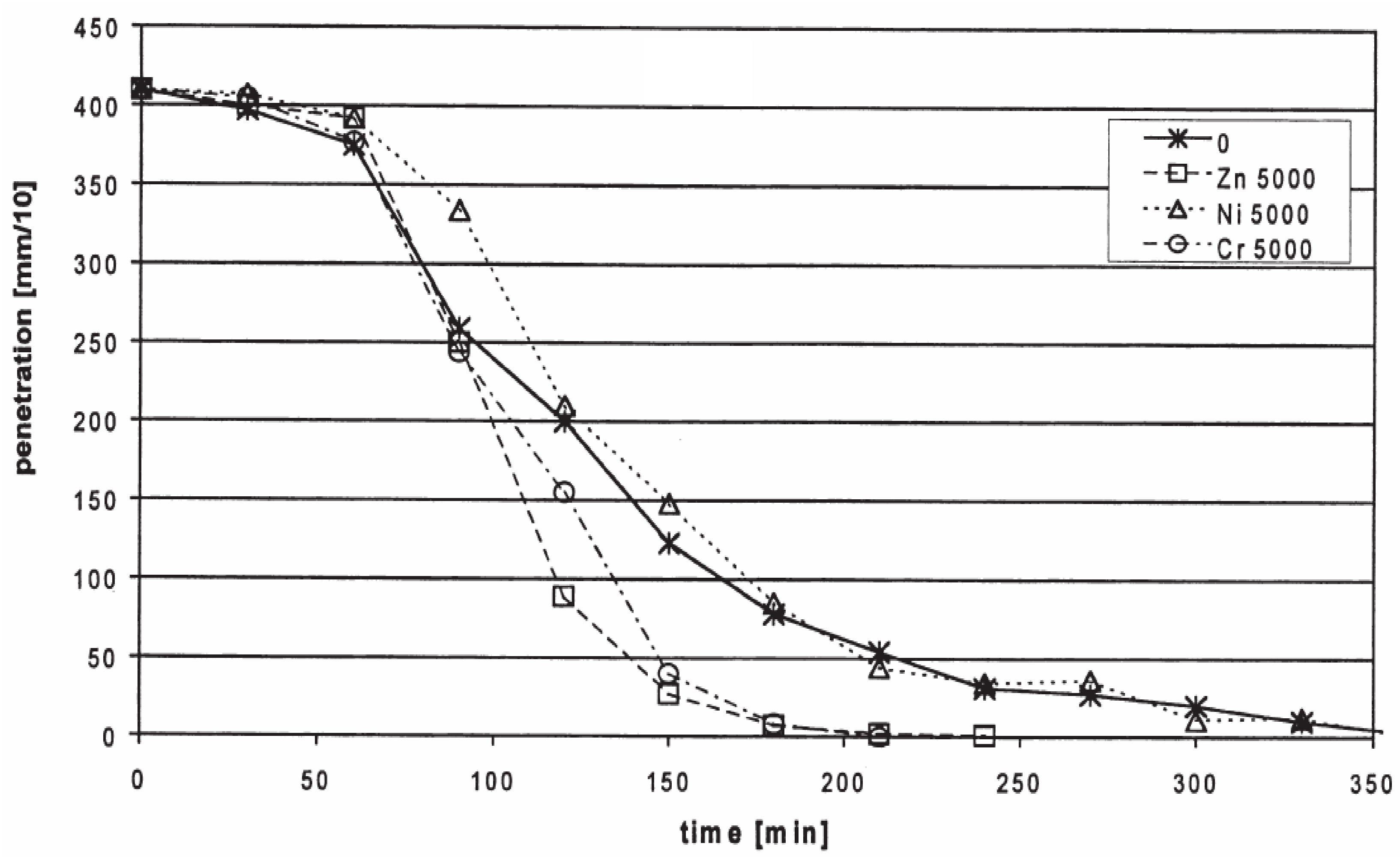


Figure 2.11: Penetration of Cements Dosed with 5,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

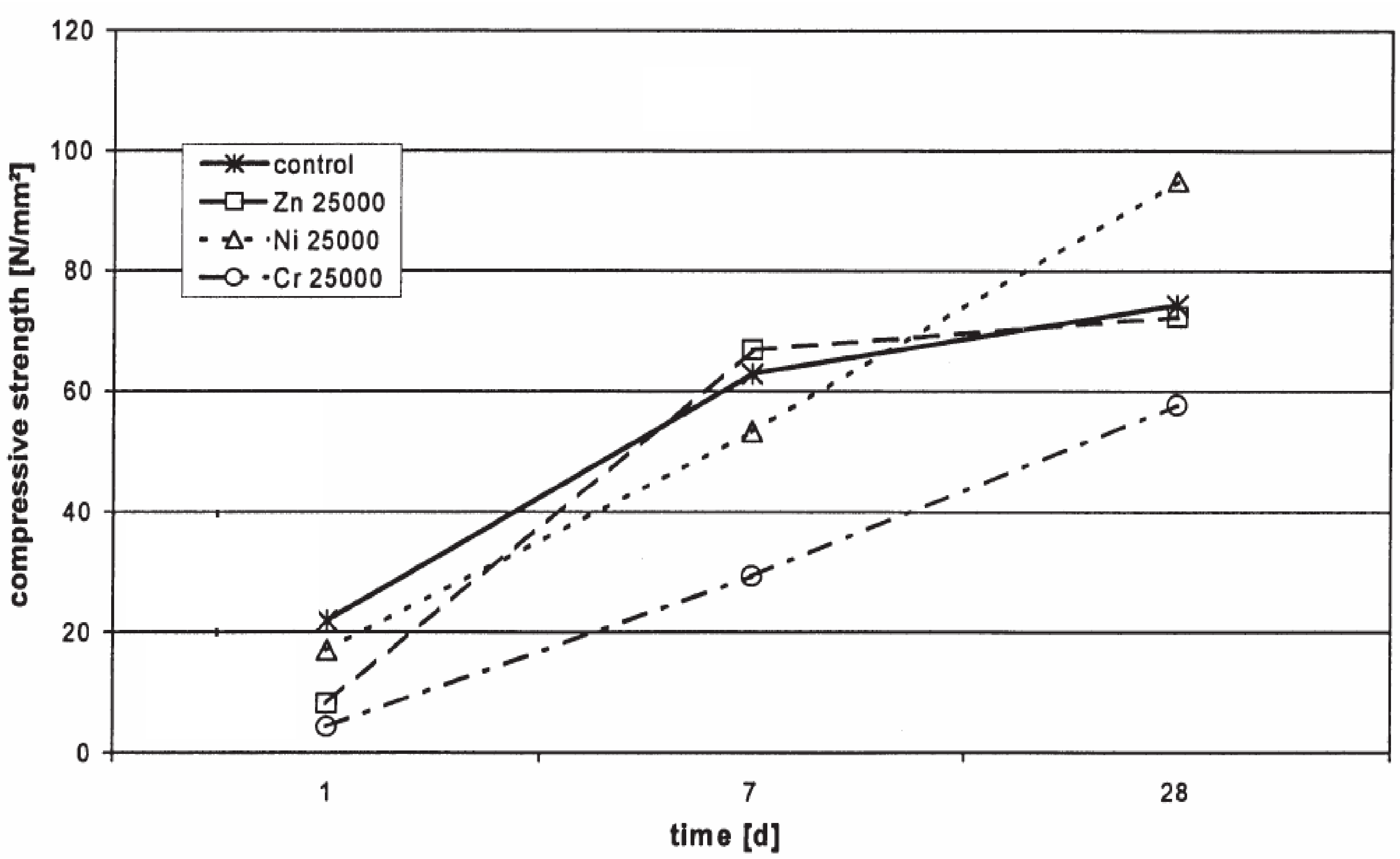


Figure 2.12: Compressive Strength of Cements Dosed with 25,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

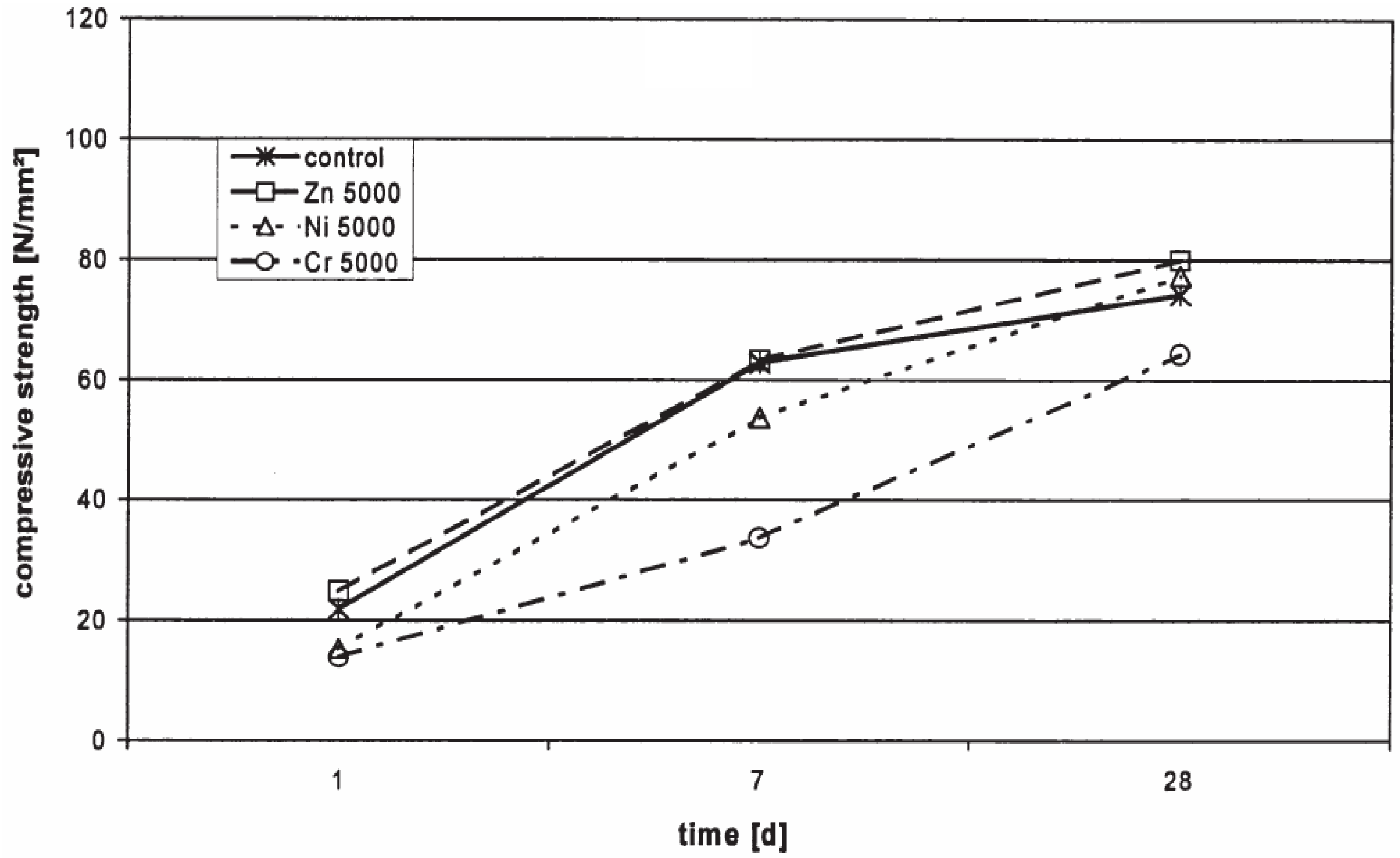


Figure 2.13: Compressive Strength of Cements Dosed with 5,000 ppm of Cr, Ni, and Zn (Stephan et al. 2000)

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).

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 decreased as the quantity of Li_2CO_3 increased.

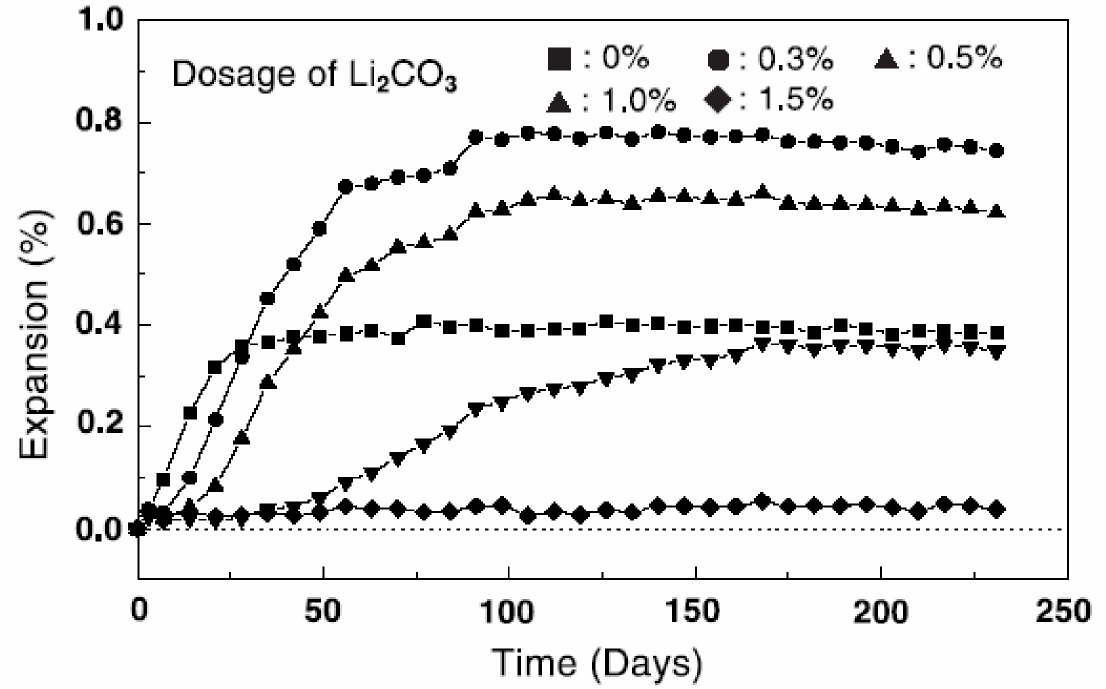


Figure 2.14: Effect of Various Doses of Li_2CO_3 on ASR Expansion (Kawamura and Fuwa 2001)

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. However, it can lead to destructive expansion of concrete. 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.

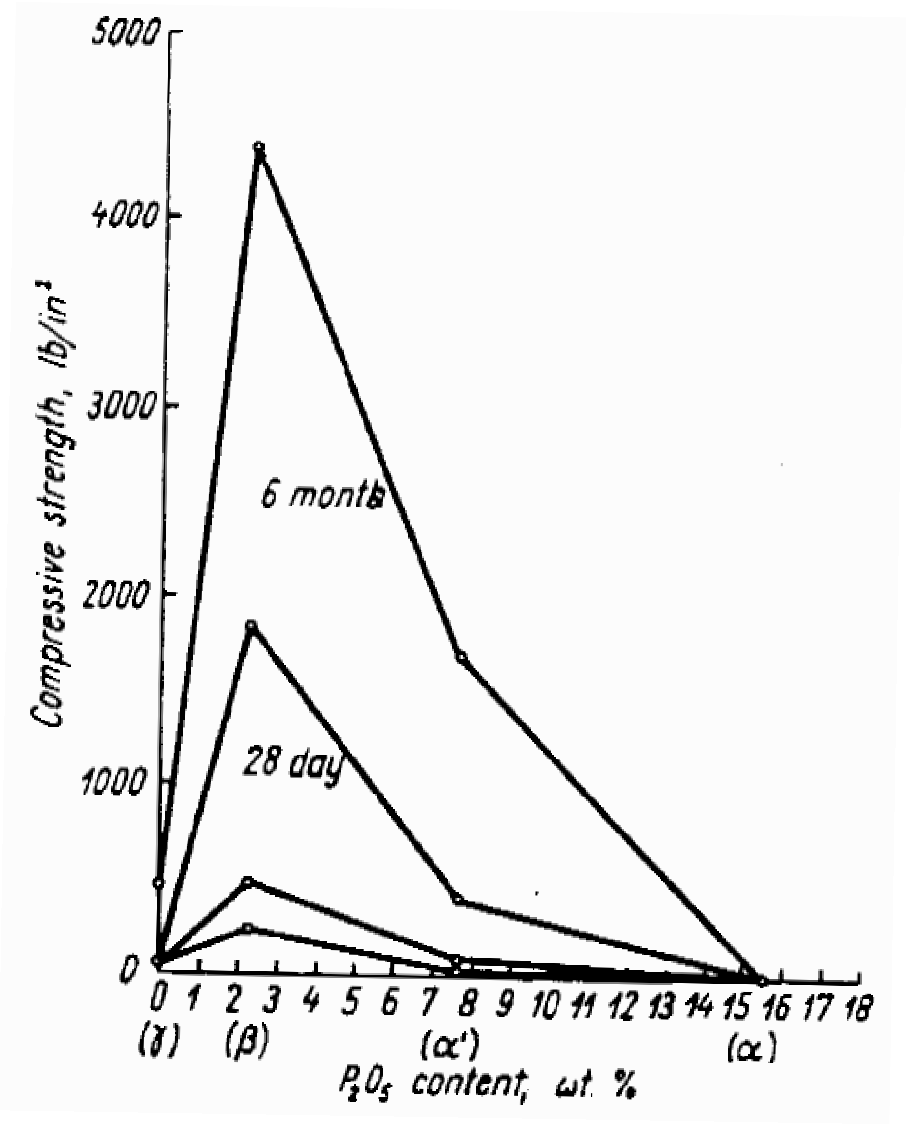


Figure 2.15: Compressive Strength for Different P_2O_5 Concentrations (Miller 1976)

2.6.24 Rubidium (*Rb*)

Rubidium is 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 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 Sulfur (S)

Sulfur is a nonmetal and element number 16. Sulfur 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 sulfur (Gartner 1980). Limestone, clayey sediments, and marl also contain appreciable quantities of sulfur (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 limites the amount of gypsum that may be added.

Some sulfur in the form of SO_2 is released through the stack emissions. A detailed discussion of sulfur emissions can be found in Section 2.4.3. The most common place for sulfur to be found is in the clinker. This is likely to occur because sulfur 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 sulfur 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 sulfur 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 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 been 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 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 affects 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, Figure 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 cooperation with one another. For a detailed discussion of the portland cement production process, see Section 2.2. 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 four distinct collection and testing periods, which are referred to as burn periods. They are as follows:

1. Burn period one utilized only coal as fuel.
2. Burn period two utilized coal and tires. This is the standard fuel combination used at the cement plant, and was therefore considered the baseline for comparison purposes.
3. Burn period three used coal, tires, and recycled post-industrial plastics. These plastics were considered alternative fuel one.
4. Burn period four used coal, tires, and broiler litter. The broiler litter was considered alternative fuel two.

In each burn period, 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 step 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. For the sake of simplicity, as well as to reduce the amount of additional work required of the cement plant personnel, 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. Just as with the sampling of the materials, one goal of the testing portion of the program was 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.

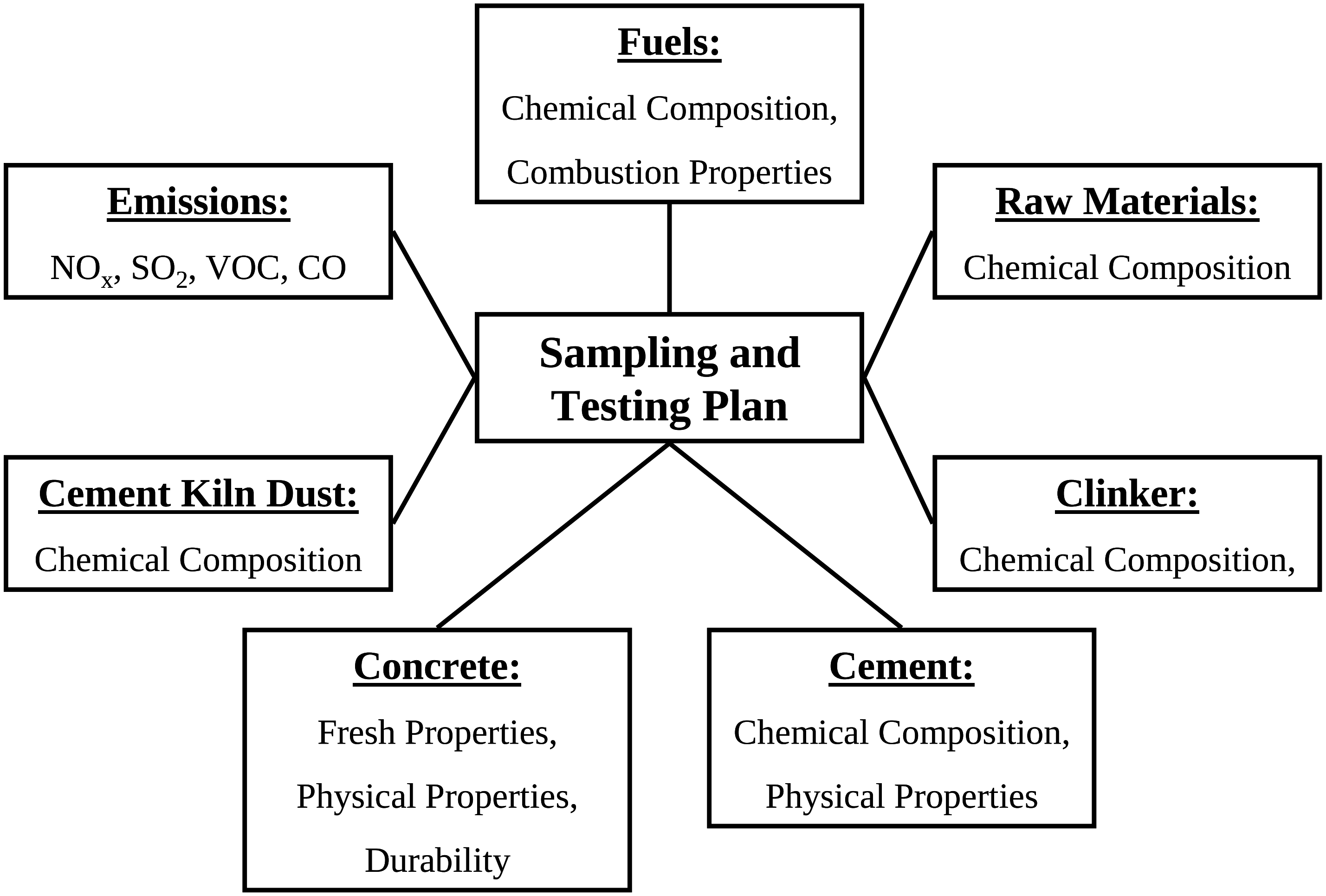


Figure 3.1: Overall Sampling and Testing Plan

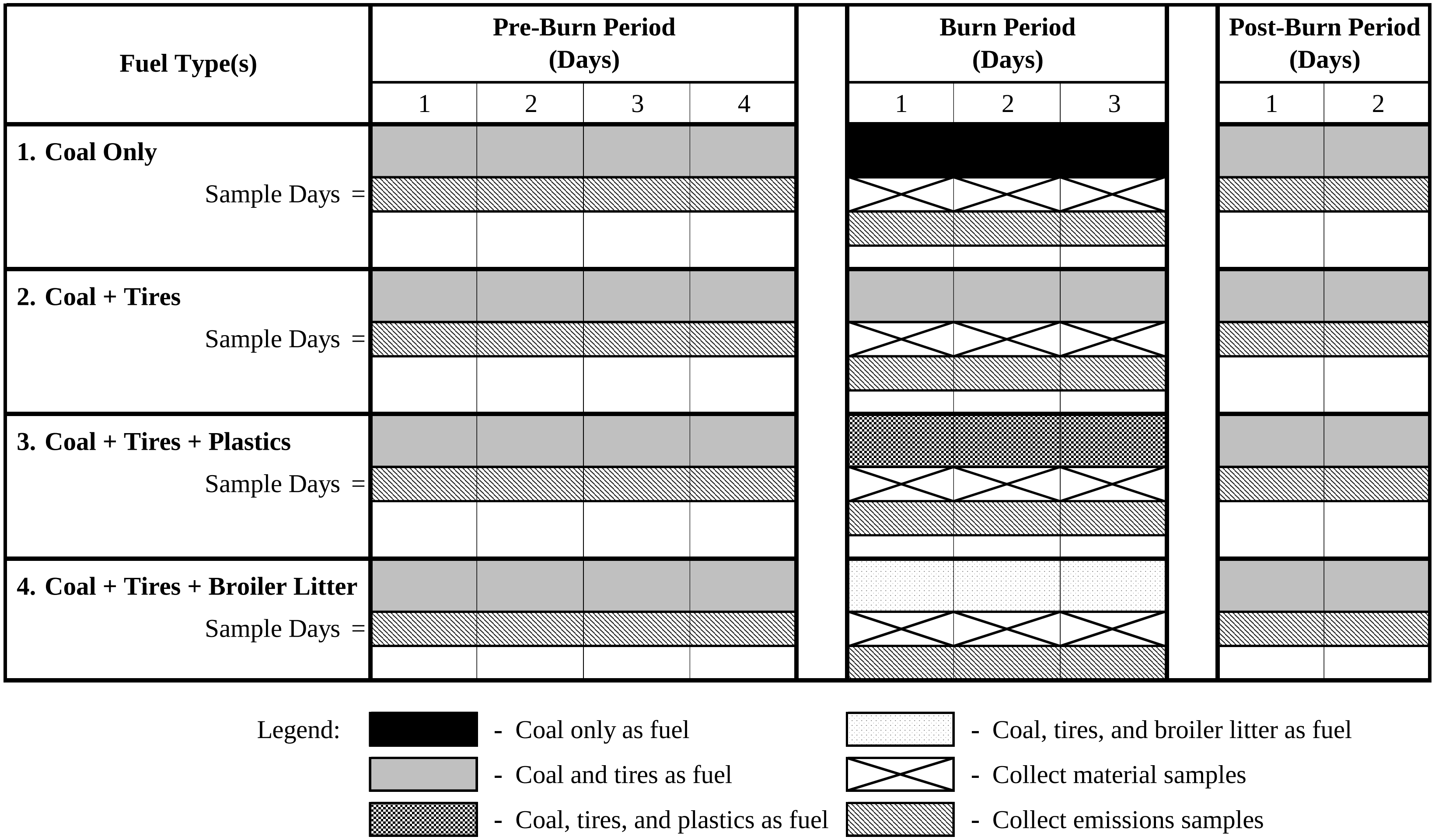
3.1.1 Definitions

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 the material collected at various times and locations 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 using discrete samples taken 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 presented 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.

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; namely, whether the discrete samples collected at the plant were tested, or if composite specimens were prepared from the discrete samples collected. Discussion of specimen preparation methods is given in Section 3.3.2. The typical sampling period was during Burn One, during Burn Two, during Burn Three, and during Burn four. A graphical timeline for the typical sampling period can be found in Figure 3.2.



Fuel Type(s)	Pre-Burn Period (Days)				Burn Period (Days)			Post-Burn Period (Days)	
	1	2	3	4	1	2	3	1	2
1. Coal Only	▒	▒	▒	▒	■	■	■	▒	▒
Sample Days =	▨	▨	▨	▨	☒	☒	☒	▨	▨
					▨	▨	▨		
2. Coal + Tires	▒	▒	▒	▒	▒	▒	▒	▒	▒
Sample Days =	▨	▨	▨	▨	☒	☒	☒	▨	▨
					▨	▨	▨		
3. Coal + Tires + Plastics	▒	▒	▒	▒	▩	▩	▩	▒	▒
Sample Days =	▨	▨	▨	▨	☒	☒	☒	▨	▨
					▨	▨	▨		
4. Coal + Tires + Broiler Litter	▒	▒	▒	▒	░	░	░	▒	▒
Sample Days =	▨	▨	▨	▨	☒	☒	☒	▨	▨
					▨	▨	▨		

Legend:
■ - Coal only as fuel
▒ - Coal and tires as fuel
▩ - Coal, tires, and plastics as fuel
░ - Coal, tires, and broiler litter as fuel
☒ - Collect material samples
▨ - Collect emissions samples

Figure 3.2: Sampling Timeline

3.2.1 Collection of Materials

All of the materials used in the production process were sampled and tested for various properties. All but one of these materials can be divided into two categories. These categories are process inputs and process outputs. For a detailed description of the production of portland cement, see Section 2.2.

Process input materials are those that are used to produce portland cement. The inputs at this specific cement plant were the raw materials, of which there were six, as well as the fuels. Five of the six raw materials were combined in strictly controlled proportions in order to produce a material known as kiln feed, also considered raw material seven. 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 were sampled and tested for various properties as described in the following sections.

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

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

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 a percent by weight (wt. %), or as parts per million (ppm). The former is the percentage of the total unit weight comprised by 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 is 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. Table 3.1 shows the standard parameters that were tested for by the cement plant and by the external laboratory. Each of the parameters shown in Table 3.1 was determined by XRF, except for Na_2O_{eq}, which is 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.

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)

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

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. 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), to be discussed in Section 3.3.3, which determines its chemical composition. 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.

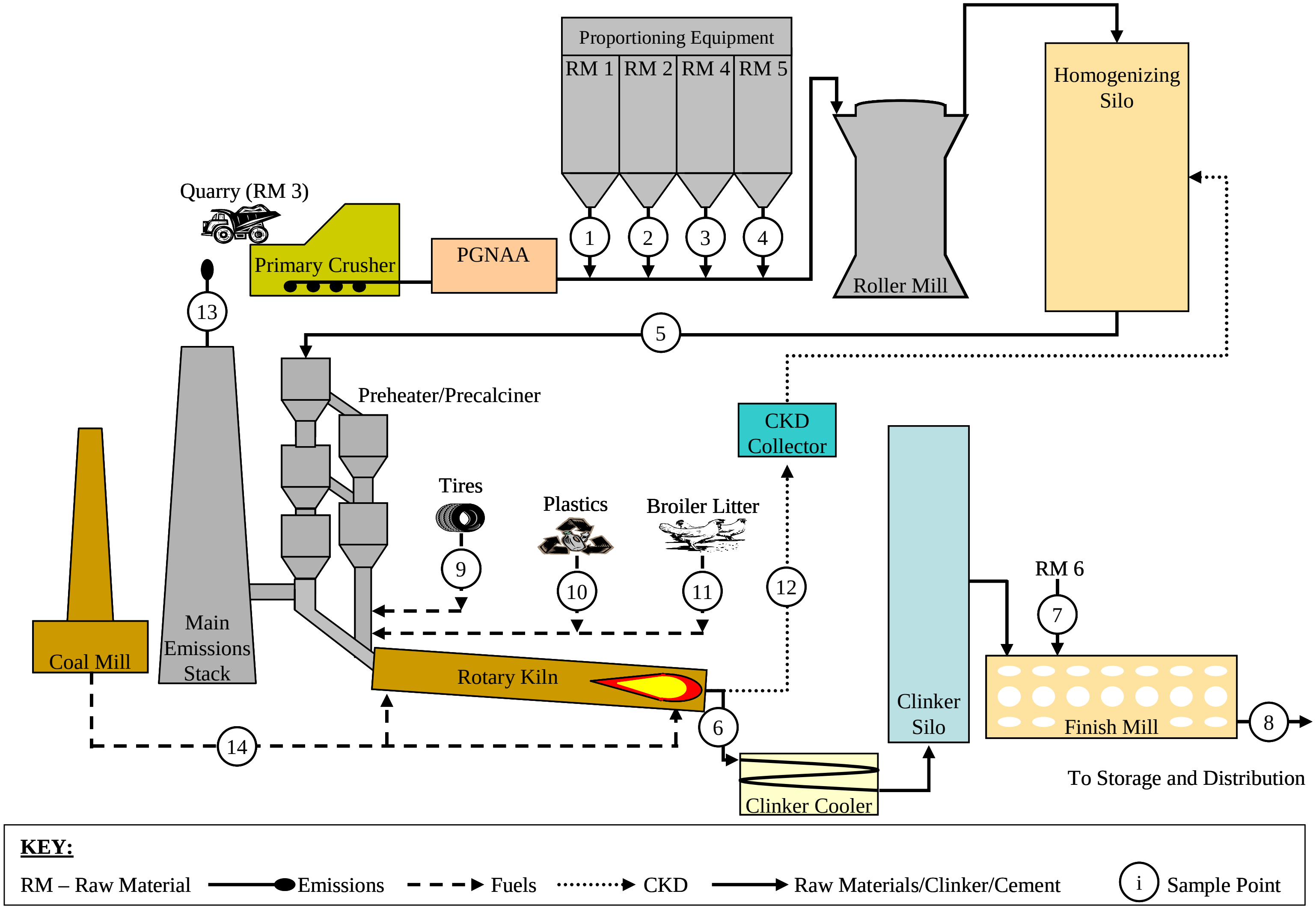


Figure 3.3: Diagram of the Cement Plant

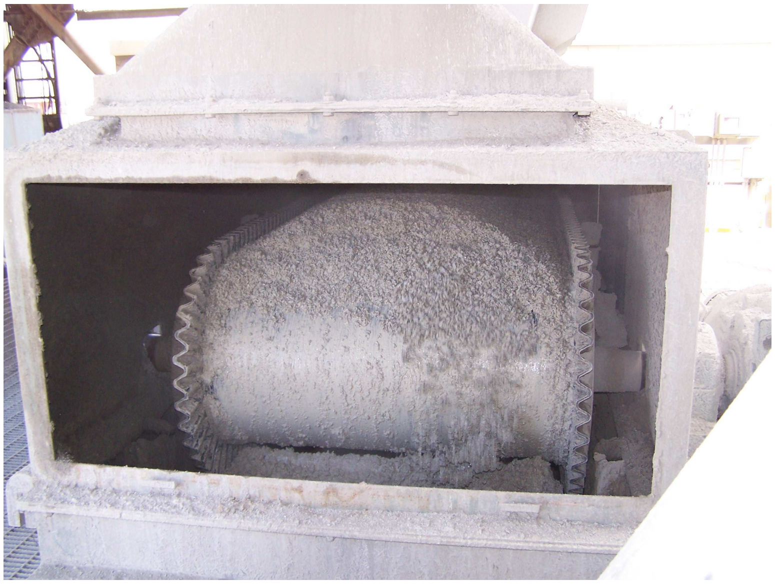


Figure 3.4: Raw Material Sample Point

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, or Raw Material Seven. After the kiln feed has been 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 is added to the raw materials, a sample was collected at Sample Point 12 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 3.6**.** 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.

Figure 3.5: Kiln Feed Sampling

Figure 3.6: Sampling of Clinker

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. Additionally, 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 14 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 and plastics utilize an injection point just above the tires', and are inserted using a conveyor and screw system as shown in Figure 3.10**.** The tires, plastics, and broiler litter were sampled at Sample Points Nine, Ten, and Eleven 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**.** The plastics and broiler litter 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

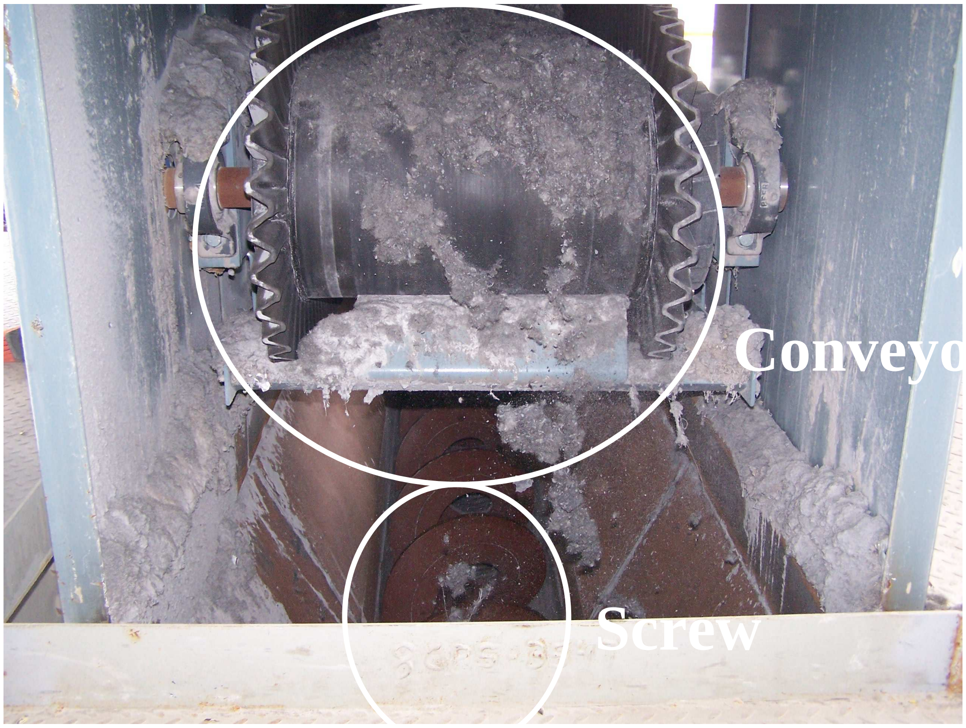


Figure 3.10: Plastics and Broiler Litter Kiln Injection System

Once the clinker has been 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 3.11. 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 had to be prepared for shipping and/or testing. All of the typical containers that were filled with samples were each emptied into two-gallon, heavy-duty, plastic bags, which were 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 following the same path. This method was used in order 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. All of the specimens that were tested by the cement plant did not require preparation by staff from Auburn University.

3.3.3 Analyzing the Chemical Composition of Raw Materials

There were seven raw materials that were tested in all. Each of the particular raw materials' source and name 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, 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, were 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 period. 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 four 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 period. 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 period in which they were used.

Sampling of the two 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, a proximate and an ultimate analysis were conducted on each sample. Table 3.3 shows a detailed list of the data collected in each of these analyses. In addition to the proximate and ultimate analysis, 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, or broiler litter. 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	Nitrogen
Fixed Carbon	Sulfur
	Oxygen
	Ash
	Moisture

3.3.5 Analyzing the Chemical Composition of Cement Kiln Dust

The cement kiln dust (CKD) was sampled two times per 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 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 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 content was determined on each of the daily composites using a total organic carbon (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. The tests performed by Auburn University were done so on a single composite specimen prepared over each of the burn periods. Table 3.4, Table 3.5, and Table 3.6 show the physical properties of cement tested by Auburn University, the cement plant, and the cement plant's specialty laboratory, respectively. These tables also show the specifications and units used for 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 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
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 Specialty Laboratory

Property	Units	ASTM Specification
Heat of Hydration 7 days	kJ/kg	C 186
Heat of Hydration 28 days	kJ/kg	C 186
Particle Size Distribution	N/A	Laser Diffraction

3.3.9 Analyzing the Properties of Concrete

For each of the burn periods, 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 the first 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 period using the 5-gallon 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

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
Mixture Properties		
Water/Cement ratio:	***0.44***	***Total Volume*** ***27.00*** ***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. Table 3.9 shows the tests conducted by both entities, as well as those conducted only by Auburn University. The specification associated with each test is also shown.

Table 3.8: Mix B Proportions

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
Mixture Properties		
Water/Cement ratio:	***0.37***	***Total Volume = 27.00*** ***ft^3***

The typical concrete mix at Auburn University was made by preparing enough material, in the proportions shown in Table 3.7 or Table 3.8, to produce seven cubic feet 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.

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.

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 thorough 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 variances 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.

Chapter 4

Presentation and Analysis of Data

4.1 Introduction

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

The first task of this chapter is simply to present the data pertaining to each test or parameter for that material. When there are ten or more data points for a set of results, a complete set of summary statistics are given. 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. The latter statistic is given in the form of a P-value based on Anderson-Darling statistics. 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.3.

The second task of this chapter is to provide an analysis of the data. In this section, graphical representations are presented showing the difference in means between each of the burns relative to the primary burn, which is the coal plus tires burn (Burn Two). Burn Two was chosen as the burn to which all other burns are compared because the cement plant burns coal and tires during normal operation. In addition to the graphs, when there are more than ten data points, a table is shown that indicates whether or not any changes in means were statistically significant. A P-value is presented that serves as the indicator for statistical significance. The limiting P-value used for determination of statistical significance was selected to be 0.10. This was done because the sample sizes for all materials except emissions were considered to be small to very small. Any P-value above this limiting value will signify that the difference in means for that specific result is not statistically significant.

The final task of this chapter is discussion of 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. Finally, this task compares the parameters that are significantly changed to effects reported in the literature review. Where applicable, 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 two alternative fuels. It was the goal of this study to produce portland cement using both recycled industrial plastics and broiler litter. The implementation of these alternative fuels is a complex endeavor for the cement plant. Because of this fact, the broiler litter test was not completed within the timeframe necessary for the results to be presented and discussed in this document. Therefore, only data pertaining to Burn One, Burn Two, and Burn Three are presented. However, this study will continue, and the data associated with the broiler litter burn will be presented in future documentation related to this project.

4.2 Research Conditions

Each of the test burn periods lasted a total of three days. Considerable time elapsed between each burn period, 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 were changed relative to each burn, in order to assure maximum production. Some of these aspects that were variable were the kiln feed rate, fuel feed rates, and production rates. Since these aspects of the production process are proprietary information, the ranges for each of these parameters are given, instead of the averages.

Burn One utilized coal as the only fuel, and was conducted between 7 AM on April 18, 2006 and 7 AM on April 21, 2006. The kiln feed rate for Burn One was between 250 and 310 tons per hour. The total coal feed rate was between 18 and 20 tons per hour. Finally, the clinker production rate for Burn One was between 160 and 200 tons per hour.

Burn Two utilized coal and tires as fuel, and was conducted between 7 AM on July 11, 2006 and 7 AM on July 14, 2006. The kiln feed rate during Burn Two was between 90 and 330 tons per hour. The total coal feed rate was between 10 and 20 tons per hour. The total tire feed rate was between 0.03 and 1.4 tons per hour. These rates correspond to between a 1 and 10 percent tire-to-fuel replacement rate on an energy basis. The rate of tire replacement was controlled by the development of sulfur build-ups which limited airflow within the system. The clinker rates for this burn period were between 100 and 200 tons per hour.

Burn Three utilized coal, tires, and recycled post-industrial plastics as the fuel, and was conducted between 7 AM on April 3, 2007 and 7 AM on April 6, 2007. The kiln feed rate during Burn Three was between 260 and 330 tons per hour. The total coal feed rate was between 10 and 20 tons per hour. The tire feed rate was between 0.3 and 4 tons per hour. This results in a tire-to-fuel replacement rate of 2 to 8 percent, on a heat replacement basis. Just as with Burn Two, this rate was controlled by the development of sulfur build-ups in the system. The feed rate for the plastics was between 2.5 and 3.5 tons per hour. This rate was found to be controlled by the low density of the plastics, and the ability of the equipment at the cement plant to handle it. Finally, the clinker rates for Burn Three were between 170 and 240 tons per hour.

4.3 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 collected or tested at the cement plant. 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. 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. This was done because the major parameters were determined by both the cement plant and the external laboratory. Finally, specialty laboratory results (SLR) are those that were collected at the cement plant's specialty laboratory.

In all tables that present summary statistics, the abbreviation C.V. stands for coefficient of variation. It is calculated by dividing the standard deviation of the data set by the average, and is reported as a percentage. In addition, as the normality P-value decreases, the coefficient becomes less meaningful. 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. In the tables where a percent difference is given, this statistic is abbreviated as % Diff. This difference is relative to the results of the coal plus tires burn, from the testing agency in question. For instance, in any given table of results as presented by the cement plant, the percent difference is relative to the coal plus tires, as reported by the cement plant. If the data were reported by the external laboratory, the percent difference is relative to the coal plus tires burn, as reported by the external laboratory.

Summary statistics will not include the coefficient of variation or the P-value relative to normality for data sets which contain less than ten data points. The same limit will be utilized for determining statistically significant differences relative to Burn Two. Even though statistical significance will not be reported for such small data sets, a graphical representation of percent difference between means relative to Burn Two will be given. These percent difference plots may show the results from different testing agencies. Once again, these differences are relative to the coal plus tires burn as reported by the testing agency in question. In the plots of percent difference for chemical compositions, the same set of major parameters will be plotted. These major parameters are Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, Na_2O, SiO_2, and SO_3.

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. Table 4.1 shows the results of the chemical analysis conducted by the cement plant on Raw Materials One, Two, and Three. Table 4.2 shows the results of the chemical analyses conducted by the external laboratory on the same three raw materials. Table 4.3 and Table 4.4 show the chemical composition of Raw Materials Four, Five, and Six for the cement plant and the external laboratory, respectively.

Table 4.1: CPR - Chemical Composition of Raw Materials One, Two, and Three

Parameter (wt. %)	**Raw Material One**			**Raw Material Two**			**Raw Material Three**		
	Burn 1	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**
Al_2O_3	25.80	22.80	23.22	0.33	0.30	0.39	2.68	3.16	2.98
CaO	3.95	4.38	4.27	54.00	54.10	52.85	41.54	40.94	41.59
Fe_2O_3	10.20	9.27	14.41	0.14	0.17	0.00	1.63	1.43	1.30
K_2O	2.57	2.08	2.15	0.07	0.01	0.07	0.18	0.17	0.26
MgO	1.21	1.09	2.21	1.15	0.95	0.97	3.50	3.48	3.29
Na_2O	0.38	0.40	0.42	0.00	0.00	0.03	0.01	0.07	0.10
SiO_2	43.70	44.90	43.03	0.96	0.85	2.04	14.00	14.35	13.77
SO_3	0.66	1.21	0.13	0.18	1.05	0.10	0.12	0.14	0.15
Moisture	9.07	19.81	34.60	5.80	1.80	3.00	NC	NC	NC
LOI	9.07	11.63	7.10	43.18	42.47	43.20	NC	NC	NC

Notes:

NC - Not Collected

Table 4.2: ELR - Chemical Composition of Raw Materials One, Two, and Three

Property	**Raw Material One**			**Raw Material Two**			**Raw Material Three**		
	Burn 1	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**
Al_2O_3 (wt. %)	24.76	24.07	26.87	0.19	0.07	0.87	3.23	5.32	8.09
CaO (wt. %)	2.95	2.74	3.20	50.49	54.92	91.85	43.00	36.02	43.79
Fe_2O_3 (wt. %)	9.96	10.97	12.35	0.13	0.15	0.47	1.89	2.75	3.56
K_2O (wt. %)	2.25	2.25	2.69	0.06	0.06	0.14	0.34	0.40	0.69
MgO (wt. %)	1.26	1.07	1.52	0.77	0.82	3.04	1.17	1.18	1.86
Na_2O (wt. %)	0.53	0.55	0.60	0.00	0.03	0.47	0.00	0.08	0.11
P_2O_5 (wt. %)	0.63	0.56	0.63	0.01	0.00	0.01	0.03	0.06	0.04
SiO_2 (wt. %)	43.44	43.09	50.21	0.51	0.49	2.86	15.92	22.11	41.12
SO_3 (wt. %)	0.30	0.15	0.09	0.12	0.15	0.20	0.29	0.25	0.12
TiO_2 (wt. %)	1.15	1.10	1.37	0.01	0.00	0.00	0.23	1.04	0.43
Moisture (wt. %)	17.71	23.67	22.26	2.54	0.02	2.93	4.53	0.34	6.51
LOI (wt. %)	12.77	13.44	11.99	47.72	43.32	42.91	33.93	30.78	27.56
As (ppm)	173	137	299	ND	ND	6	7	18	23
Ba (ppm)	1867	1510	2000	68	88	300	316	293	300
Cd (ppm)	ND	ND	NR	ND	ND	NR	ND	ND	NR
Cl (ppm)	23	125	25	24	265	29	42	158	34
Co (ppm)	43	45	64	ND	ND	12	26	ND	15
Cr (ppm)	139	135	203	ND	ND	16	62	40	54
Cu (ppm)	269	200	219	ND	ND	18	21	ND	46
Hg (ppm)	0.07	0.01	NR	0.01	0.03	NR	0.04	0.03	NR
Mn (ppm)	280	302	1000	24	18	300	801	96	1200
Mo (ppm)	ND	ND	40	ND	ND	12	ND	ND	13
Ni (ppm)	112	114	122	ND	ND	14	ND	21	16
Pb (ppm)	63	67	195	12	12	4	17	47	27
Sb (ppm)	20	ND	NR	32	80	NR	82	30	NR
Se (ppm)	3	3	NR	1	ND	NR	1	ND	NR
Sr (ppm)	1432	1373	1800	172	225	400	240	259	400
V (ppm)	303	271	325	ND	ND	17	49	103	74
Zn (ppm)	84	150	363	ND	24	26	27	90	52

Notes:

ND - Not Detected
NR - Not Reported

Raw Material Three was not tested using XRF at the cement plant. This analysis was done using a Prompt Gamma Neutron Activation Analyzer (PGNAA). This is the reason for there not being results for moisture and loss on ignition for this raw material.

For a more thorough discussion of the chemical analysis of the raw materials, see Section 3.3.1.

Table 4.3: CPR - Chemical Composition of Raw Materials Four, Five, and Six

Parameter (wt. %)	Raw Material Four			Raw Material Five			Raw Material Six		
	Burn 1	Burn 2	Burn 3	Burn 1	Burn 2	Burn 3	Burn 1	Burn 2	Burn 3
Al_2O_3	4.22	6.28	7.60	1.79	0.76	1.14	0.87	1.87	2.62
CaO	28.90	35.10	38.10	0.87	2.16	1.66	36.80	29.10	32.57
Fe_2O_3	34.70	25.00	14.50	1.72	1.45	1.63	0.45	0.30	0.25
K_2O	0.19	0.02	0.05	0.32	0.16	0.28	0.11	0.19	0.25
MgO	8.80	10.40	12.90	0.08	0.19	0.19	1.05	1.40	3.15
Na_2O	0.00	0.00	NR	0.03	0.00	NR	0.00	0.00	0.20
SiO_2	15.40	16.50	24.60	93.70	92.20	95.90	3.98	8.14	13.56
SO_3	1.27	0.60	0.41	0.38	1.12	0.21	44.40	41.67	34.95
Moisture	8.00	4.46	6.50	7.70	4.30	3.40	12.30	8.70	10.40
LOI	2.99	1.84	0.10	0.48	1.56	0.40	12.24	17.63	11.40

Notes:

NR - Not Reported

Table 4.4: ELR - Chemical Composition of Raw Materials Four, Five, and Six

Property	**Raw Material Four**			**Raw Material Five**			**Raw Material Six**		
	Burn 1	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**	**Burn 1**	**Burn 2**	**Burn 3**
Al_2O_3 (wt. %)	3.64	3.90	4.27	1.47	1.92	1.00	1.22	0.76	2.71
CaO (wt. %)	5.57	31.68	29.01	0.19	0.37	0.41	33.31	30.90	38.80
Fe_2O_3 (wt. %)	52.83	40.25	34.03	0.91	1.17	0.59	0.74	0.25	0.50
K_2O (wt. %)	0.79	0.03	0.20	0.43	0.25	0.17	0.13	0.16	0.26
MgO (wt. %)	1.66	11.95	12.16	0.30	0.19	0.18	1.50	0.62	2.78
Na_2O (wt. %)	0.20	0.03	0.13	0.00	0.07	0.04	0.03	0.06	0.16
P_2O_5 (wt. %)	0.56	0.61	0.47	0.01	0.03	0.00	0.03	0.01	0.03
SiO_2 (wt. %)	13.51	12.37	15.27	95.59	94.77	97.37	5.93	4.58	13.21
SO_3 (wt. %)	0.69	0.20	0.30	0.25	0.01	0.00	38.60	41.90	41.23
TiO_2 (wt. %)	0.16	0.26	0.25	0.43	0.28	0.20	0.05	0.02	0.10
Moisture (wt. %)	12.49	0.31	6.01	4.31	4.20	2.29	2.09	0.80	4.06
LOI (wt. %)	20.39	ND	-1.30	0.45	0.93	0.35	18.44	20.74	18.06
As (ppm)	6	ND	4	ND	7	4	ND	ND	< 2
Ba (ppm)	308	ND	200	131	ND	200	73	ND	300
Cd (ppm)	6	3	NR	ND	ND	NR	ND	ND	NR
Cl (ppm)	114	238	100	43	59	13	7	105	30
Co (ppm)	38	ND	4	ND	ND	5	ND	ND	7
Cr (ppm)	285	2672	3249	ND	ND	9	ND	ND	32
Cu (ppm)	545	22	61	23	30	33	36	ND	< 10
Hg (ppm)	0.01	0.05	NR	0.01	0.01	NR	0.09	0.09	NR
Mn (ppm)	7919	19571	38700	153	78	200	340	82	1200
Mo (ppm)	18	72	90	ND	ND	23	ND	ND	23
Ni (ppm)	192	11	75	ND	22	< 5	ND	9	5
Pb (ppm)	450	13	21	40	8	9	8	21	23
Sb (ppm)	ND	36	NR	ND	ND	NR	ND	ND	NR
Se (ppm)	2	2	NR	ND	1	NR	1	ND	NR
Sr (ppm)	127	169	200	50	122	100	573	566	800
V (ppm)	97	687	604	ND	ND	20	ND	ND	18
Zn (ppm)	6464	134	198	80	13	2	ND	ND	8

Notes:

ND - Not Detected
NR - Not Reported

Table 4.5 shows the percent change in each parameter for Raw Materials One, Two, and Three, as reported by the cement plant. Table 4.6 shows the percent change for the same raw materials as reported by the external laboratory. Table 4.7 and Table 4.8 show the percent change for Raw Materials Four, Five, and Six, as reported by the cement plant and the external laboratory, respectively. The percent changes for each burn are relative to Burn Two. Wherever a result was not reported by the cement plant, or the result was zero for Burn Two, a value of not applicable (NA) was reported in these tables.

Table 4.5: CPR - Percent Change in Raw Materials One, Two, and Three

Parameter	Percent Change Relative to Burn Two					
	Raw Material One		Raw Material Two		Raw Material Three	
	Burn 1	Burn 3	Burn 1	Burn 3	Burn 1	Burn 3
Al_2O_3	13.2	1.8	10.0	30.0	-15.2	-5.8
CaO	-9.8	-2.5	-0.2	-2.3	1.5	1.6
Fe_2O_3	10.0	55.4	-17.6	NA	14.0	-9.3
K_2O	23.6	3.4	600.0	600.0	5.9	54.9
MgO	11.0	102.8	21.1	2.1	0.6	-5.5
Na_2O	-5.0	5.0	NA	NA	-85.7	47.6
SiO_2	-2.7	-4.2	12.9	140.0	-2.4	-4.0
SO_3	-45.5	-89.3	-82.9	-90.5	-14.3	9.5
Moisture	-54.2	74.7	222.2	66.7	NA	NA
LOI	-22.0	-39.0	1.7	1.7	NA	NA

Notes:

NA - Not Applicable

Table 4.6: ELR - Percent Change in Raw Materials One, Two, and Three

Property	**Percent Difference Relative to Burn Two**					
	Raw Material One		**Raw Material Two**		**Raw Material Three**	
	Burn 1	**Burn 3**	**Burn 1**	**Burn 3**	**Burn 1**	**Burn 3**
Al_2O_3	2.9	11.63	179.7	1167.58	-39.3	52.02
CaO	7.8	16.79	-8.1	67.25	19.4	21.56
Fe_2O_3	-9.2	12.59	-13.7	204.35	-31.4	29.32
K_2O	-0.3	19.32	-2.3	133.12	-16.2	71.10
MgO	18.4	42.52	-6.8	269.10	-1.2	57.16
Na_2O	-4.2	8.12	-100.0	1726.10	-100.0	39.41
P_2O_5	11.3	11.78	NA	NA	-43.5	-34.82
SiO_2	0.8	16.51	4.7	484.84	-28.0	85.98
SO_3	106.8	-38.94	-15.9	37.13	20.0	-51.11
TiO_2	4.4	24.41	NA	NA	-78.4	-58.78
Moisture	-25.2	-5.95	16649.6	19221.40	1250.9	1841.39
LOI	-5.0	-10.77	10.2	-0.94	10.2	-10.45
As	26.5	118.25	NA	NA	-62.3	24.93
Ba	23.6	32.41	-23.4	239.49	8.0	2.45
Cd	NA	NA	NA	NA	NA	NR
Cl	-81.6	-80.00	-90.9	-89.06	-73.4	-78.48
Co	-5.3	41.94	NA	NA	NA	NR
Cr	3.0	50.07	NA	NA	52.6	33.90
Cu	34.4	9.34	NA	NA	NA	NR
Hg	600.0	NA	-66.7	NA	33.3	NR
Mn	-7.3	231.40	33.2	1565.14	730.2	1144.35
Mo	NA	NA	NA	NA	NA	NR
Ni	-1.1	7.40	NA	NA	NA	-23.96
Pb	-6.1	192.06	-2.3	-66.70	-63.4	-42.97
Sb	NA	NA	-59.9	NA	176.2	NR
Se	34.0	NA	NA	NA	NA	NR
Sr	4.3	31.05	-23.4	77.95	-7.2	54.67
V	12.1	20.13	NA	NA	-51.8	-27.86
Zn	-44.2	141.99	NA	8.23	-70.3	-42.41

Notes:

NA - Not Applicable

Table 4.7: CPR - Percent Change in Raw Materials Four, Five, and Six

Parameter	**Percent Change Relative to Burn Two**					
	Raw Material Four		**Raw Material Five**		**Raw Material Six**	
	Burn 1	**Burn 3**	**Burn 1**	**Burn 3**	**Burn 1**	**Burn 3**
Al_2O_3	-32.8	21.0	135.5	50.0	-53.5	40.2
CaO	-17.7	8.5	-59.7	-23.1	26.5	11.9
Fe_2O_3	38.8	-42.0	18.6	12.4	50.0	-16.7
K_2O	850.0	150.0	100.0	75.0	-42.1	31.6
MgO	-15.4	24.0	-57.9	0.0	-25.0	125.0
Na_2O	NA	NA	NA	NA	NA	NA
SiO_2	-6.7	49.1	1.6	4.0	-51.1	66.6
SO_3	110.6	-32.0	-66.1	-81.3	6.6	-16.1
Moisture	79.4	45.7	79.1	-20.9	41.4	19.5
LOI	62.5	-94.6	-69.2	-74.4	-30.6	-35.3

Notes:

NA - Not Applicable

Although the percent change of each parameter is presented for the raw materials, no conclusions can be drawn based on these data alone. The proportions of each material that were combined to produce the kiln feed were 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 has been reported.

Table 4.8: ELR - Percent Change in Raw Materials Four, Five, and Six

Property	**Percent Difference Relative to Burn Two**					
	Raw Material Four		**Raw Material Five**		**Raw Material Six**	
	Burn 1	**Burn 3**	**Burn 1**	**Burn 3**	**Burn 1**	**Burn 3**
Al_2O_3	-6.7	9.48	-23.3	-47.90	61.5	257.71
CaO	-82.4	-8.44	-48.5	11.08	7.8	25.55
Fe_2O_3	31.2	-15.46	-21.9	-49.60	192.0	97.99
K_2O	2465.4	549.56	68.8	-32.83	-15.1	64.73
MgO	-86.1	1.79	56.3	-5.17	140.6	345.91
Na_2O	555.0	322.21	-100.0	-45.81	-46.9	153.43
P_2O_5	-7.0	-22.38	-62.5	-100.00	324.7	280.14
SiO_2	9.3	23.47	0.9	2.74	29.6	188.60
SO_3	253.3	53.84	2263.7	-100.00	-7.9	-1.59
TiO_2	-37.8	-2.57	50.1	-29.76	218.5	533.57
Moisture	3866.9	1808.83	2.7	-45.44	162.0	408.92
LOI	NA	NA	-51.4	-62.17	-11.1	-12.94
As	NA	NA	NA	-45.81	NA	NA
Ba	NA	NA	NA	NA	NA	NA
Cd	91.0	NA	NA	NA	NA	NA
Cl	-52.1	-57.98	-27.1	-77.97	-93.3	-71.43
Co	NA	NA	NA	NA	NA	NA
Cr	-89.3	21.61	NA	NA	NA	NA
Cu	2426.4	183.02	-23.6	11.76	NA	NA
Hg	-80.0	NA	0.0	NA	0.0	NA
Mn	-59.5	97.74	96.2	156.29	314.5	1362.09
Mo	-74.3	25.27	NA	NA	NA	NA
Ni	1604.5	564.32	NA	NA	NA	-47.20
Pb	3269.4	57.39	378.4	6.68	-64.6	7.94
Sb	NA	NA	NA	NA	NA	NA
Se	-18.1	NA	NA	NA	NA	NA
Sr	-25.1	18.10	-59.2	-18.25	1.3	41.38
V	-85.8	-12.03	NA	NA	NA	NA
Zn	4707.4	47.27	528.4	-84.20	NA	NA

Notes:

NA - Not Applicable

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, consisted of ten, twelve, and seven data points for Burns One, Two, and Three, respectively. Table 4.9 shows the summary statistics for each of the burns. Although Burn Three did not consist of ten or more data points, it was determined to be necessary to report all summary statistics due to the critical nature of the kiln feed to the overall production process.

Table 4.9: CPR - Chemical Composition of Kiln Feed

Parameter	**Burn One**			**Burn Two**			**Burn Three**		
	Average (wt. %)	**C.V. (%)**	**P-Value**	**Average (wt. %)**	**C.V. (%)**	**P-Value**	**Average (wt. %)**	**C.V. (%)**	**P-Value**
Al_2O_3	3.11	2.4	0.561	3.23	2.6 [1]	0.092	3.01	2.1	0.386
CaO	43.95	0.5	0.642	43.04	0.8	0.166	43.74	0.6 [1]	0.078
Fe_2O_3	2.03	3.9	0.526	2.01	3.2	0.965	1.90	4.0	0.356
K_2O	0.33	2.9 [1]	0.005	0.29	5.3 [1]	<0.005	0.28	1.7 [1]	<0.005
MgO	1.92	2.4	0.954	2.51	6.6 [1]	0.064	2.07	2.9	0.440
Na_2O	0.04	14.4 [1]	0.008	0.10	18.6	0.238	0.04	17.8 [1]	0.021
Na_2O_{eq}	0.26	4.2	0.241	0.29	5.3	0.336	0.23	3.9 [1]	0.091
SiO_2	13.67	1.1	0.960	14.38	1.7	0.181	13.66	1.4	0.156
SO_3	0.29	12.4	0.502	0.29	12.1	0.611	0.11	18.3	0.223
LOI	36.59	0.4	0.430	35.05	1.2	0.249	34.72	0.7	0.183

Notes:

[1] Data Not Normally Distributed

Table 4.10 shows the percent change in chemical parameters in the kiln feed based on the cement plant data. All parameters exhibited a statistically significant change relative to the kiln feed used in Burn Two, except for Fe_2O_3 and SO_3 from Burn One and K_2O from Burn Three.

Table 4.10: CPR - Percent Change in Mean for Kiln Feed

Parameter	Burn One			Burn Three		
	Percent Difference	P-Value	Significant	Percent Difference	P-Value	Significant
Al_2O_3	-3.7	0.002	Yes	-6.8	0.000	Yes
CaO	2.1	0.000	Yes	1.6	0.000	Yes
Fe_2O_3	1.0	0.476	No	-5.5	0.003	Yes
K_2O	13.8	0.000	Yes	-3.4	0.130	No
MgO	-23.5	0.000	Yes	-17.5	0.000	Yes
Na_2O	-60.0	0.000	Yes	-60.0	0.000	Yes
Na_2O_{eq}	-10.3	0.000	Yes	-20.7	0.000	Yes
SiO_2	-4.9	0.000	Yes	-5.0	0.000	Yes
SO_3	0.0	0.983	No	-62.1	0.000	Yes
LOI	4.4	0.000	Yes	-0.9	0.071	Yes

The kiln feed was analyzed by the external laboratory in the form of a single composite sample collected during each burn period. Table 4.11 shows the results of the XRF scan conducted by the external laboratory, along with the relative differences between the burns. Burn One showed a number of parameters that exhibited a percent change greater than ten percent relative to Burn Two. These parameters, in decreasing order of the absolute value of percent change are: Na_2O, Moisture, SO_3, P_2O_5, SiO_2, TiO_2, K_2O, Fe_2O_3, and Al_2O_3. The results from Burn Three showed a very different trend than the same burn as reported by the cement plant. Each of the major parameters showed an increase of more than 15 percent relative to Burn Two. The only exceptions were Na_2O, moisture, and LOI. The apparent complete change in chemical composition of the kiln feed for Burn Three was most likely purposefully done by the cement plant.

Table 4.11: ELR - Chemical Composition of Kiln Feed

Parameter	Burn One		Burn Two	Burn Three	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Al_2O_3	3.04	10.5	2.75	4.91	78.5
CaO	44.17	9.8	40.23	65.27	62.2
Fe_2O_3	2.15	12.0	1.92	3.01	56.8
K_2O	0.32	10.3	0.29	0.50	72.4
MgO	1.90	-8.7	2.08	3.35	61.1
Na_2O	0.01	-66.7	0.03	0.01	-66.7
P_2O_5	0.05	25.0	0.04	0.07	75.0
SiO_2	13.37	-21.4	17.00	21.87	28.6
SO_3	0.35	45.8	0.24	0.34	41.7
TiO_2	0.17	-15.0	0.20	0.24	20.0
Moisture	0.06	-66.7	0.18	0.10	-44.4
LOI	34.44	-2.1	35.18	34.67	-1.4
	Value (ppm)	**% Diff.**	**Value (ppm)**	**Value (ppm)**	**% Diff.**
As	2	-83.3	12	18	50.0
Ba	191	-25.4	256	400	56.3
Cd	ND	NA	ND	NR	NA
Cl	111	46.1	76	63	-17.1
Co	ND	NA	20	14	-30.0
Cr	51	-15.0	60	86	43.3
Cu	42	NA	ND	41	NA
Hg	0	NA	0	NR	NA
Mn	664	110.1	316	1700	438.0
Mo	ND	NA	ND	16	NA
Ni	ND	NA	14	12	-14.3
Pb	23	155.6	9	< 4	NA
Sb	32	-63.2	87	NR	NA
Se	0	NA	ND	NR	NA
Sr	260	13.5	229	500	118.3
V	39	-18.8	48	73	52.1
Zn	112	5.7	106	37	-65.1

Notes:

ND - Not Detected
NA - Not Applicable

Figure 4.1 shows a plot of the percent difference for the primary parameters, as reported by both testing agencies. For each testing agency, the percent differences are relative to Burn Two as reported by that testing agency. The cement plant results show two parameters, MgO and Na_2O, which showed a decrease of more than ten percent for Burn One and Burn Three. Additionally, K_2O for Burn One also showed a change of more than ten percent. The greatest difference in kiln feed was in SO_3 for Burn Three. This parameter exhibited a decrease of more than 60 percent. Figure 4.1 shows just how dramatic the changes were between Burn Three and Burn Two for the results from the external laboratory. The results from the external laboratory for Burn One were much less dramatic. The only parameters between these burns that showed a large change were Na_2O with a 70 percent decrease, and SO_3 with a 48 percent increase.

The reasons for the changes in chemical composition of the kiln feed can be many. One primary explanation is that the cement plant changed the composition purposely in order to assist in the production process. For instance, a change in many different parameters may result in more efficient conversion from kiln feed to clinker. An additional explanation may be that a change in composition of the kiln feed may result in a significant change in emissions properties. Since the composition of the kiln feed is closely monitored and adjusted by the cement plant, modifications to blending of raw materials are made with a purpose.

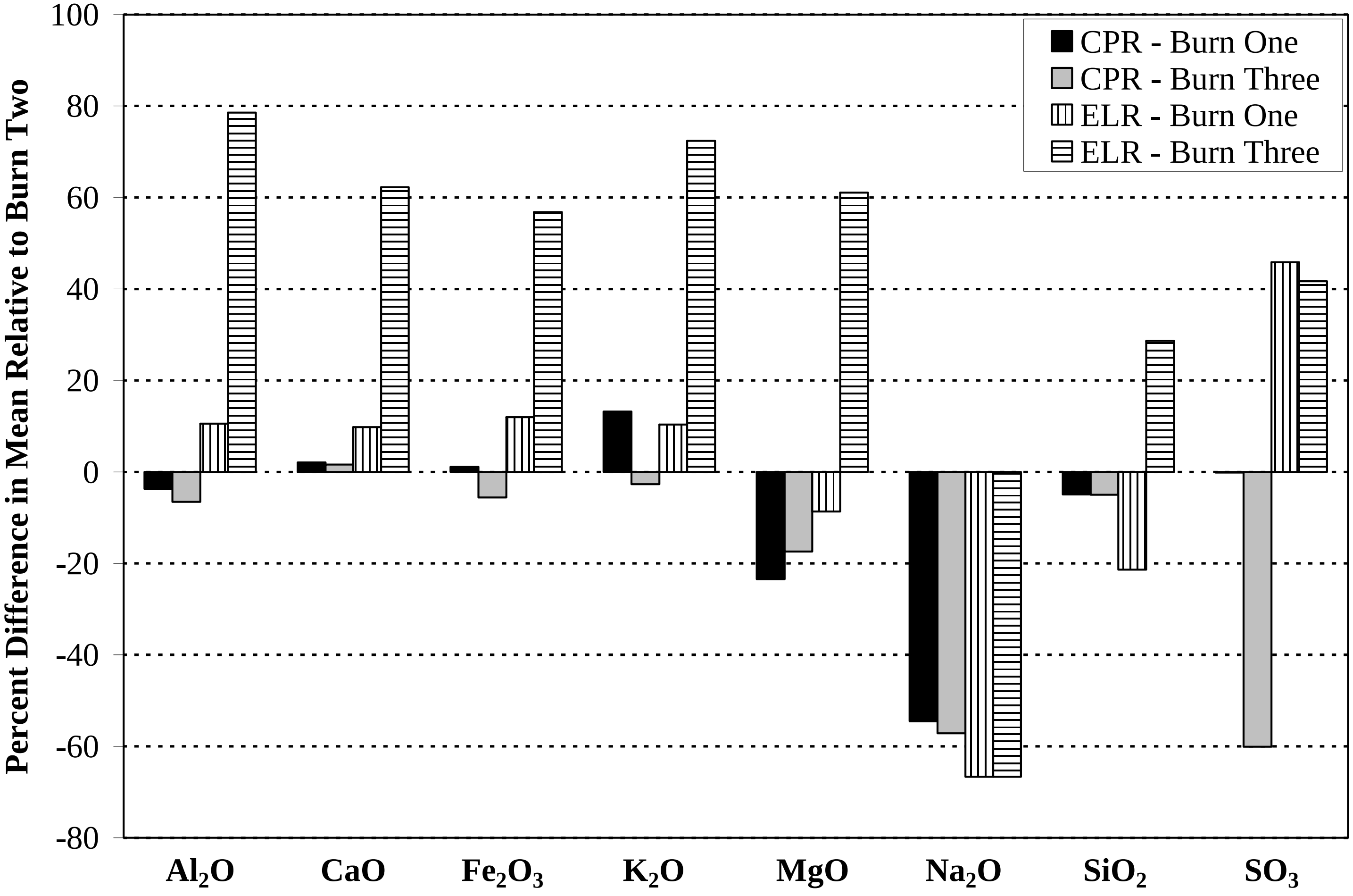


Figure 4.1: Percent Changes in Mean for Kiln Feed Relative to Burn Two

4.3.3 Chemical Composition of Fuel Sources

Pulverized coal is the primary fuel used to produce clinker from the kiln feed at the cement plant. A proximate, ultimate, and combustion analysis 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 discrete sample during each burn period. The results of these tests, along with the percent differences for Burn One and Burn Three relative to Burn Two are presented in Table 4.12.

The parameters in the Burn One coal which showed the greatest increase relative to Burn Two were oxygen, Na_2O, and SO_3, which showed increases of 42, 26, and 13 percent, respectively. The parameters showing the greatest decrease between these two burns were sulfur and MgO, which showed decreases of 31 and 21 percent, respectively. Overall, the chemical composition of the coal used during Burn One, and the coal used during Burn Two were reasonably similar.

Unfortunately, the coal source used by the cement plant was changed between Burn Two and Burn Three. This decision was made with production and economic issues in mind. The result of this new coal source can be seen in the percent differences between Burn Three and Burn Two, as shown in Table 4.12. The parameters showing the greatest change were sulfur and Fe_2O_3, which increased by 149 and 481 percent, respectively.

Table 4.12: CPR - Chemical Analysis and Percent Difference for Coal

Test	**Parameter**	**Burn One**		**Burn Two**	**Burn Three**	
		Value (wt. %)	**% Diff.**	**Value (wt. %)**	**Value(wt. %)**	**% Diff.**
Proximate Analysis	**Ash**	18.9	6.1	17.82	23.43	31.5
	Fixed Carbon	50.17	-3.6	52.05	48.43	-7.0
	Volatile Matter	30.93	2.7	30.13	28.14	-6.6
Ultimate Analysis	**Carbon**	69.06	-3.0	71.17	64.41	-9.5
	Hydrogen	4.25	-2.1	4.34	4.01	-7.6
	Nitrogen	1.51	4.1	1.45	1.31	-9.7
	Oxygen	5.22	41.5	3.69	3.05	-17.3
	Sulfur	1.06	-30.7	1.53	3.79	147.7
Standard Parameters	**Al_2O_3**	24.67	5.2	23.45	15.43	-34.2
	CaO	13.32	4.6	12.74	3.23	-74.6
	Fe_2O_3	5.83	-6.6	6.24	36.24	480.8
	K_2O	1.97	-8.8	2.16	1.94	-10.2
	MgO	1.18	-20.8	1.49	1.04	-30.2
	Na_2O	0.39	25.8	0.31	0.36	16.1
	SiO_2	42.89	-7.2	46.21	36.17	-21.7
	SO_3	8.36	12.8	7.41	4.4	-40.6
Heat Value [1]		12102	-3.2	12506	11255	-10.0

Notes:

[1] Value is Reported as BTU/lb

The tests conducted by the cement plant were also conducted by the external laboratory. However, the specimens that were tested by the external laboratory were composites prepared from six discrete samples collected throughout each of the burn periods. For this reason, the results presented by the external laboratory more accurately reflect the chemical composition of the coal over the entire burn phase. The results from the proximate, ultimate, and combustion analysis conducted by the external laboratory are shown in Table 4.13. These results showed that the ash content of Burn One showed the largest increase relative to Burn Two. Just as was reported by the cement plant, the oxygen composition between Burn One and Burn Two showed a large increase; in this case it was 26 percent. Hydrogen and moisture showed the largest decrease between Burns One and Two, with decreases of 27 and 11 percent.

As was expected, the results between Burns Three and Two showed dramatic differences in just about all parameters. The largest increases were for ash and sulfur. The largest decreases were between hydrogen and fixed carbon.

Table 4.13: ELR – Proximate, Ultimate, and Combustion Analysis for Coal

Test	Parameter	Burn One		Burn Two	Burn Three	
		Value (wt. %)	% Diff.	Value (wt. %)	Value(wt. %)	% Diff.
Proximate Analysis	**Ash**	22.45	34.1	16.74	24.54	46.6
	Fixed Carbon	49.58	-9.5	54.81	47.68	-13.0
	Volatile Matter	27.97	-1.7	28.45	27.78	-2.4
Ultimate Analysis	**Carbon**	67.61	-7.5	73.09	64.68	-11.5
	Hydrogen	3.61	-22.5	4.66	3.93	-15.7
	Nitrogen	1.1	-9.8	1.22	1.08	-11.5
	Oxygen	3.95	25.8	3.14	4.11	30.9
	Sulfur	1.28	11.3	1.15	1.66	44.3
Heat Value [1]		11698 [1]	-7.3	12624 [1]	11369 [1]	-9.9

Notes:

[1] Value is Reported as BTU/lb

In addition to the results shown in Table 4.13, the standard external laboratory parameters for the coal, along with the differences relative to Burn Two, are shown in

Table 4.14. All of these results were determined by XRF. Two different sets of units were used to report these data. The primary parameters, those that showed a more prominent presence, are reported as a percent of the total weight, while the less prominent parameters were reported as parts per million (ppm). The parameters that showed a presence less than the detection limit of the XRF are reported as not detected (ND). The majority of the standard parameters shown in Table 4.14 were determined on the ash of the fuel. Select parameters could only be determined on the dry coal. In such cases, this is noted.

The results presented in Table 4.14 show primary parameters for the coal from Burns One and Two to be reasonably similar. Na_2O and P_2O_5 were the only parameters that showed a change of more than ten percent. Of the less prominent parameters, the arsenic showed the greatest change between Burns One and Two. However, since the composition of the arsenic in Burn Two was only 80 ppm, it is difficult to determine whether this difference is practically significant. Cl, Cu, Mn, and Zn also showed large changes between Burns One and Two.

Just as with the results already presented for the coal from Burn Three relative to the coal from Burn Two, Table 4.14 shows large differences in most parameters. Of the primary parameters, Fe_2O_3 showed the greatest difference, with an increase of over 100 percent. The less prominent parameters mostly showed large changes as well, most notable were Mn and Mo, both of which showed an increase of more than 300 percent.

Figure 4.2 presents the percent change in the primary parameters from both testing agencies. Fe_2O_3 is not shown simply because of the large percent difference from the cement plant concerning Burn Two, relative to the other parameters.

Table 4.14: ELR – Standard Parameters for Coal

Test	Parameter	Burn One		Burn Two	Burn Three	
		Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Standard Parameters	Al_2O_3	25.07	-1.8	25.53	21.04	-17.6
	CaO	7.52	-5.6	7.97	8.25	3.5
	Fe_2O_3	7.60	3.4	7.35	15.16	106.3
	K_2O	2.57	-3.4	2.66	2.49	-6.4
	MgO	1.35	0.7	1.34	1.25	-6.7
	Na_2O	0.22	-47.6	0.42	0.36	-14.3
	P_2O_5	0.18	-10.0	0.20	0.23	15.0
	SiO_2	47.39	3.0	46.01	43.44	-5.6
	SO_3	6.95	-5.2	7.33	6.5	-11.3
	TiO_2	1.12	-2.6	1.15	0.96	-16.5
		Value (ppm)	% Diff.	Value (ppm)	Value (ppm)	% Diff.
	As	325	306.3	80	315	293.8
	Ba	1273	17.5	1083	1300	20.0
	Cd	ND	NA	ND	5[1]	NA
	Cl	125[1]	-31.3	182	134[1]	-26.4
	Co	ND	NA	29	43	48.3
	Cr	109	-14.2	127	116	-8.7
	Cu	150	29.3	116	102	-12.1
	Hg	< 1	NA	ND	< 1	NA
	Mn	220	-38.0	355	1500	322.5
	Mo	ND	NA	9	39	333.3
	Ni	80	-19.2	99	92	-7.1
	Pb	41	-12.8	47	45	-4.3
	Sb	ND	NA	ND	NR	NA
	Se	ND	NA	8	1[1]	-87.7
	Sr	487	-17.5	590	500	-15.3
	V	225	0.0	225	214	-4.9
	Zn	67	-49.6	133	197	48.1

Notes:

ND - Not Detected **NA - Not Applicable**

NR - Not Reported **[1] Dry Basis**

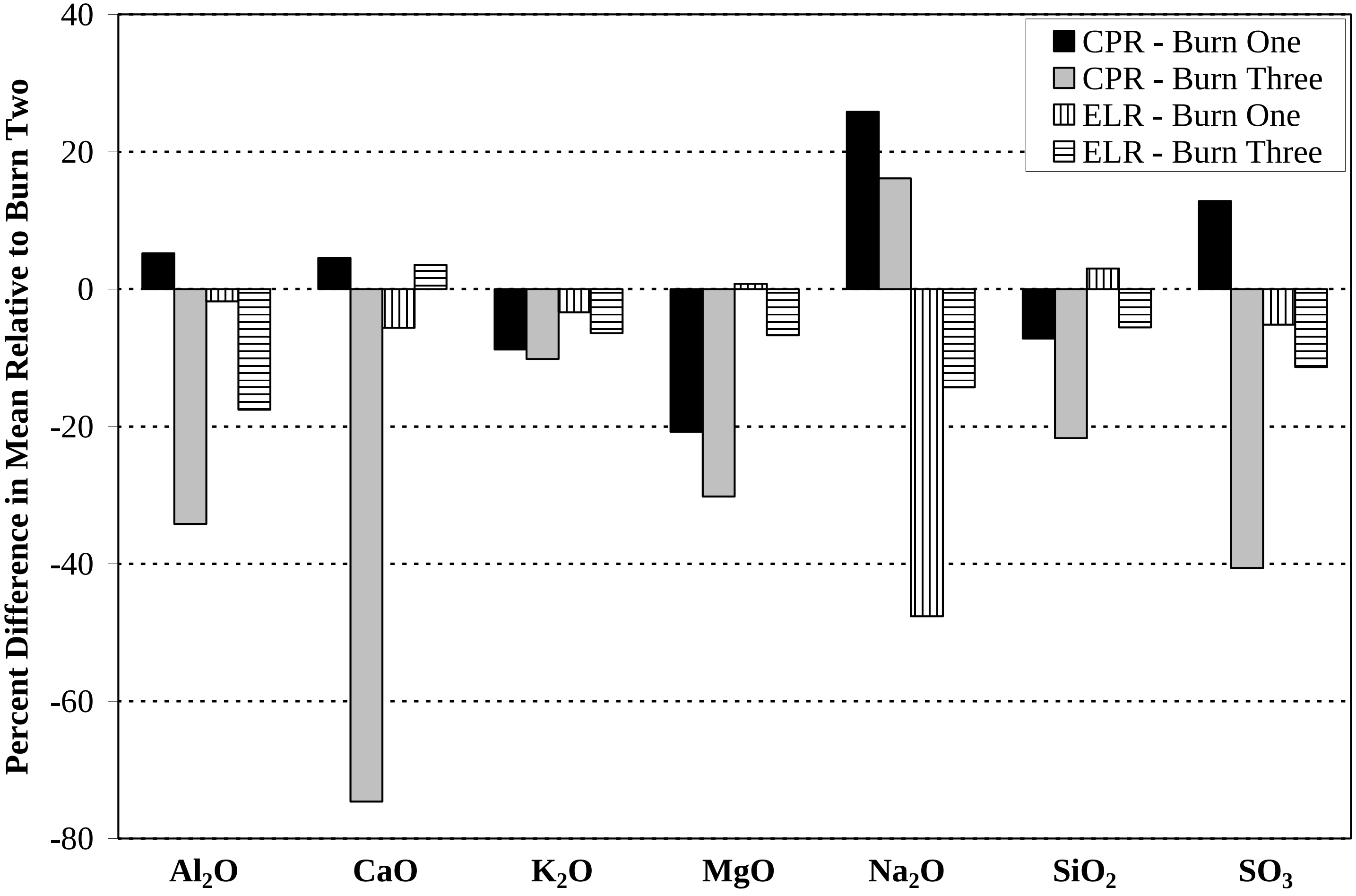


Figure 4.2: Percent Differences in Coal Relative to Burn Two

The second fuel that was used at the cement plant was whole tires. These tires are not tested for their chemical composition by the cement plant. They were however, sampled by Auburn University, and tested by the external laboratory. The samples were collected by removing approximately eight tires from the feed stream, reducing a section of each to one inch squares, and making a single composite specimen from the pieces. One composite sample, 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, are shown in Table 4.15. The percent difference between the tires used in Burn Three and the tires used in Burn Two are also shown. Overall, there was a relatively large difference in many of the parameters. Oxygen and moisture showed the greatest decreases, while nitrogen, sulfur, and heat content 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.

Table 4.16 shows the standard external laboratory parameters for the tires. Every primary parameter except for Fe_2O_3 showed a decrease. Of those which decreased, all but Al_2O_3 and MgO showed decreases of more than 28 percent. Most of the less prominent parameters also showed substantial changes. Once again, these differences are most likely simply due to the variability in the actual tire feed stream.

Table 4.15: **ELR - Proximate, Ultimate, and Combustion Analysis for Tires**

Test	Parameter	Burn Two	Burn Three	
		Value (wt. %)	Value (wt. %)	% Diff.
Proximate Analysis	**Ash**	13.72	14.56	6.1
	Fixed Carbon	24.6	26.38	7.2
	Moisture [1]	0.14	0.07	-50.0
	Volatile Matter	61.68	59.06	-4.2
Ultimate Analysis	**Carbon**	72.34	75.94	5.0
	Hydrogen	7.05	6.53	-7.4
	Nitrogen	0.36	0.52	44.4
	Oxygen	4.98	0.46	-90.8
	Sulfur	1.54	2.00	29.9
Heat Value [2]		14467	14687	1.5

Notes:

[1] As Received

[2] Values Reported as BTU/lb

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. Figure 4.3 shows the percentage of the total fuel consumed that is tires. This percentage was calculated using the average heat value of the fuels (reported from each burn period) 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. The data reported in Figure 4.3 is a 30-minute rolling average, reported over each of the 72-hour burn periods in which tires were used. Where data were not reported by the cement plant, gaps in the plots are shown. The average tire replacement rate during Burn Two was 6.5 percent. The average replacement rate during Burn Three was 4.8 percent. The lower rate for Burn Period Three was due to the fact that a portion of the coal was also replaced by the plastics.

Table 4.16: ELR - Standard Parameters for Tires

Test	Parameter	Burn Two	Burn Three	
		Value (wt. %)	Value (wt. %)	% Diff.
Standard Parameters	Al_2O_3	1.18	1.15	-2.5
	CaO	2.36	1.68	-28.8
	Fe_2O_3	68.64	84.72	23.4
	K_2O	0.33	0.17	-48.5
	MgO	0.35	0.33	-5.7
	Na_2O	0.31	0.19	-38.7
	P_2O_5	0.21	0.12	-42.9
	SiO_2	16.87	4.91	-70.9
	SO_3	2.64	0.51	-80.7
	TiO_2	0.20	0.01	-95.0
		Value (ppm)	Value (ppm)	% Diff.
	As (ppm)	NR	NR	NA
	Ba (ppm)	300	300	0.0
	Cd (ppm) [1]	6	3	-50.0
	Cl (ppm) [1]	405	NR	NA
	Co (ppm)	616	536	-13.0
	Cr (ppm)	118	178	50.8
	Cu (ppm)	1398	900	-35.6
	Hg (ppm) [1]	0.4	0	NA
	Mn (ppm)	4100	5200	26.8
	Mo (ppm)	28	23	-17.9
	Ni (ppm)	367	239	-34.9
	Pb (ppm)	11	13	18.2
	Sb (ppm)	NR	NR	NA
	Se (ppm) [1]	< 1	< 1	NA
	Sr (ppm)	200	100	-50.0
	V (ppm)	37	50	35.1
	Zn (ppm)	54000	48400	-10.4

Notes:

NR - Not Reported

ND - Not Detected

NA - Not Applicable

[1] Dry Basis

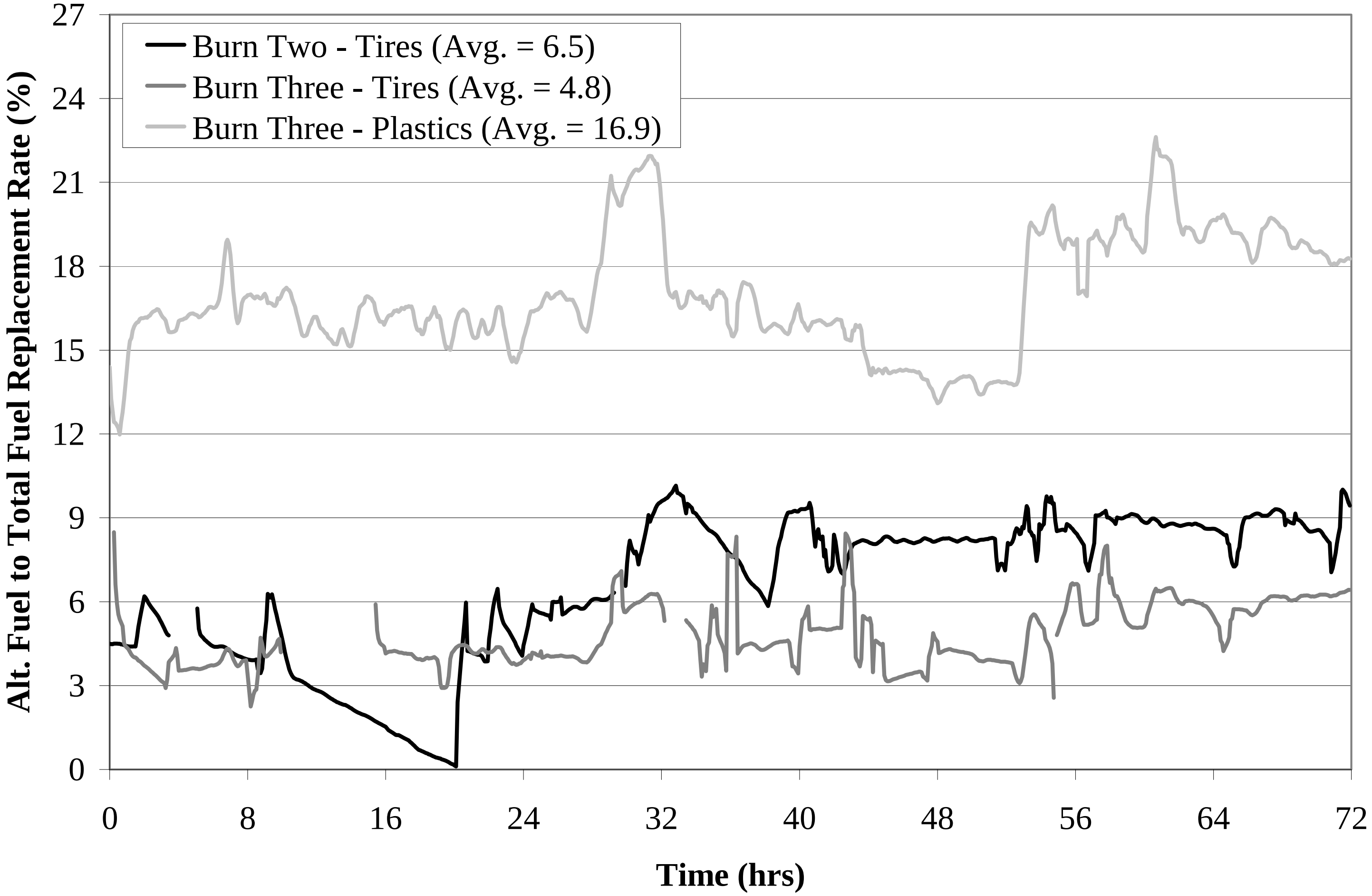


Figure 4.3: Alternative Fuel to Total Fuel Substitution Rate by Heat Equivalency Basis

The plastics used in Burn Three were 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 4.17. Table 4.18 shows the summary statistics which apply to the standard external laboratory parameters for the plastics. Perhaps the most interesting result was the extremely high concentration of CaO in the plastics, which composed 92 percent of the total weight.

Table 4.17: ELR – Proximate, Ultimate, and Combustions Analysis of Plastics for Burn Three

Test	Parameter	Average	C.V. (%)	P-Value [2]
Proximate Analysis	**Ash (wt. %)**	8.75	40.8 [1]	0.013
	Fixed Carbon (wt. %)	2.95	43.9 [1]	0.026
	Moisture (wt. %)	0.32	40.5 [1]	0.026
	Volatile Matter (wt. %)	88.30	2.7 [1]	<0.005
Ultimate Analysis	**Carbon (wt. %)**	64.23	13.1 [1]	<0.005
	Hydrogen (wt. %)	8.06	18.4 [1]	<0.005
	Nitrogen (wt. %)	1.27	31.6	0.888
	Oxygen (wt. %)	17.46	49.3 [1]	<0.005
	Sulfur (wt. %)	0.22	185.6 [1]	<0.005
Heat Value [4]		12754	7.9	0.313

Notes:

[1] Not Normally Distributed

[2] Based on Anderson-Darling Statistics

[3] As Received

[4] Value is as BTU/lb

Table 4.18: ELR - Standard Parameters of Plastics for Burn Three

Test	Parameter	Average (wt. %)	C.V. (%)	P-Value [2]
Standard Parameters	**Al_2O_3**	0.48	59.8 [1]	<0.005
	CaO	92.00	2.0 [1]	0.034
	Fe_2O_3	0.54	25.8 [1]	0.041
	K_2O	0.13	40.4 [1]	<0.005
	MgO	1.75	4.2	0.727
	Na_2O	0.17	91.9 [1]	<0.005
	P_2O_5	0.14	41.3	0.429
	SiO_2	2.12	34.6 [1]	<0.005
	SO_3	0.41	30.5	0.116
	TiO_2	1.77	46.8	0.177
	Parameter	**Average (ppm)**	**C.V. (%)**	**P-Value [2]**
	As	62	62.7 [1]	0.067
	Ba	4100	47.1	0.518
	Cd	7 [3]	9.3 [1]	<0.005
	Cl	54 [3]	25.8 [1]	<0.005
	Co	142	27.8	0.113
	Cr	356	33.0	0.504
	Cu	369	28.4	0.279
	Hg	<0.001 [3]	NA	NA
	Mn	300	20.9 [1]	<0.005
	Mo	6	172.3	0.144
	Ni	50	165.2 [1]	<0.005
	Pb	628	59.6 [1]	0.009
	Sb	NR	NA	NA
	Se	< 1 [3]	NA	NA
	Sr	600	8.8 [1]	<0.005
	V	66	83.8 [1]	<0.005
	Zn	283	50.0	0.275

Notes:

NR - Not Reported
NA - Not Applicable

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

Figure 4.3 shows the replacement rate of the plastics relative to the total amount of fuels consumed. 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 12,812 BTU/lb for the plastics, and 11,897 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 84.3 kg/m^3.

Table 4.19 shows the chemical composition of all of the fuels. 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 4.19 shows the heat value for each of the fuels. The tires used during Burn Three had the highest heat value, followed by the tires from Burn Two. The plastics had a higher heat value than any of the coal samples.

Many differences between the fuels are shown in Table 4.19. The tires and the plastics contained very little Al_2O_3, but each of the coal samples was approximately 25 percent Al_2O_3. The plastics were over 90 percent CaO, whereas the coal and tires contained less than 10 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 4.19: ELR – Chemical Composition of all Fuels

Test	**Parameter**	**Burn One**	**Burn Two**		**Burn Three**		
		Coal	**Coal**	**Tires**	**Coal**	**Tires**	**Plastics**
Standard Parameters	**Al_2O_3 (wt. %)**	25.08	25.54	1.18	21.04	1.15	0.48
	CaO (wt. %)	7.53	7.97	2.36	8.25	1.68	92.00
	Fe_2O_3 (wt. %)	7.61	7.35	68.64	15.16	84.72	0.54
	K_2O (wt. %)	2.58	2.67	0.33	2.49	0.17	0.13
	MgO (wt. %)	1.35	1.34	0.35	1.25	0.33	1.75
	Na_2O (wt. %)	0.22	0.43	0.31	0.36	0.19	0.17
	P_2O_5 (wt. %)	0.18	0.20	0.21	0.23	0.12	0.14
	SiO_2 (wt. %)	47.39	46.01	16.87	43.44	4.91	2.12
	SO_3 (wt. %)	6.95	7.33	2.64	6.5	0.51	0.41
	TiO_2 (wt. %)	1.12	1.15	0.20	0.96	0.01	1.77
	As (ppm)	325	80	NR	316	NR	62
	Ba (ppm)	1274	1083	300	1300	300	4100
	Cd (ppm) [1]	ND	ND	6	5	3	7
	Cl (ppm) [1]	125	182	405	134	NR	54
	Co (ppm)	ND	30	616	44	536	142
	Cr (ppm)	109	127	118	117	178	356
	Cu (ppm)	150	116	1398	103	900	369
	Hg (ppm) [1]	0	ND	0	0	0	0
	Mn (ppm)	221	355	4100	1500	5200	300
	Mo (ppm)	ND	9	28	39	23	6
	Ni (ppm)	81	100	367	92	239	50
	Pb (ppm)	42	48	11	45	13	628
	Sb (ppm)	ND	ND	NR	NR	NR	NR
	Se (ppm) [1]	ND	8	< 1	1	< 1	< 1
	Sr (ppm)	487	591	200	500	100	600
	V (ppm)	226	225	37	214	50	66
	Zn (ppm)	68	133	0	197	0	283
Heat Value (BTU/lb)		11698	12624	14467	11369	16754	12754

Notes:

ND - Not Detected
NR - Not Reported
[1] Dry Basis

4.3.4 Chemical Composition of Cement Kiln Dust

The cement plant collected two cement kiln dust samples every day during each of the burn periods. Each of these samples was tested once for the standard cement plant parameters, except for moisture and loss on ignition. Table 4.20 shows the results of these tests, along with the percent differences of Burns One and Three relative to Burn Two.

Table 4.20: CPR – Chemical Analysis and Percent Difference for CKD

Test	Parameter	Burn One		Burn Two	Burn Three	
		Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Standard Parameters	Al_2O_3	3.69	-7.5	3.99	3.65	-8.5
	CaO	47.54	6.4	44.69	47.63	6.6
	Fe_2O_3	1.81	-10.0	2.01	1.73	-13.9
	K_2O	0.48	14.3	0.42	0.38	-9.5
	MgO	1.65	0.0	1.65	1.80	9.1
	Na_2O	0.07	-12.5	0.08	0.05	-37.5
	SiO_2	11.68	-3.0	12.04	11.56	-4.0
	SO_3	1.13	18.9	0.95	0.84	-11.6

The six cement kiln dust samples that were collected at the cement plant were also tested by the external laboratory. Once again, there were not enough data points to present a complete set of summary statistics. The averages and percent differences from the external laboratory are presented in Table 4.21. From this table one can see that many of the parameters showed a change of more than ten percent for Burns One and Three relative to Burn Two.

Table 4.21: ELR - Chemical Composition of Cement Kiln Dust

Parameter	Burn One		Burn Two	Burn Three	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Al_2O_3	3.76	1.3	3.71	5.11	37.7
CaO	56.32	20.4	46.77	72.01	54.0
Fe_2O_3	2.00	-4.3	2.09	2.57	23.0
K_2O	0.42	-25.0	0.56	0.46	-17.9
MgO	1.89	23.5	1.53	2.54	66.0
Na_2O	0.01	0.0	0.01	0.08	700.0
P_2O_5	0.05	25.0	0.04	0.06	50.0
SiO_2	11.32	2.3	11.07	15.70	41.8
SO_3	1.43	14.4	1.25	1.01	-19.2
TiO_2	0.21	0.0	0.21	0.25	19.0
Moisture	0.06	-72.7	0.22	0.13	-40.9
LOI	22.54	-30.7	32.54	33.25	2.2
	Value (ppm)	**% Diff.**	**Value (ppm)**	**Value (ppm)**	**% Diff.**
As	3	-83.3	18	29	61.1
Ba	278	-10.0	309	333	7.8
Cd	ND	NA	ND	NR	NA
Cl	482	716.9	59	131	122.0
Co	14	-12.5	16	13	-18.8
Cr	32	-27.3	44	54	22.7
Cu	49	226.7	15	47	213.3
Hg	0.02	NA	< 0.01	NR	NA
Mn	315	87.5	168	883	425.6
Mo	ND	NA	ND	16	NA
Ni	11	-21.4	14	14	0.0
Pb	20	11.1	18	22	22.2
Sb	55	-5.2	58	NR	NA
Se	1	-50.0	2	NR	NA
Sr	320	9.2	293	533	81.9
V	54	10.2	49	64	30.6
Zn	91	-9.0	100	38	-62.0

Notes:

ND - Not Detected
NA - Not Applicable

Some of the less prominent parameters are also a concern in the cement kiln dust. From Table 4.21 one can see that the Arsenic (As), which is a toxic element, was higher for both of the burns that used tires. It showed the greatest concentration in the burn that utilized both tires and plastics. It is also interesting to note that the chlorine (Cl) was over 700 percent higher in Burn One than in Burn Two, and about 600 percent higher than Burn Three. Cu and Mn also showed a large change in both Burns One and Three.

Figure 4.4 shows a graphical representation of the percent differences in values from both the cement plant and the external laboratory, for the primary parameters. The result for Na_2O is not shown, because of the difference between Burns Three and Two from the external laboratory relative to the rest of the percent differences. The primary point to notice is that the result from the external laboratory concerning Burn Three showed relatively large changes in all of the parameters. CaO and MgO showed an increase for all burns from both laboratories. The rest of the parameters do not consistently show the same relative change in the data obtained from both testing laboratories.

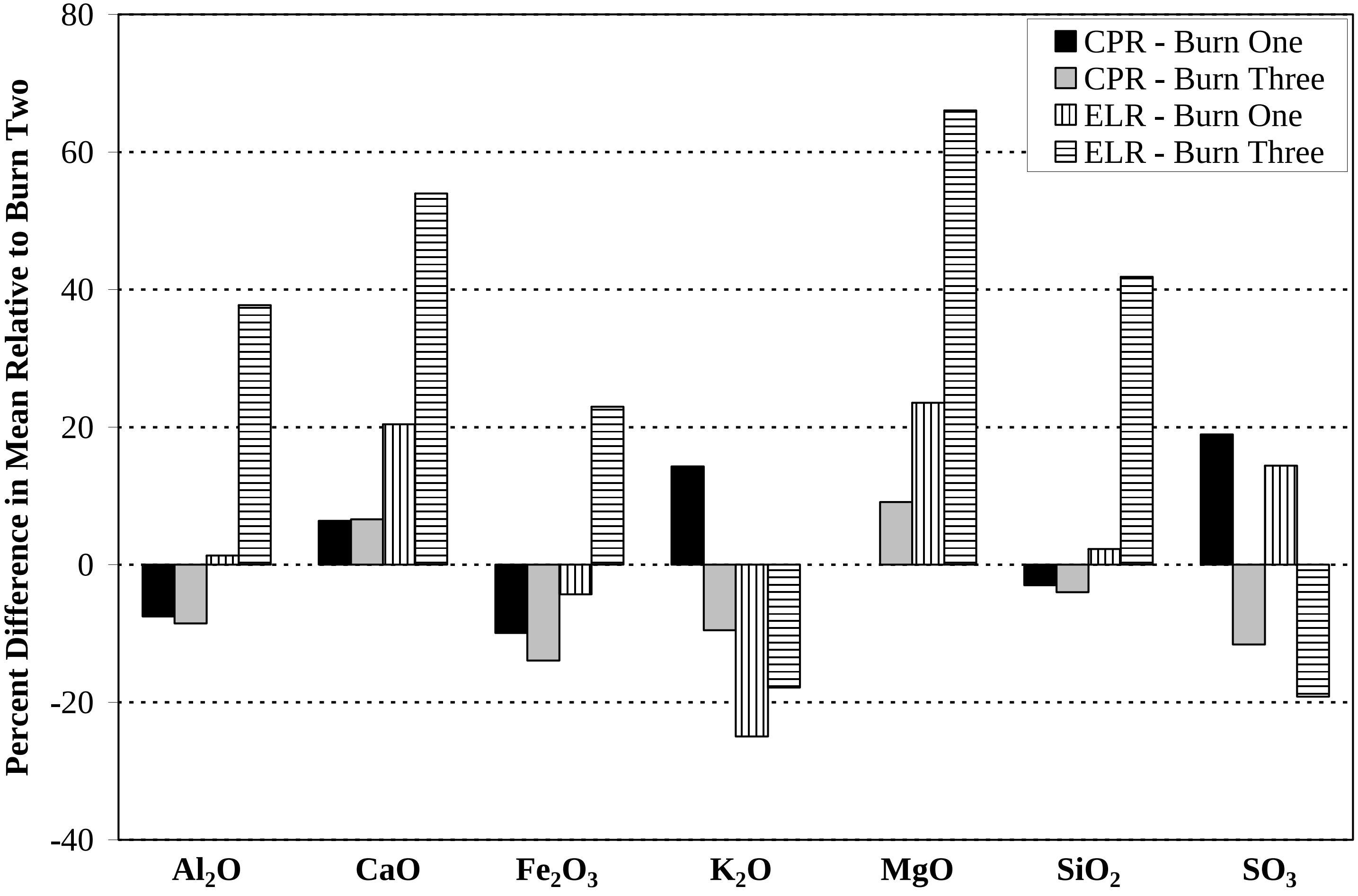


Figure 4.4: Percent Change in Means of CKD Relative to Burn Two

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. There were twelve samples collected per day by the cement plant. Each of these samples was tested for chemical composition. The results shown in Table 4.22 are the summary statistics from at least 36 discrete samples collected for each burn at the cement plant.

Table 4.22: CPR - Summary Statistics of Chemical Composition of Clinker

Parameter	Burn One			Burn Two			Burn Three		
	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	5.07	2.0	0.840	5.14	2.0 [1]	<0.005
CaO	64.96	0.4	0.116	64.48	0.2	0.908	64.55	0.6 [1]	0.039
Fe_2O_3	3.41	6.6 [1]	0.012	3.35	4.7	0.289	3.56	6.1 [1]	<0.005
K_2O	0.56	4.1 [1]	0.022	0.48	3.8	0.118	0.46	4.6 [1]	0.077
MgO	2.93	2.3	0.453	3.48	5.4 [1]	<0.005	3.25	3.3	0.589
Na_2O	0.07	6.8 [1]	<0.005	0.10	9.6 [1]	<0.005	0.07	5.8 [1]	<0.005
Na_2O_{eq}	0.44	3.7 [1]	0.022	0.41	3.7 [1]	0.069	0.37	4.4 [1]	0.053
SiO_2	21.38	0.9	0.391	21.23	0.9	0.869	21.31	1.2 [1]	<0.005
SO_3	0.84	12.1	0.323	0.66	12.1	0.117	0.91	21.1 [1]	<0.005
Free CaO	1.10	37.1	0.605	1.06	38.8 [1]	<0.005	1.24	41.0	0.374
C_3A	8.28	6.8 [1]	0.043	7.78	4.9	0.416	7.61	5.4 [1]	0.021
C_4AF	10.37	6.7 [1]	0.009	10.21	4.7	0.206	10.86	6.2 [1]	<0.005
C_3S	61.49	4.4	0.362	62.24	2.8	0.544	61.15	3.9 [1]	0.033
C_2S	14.90	16.6	0.742	13.91	13.2	0.602	14.96	16.4 [1]	0.007

Notes:

[1] Data Not Normally Distributed

Table 4.23 shows the percent difference of the means for Burns One and Three relative to the mean of Burn Two. 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. In most cases, there was a statistically significant difference between means. This does not mean they are practically significant, however. The parameters that did not show a statistically significant difference were Free CaO, C_4AF, and C_3S for Burn One, along with CaO and SiO_2 for Burn Three. One point worth noting is that the P-value for most of the Bogue compounds are above 0.03. This indicates that all of these compounds showed at least some statistical similarity. Selected differences presented in Table 4.23 are shown graphically in Figure 4.5.

Table 4.23: CPR – Percent Differences and Statistical Significance for Clinker

Parameter	Burn One			Burn Three		
	Percent Difference	P-Value	Significant	Percent Difference	P-Value	Significant
Al_2O_3	4.54	0.000	Yes	1.38	0.005	Yes
CaO	0.74	0.000	Yes	0.11	0.310	No
Fe_2O_3	1.79	0.241	No	6.27	0.000	Yes
K_2O	16.67	0.000	Yes	-4.17	0.000	Yes
MgO	-15.80	0.000	Yes	-6.61	0.000	Yes
Na_2O	-30.00	0.000	Yes	-30.00	0.000	Yes
Na_2O_{eq}	7.32	0.000	Yes	-9.76	0.000	Yes
SiO_2	0.71	0.001	Yes	0.38	0.135	No
SO_3	27.27	0.000	Yes	37.88	0.000	Yes
Free CaO	3.77	0.647	No	16.98	0.000	Yes
C_3A	6.43	0.000	Yes	-2.19	0.086	Yes
C_4AF	1.57	0.253	No	6.37	0.000	Yes
C_3S	-1.21	0.166	No	-1.75	0.031	Yes
C_2S	7.12	0.055	Yes	7.55	0.042	Yes

Based on the cement plant results, a few parameters showed large changes. There was a 27 percent and a 37 percent increase in SO_3 for Burns One and Three, respectively. Burn One showed a 26 percent decrease in Na_2O, and Burn Three showed a 30 percent decrease in the same parameter. Other parameters from Burn One that showed changes greater than ten percent were K_2O and MgO, which showed an increase of 16 percent and a decrease of 15.8 percent, respectively. Many of these notable changes in chemical composition are discussed with reference to the chemical changes present in the cement.

From the discrete clinker samples collected at the cement plant, a single composite sample was prepared for each day during each burn period. Each of these composite samples was tested in duplicate for chemical composition by the external laboratory. Table 4.24 shows these results, along with the percent differences between burn periods. Of the less prominent parameters, both Cu and Ni showed an increase of more than 100 percent for Burn One. Mn exhibited the largest change during Burn Three, where it showed and increase of more than 200 percent.

From Figure 4.5 it can be seen that the SO_3 showed an increase of at least 37 percent in each burn. Another large change was the Na_2O. It showed a decrease of 70 percent for Burn One and an increase of over 100 percent for Burn Three. However, because the overall concentration of Na_2O is so small, a small change in concentration results in a large percent change. K_2O and MgO also showed a change of over ten percent for Burn Period One.

The most significant result shown in Figure 4.5 is the percent change in Al_2O_3, CaO, Fe_2O_3, and SiO_2. Each showed very little change between either of the burns from both the cement plant and the external laboratory. 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.

After comparing the results from Table 4.19 and Table 4.24, it is very difficult to conclude that the chemical composition of the fuels directly impacts the chemical composition of the clinker. In fact, it appears as though the effect that the fuels directly have on the composition of the clinker is minimal with respect to the many other aspects of the production process that are designed to produce clinker with a consistent chemical composition. Perhaps the most important thing to conclude is that the four primary parameters of the clinker, Al_2O_3, CaO, Fe_2O_3, and SiO_2, each showed no practically significant change, regardless of the fuel that was used.

Table 4.24: ELR - Chemical Composition of Clinker

Parameter	Burn One		Burn Two	Burn Three	
	Value	% Diff.	Value	Value	% Diff.
Al_2O_3	5.26	4.57	5.03	4.96	-1.4
CaO	65.15	1.37	64.27	64.71	0.7
Fe_2O_3	3.34	2.45	3.26	3.32	1.8
K_2O	0.59	15.69	0.51	0.42	-17.6
MgO	2.88	-18.41	3.53	3.40	-3.7
Na_2O	0.01	-75.00	0.04	0.10	150.0
P_2O_5	0.08	33.33	0.06	0.07	16.7
SiO_2	21.23	-2.93	21.87	21.50	-1.7
SO_3	0.96	37.14	0.70	0.98	40.0
TiO_2	0.30	15.38	0.26	0.26	0.0
Moisture	0.01	-50.00	0.02	0.00	NA
LOI	0.15	-60.53	0.38	0.13	-65.8
	Value (ppm)	**% Diff.**	**Value (ppm)**	**Value (ppm)**	**% Diff.**
As	8	-61.90	21	36	71.4
Ba	365	79.80	203	367	80.8
Cd	ND	NA	3	NR	NA
Cl	238	-43.87	424	177	-58.3
Co	15	NA	ND	12	NA
Cr	72	-7.69	78	90	15.4
Cu	65	160.00	25	28	12.0
Hg	0.00	NA	0.00	NR	NA
Mn	958	81.78	527	1683	219.4
Mo	11	NA	ND	19	NA
Ni	43	152.94	17	15	-11.8
Pb	36	9.09	33	12	-63.6
Sb	57	16.33	49	NR	NA
Se	0	NA	2	NR	NA
Sr	402	1.52	396	500	26.3
V	64	-1.54	65	66	1.5
Zn	134	-28.34	187	68	-63.6

Notes:

ND - Not Detected
NA - Not Applicable

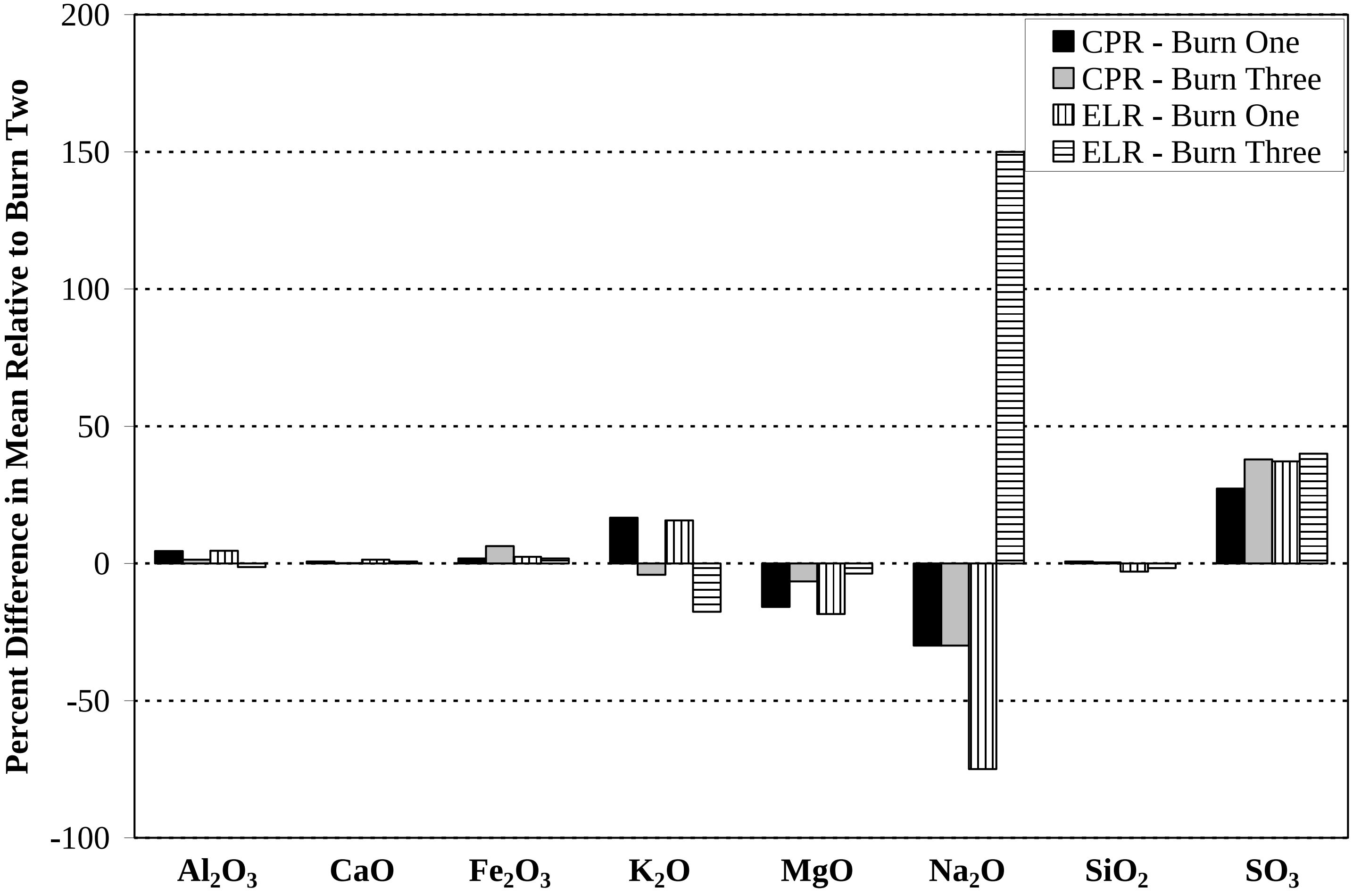


Figure 4.5: Percent Change in Chemical Composition Means for Clinker

The final result concerning the chemical composition of clinker is the Rietveld analysis. This test determines the Bogue compounds of the material, and does so more accurately than the formulae used in ASTM C 150. Table 4.25 shows these results, along with the percent difference relative to Burn Two. The results for Burn Three were not available at the time of preparation of this document.

Table 4.25: SLR - Rietveld Analysis of Clinker

Parameter	Burn One		Burn Two	Burn Three	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Alite	68.23	9.1	62.52	CIP	NA
Belite	13.17	-29.0	18.54	CIP	NA
Ferrite	10.23	-3.8	10.63	CIP	NA
Aluminate	5.17	20.8	4.28	CIP	NA

Notes:

CIP - Collection in Progress
NR - Not Reported
NA - Not Applicable

4.3.6 Chemical Composition of 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. The tests at the cement plant were conducted on eight discrete specimens each day during all three burn periods. The complete set of summary statistics, based on the results collected by the cement plant, is shown in Table 4.26.

Table 4.26: CPR - Summary Statistics for Cement Chemical Composition

Parameter	Burn One			Burn Two			Burn Three		
	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
CaO	63.49	0.5	0.843	62.56	0.7^{1}	0.008	62.79	0.8^{1}	0.009
Fe_2O_3	3.10	3.2^{1}	0.056	3.02	3.0	0.297	3.21	3.8^{1}	<0.005
K_2O	0.52	1.9^{1}	<0.005	0.44	3.4^{1}	0.023	0.44	2.5^{1}	0.021
MgO	2.87	2.9^{1}	<0.005	3.27	5.5^{1}	<0.005	3.21	1.8^{1}	0.095
Na_2O	0.09	7.8^{1}	<0.005	0.11	12.0^{1}	<0.005	0.08	8.0^{1}	<0.005
Na_2O_{eq}	0.43	1.6	<0.005	0.41	2.9^{1}	<0.005	0.37	2.1^{1}	<0.005
SiO_2	20.56	0.5	0.646	19.96	1.4	0.810	20.59	1.0^{1}	0.049
SO_3	2.61	6.2^{1}	0.075	2.63	7.5	0.751	2.68	8.8	0.126
Free CaO	0.94	23.3^{1}	<0.005	0.99	21.5	0.751	1.39	19.6	0.183
LOI	1.03	17.4	0.859	1.22	13.1	0.270	1.25	18.0	0.347
C_3A	7.94	3.3	0.118	7.23	3.3^{1}	0.030	7.43	4.7	0.413
C_4AF	9.45	3.2^{1}	0.016	9.20	3.0	0.109	9.79	3.8^{1}	<0.005
C_3S	56.75	4.7	0.738	59.76	5.6	0.623	54.26	4.0	0.330
C_2S	16.15	13.5	0.380	12.15	26.2	0.281	18.10	10.4	0.732
Blaine SSA	377^{2}	2.9^{1}	<0.005	380^{2}	3.0	0.376	369^{2}	5.9	0.927

Notes:

[1] Data Not Normally Distributed

[2] Units are m^2/kg

Table 4.27 shows the percent difference relative to Burn Two between all of the parameters tested for at the cement plant. Almost every parameter showed a statistically significant change relative to Burn Two. From Burn One, the only parameters that did not show a statistically significant change relative to Burn Two were SO_3 and Blaine specific surface area. Burn Three and Burn Two showed more similarities than Burn One and Burn Two. CaO, K_2O, MgO, SO_3, LOI, and Blaine specific surface area (SSA) all showed no statistically significant difference. One thing to consider, however, is that just because many parameters showed a statistically significant difference, does not mean that these same parameters have shown a practically significant difference. 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.

Table 4.27: CPR – Chemical Composition Percent Difference in Mean for Cement

Parameter	Burn One			Burn Three		
	Percent Difference	P-Value	Significant	Percent Difference	P-Value	Significant
Al_2O_3	6.87	0.000	Yes	4.08	0.000	Yes
CaO	1.49	0.000	Yes	0.37	0.158	No
Fe_2O_3	2.65	0.003	Yes	6.29	0.000	Yes
K_2O	18.18	0.000	Yes	0.00	0.231	No
MgO	-12.23	0.000	Yes	-1.83	0.123	No
Na_2O	-18.18	0.000	Yes	-27.27	0.000	Yes
Na_2O_{eq}	4.88	0.000	Yes	-9.76	0.000	Yes
SiO_2	3.01	0.000	Yes	3.16	0.000	Yes
SO_3	-0.76	0.787	No	1.90	0.531	No
Free CaO	-5.05	0.000	Yes	40.40	0.000	Yes
LOI	-15.57	0.000	Yes	2.46	0.698	No
C_3A	9.82	0.000	Yes	2.77	0.046	Yes
C_4AF	2.72	0.005	Yes	6.41	0.000	Yes
C_3S	-5.04	0.000	Yes	-9.20	0.000	Yes
C_2S	32.92	0.000	Yes	48.97	0.000	Yes
Blaine SSA	-0.98	0.271	No	-3.19	0.103	No

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 Burn Two, are shown in Table 4.28. Of the less prominent parameters, Ba, Cu, and Mn showed an increase of approximately 100 percent for Burn One. As and Cl showed a decrease of more than 50 percent in Burn One. Ba and Mn each showed an increase of over 100 percent in Burn Three. Cl, Cu, and Zn showed decreases of approximately 50 percent or more in Burn Three.

Figure 4.6 graphically shows the major parameters for both testing agencies. Al_2O_3, CaO, Fe_2O_3, and SiO_2, are the primary compounds in the cement, and have the greatest impact on the physical properties of cement, and on the properties of concrete. Figure 4.6 shows that there was very little change in concentration of each of these parameters. Just as with the clinker, these results suggest that, regardless of the fuel that is being burned, the cement plant is capable of maintaining consistent concentrations in Al_2O_3, CaO, Fe_2O_3, and SiO_2.

Figure 4.6 shows that K_2O, MgO, and Na_2O each showed appreciable differences in at least one burn. These parameters make up a small portion of the cement, therefore, a small change in concentration shows a large percent difference. Also, once again, just because the difference is appreciable, does not necessarily mean that it is practically significant. Additionally, each of these compounds are less important to the properties of cement and concrete than Al_2O_3, CaO, Fe_2O_3, and SiO_2.

Just as with the clinker, when the data shown in Table 4.19 is compared with the results shown for the cement, it not possible to conclude that the chemical composition of the fuels has any effect on the chemical composition of the cement. This is to be expected based on the results from the clinker, because the only chemical difference between the clinker and cement is the addition of a relatively small amount of Raw Material 6.

Table 4.28: ELR - Chemical Composition of Cement

Parameter	Burn One		Burn Two	Burn Three	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Al_2O_3	5.04	4.8	4.81	4.93	2.5
CaO	63.99	1.5	63.05	63.18	0.2
Fe_2O_3	3.20	4.6	3.06	3.11	1.6
K_2O	0.49	4.3	0.47	0.40	-14.9
MgO	2.89	-14.5	3.38	3.47	2.7
Na_2O	0.01	-85.7	0.07	0.12	71.4
P_2O_5	0.08	33.3	0.06	0.06	0.0
SiO_2	20.53	-2.5	21.05	21.51	2.2
SO_3	2.78	-4.1	2.90	2.71	-6.6
TiO_2	0.26	8.3	0.24	0.26	8.3
Moisture	0.28	-41.7	0.48	0.39	-18.8
LOI	0.69	-17.9	0.84	0.91	8.3
C_3S	58.06	12.5	51.62	48.39	-6.3
C_2S	15.06	-29.7	21.42	25.16	17.5
C_3A	7.96	5.2	7.57	7.80	3.0
C_4AF	9.74	4.4	9.33	9.46	1.4
TOC	ND	NA	ND	0.05	NA
	Value (ppm)	**% Diff.**	**Value (ppm)**	**Value (ppm)**	**% Diff.**
As (ppm)	8	-55.6	18	27	50.0
Ba (ppm)	321	134.3	137	300	119.0
Cd (ppm)	ND	NA	ND	NR	NA
Cl (ppm)	80	-85.2	541	57	-89.5
Co (ppm)	14	NA	ND	13	NA
Cr (ppm)	82	3.8	79	92	16.5
Cu (ppm)	64	106.5	31	14	-54.8
Hg (ppm)	0.00	NA	0.00	NR	NA
Mn (ppm)	958	91.2	501	1600	219.4
Mo (ppm)	8	NA	ND	2	NA
Ni (ppm)	ND	NA	ND	12	NA
Pb (ppm)	33	-10.8	37	27	-27.0
Sb (ppm)	51	-19.0	63	NR	NA
Se (ppm)	1	0.0	1	NR	NA
Sr (ppm)	409	2.0	401	500	24.7
V (ppm)	62	19.2	52	69	32.7
Zn (ppm)	126	-30.8	182	62	-65.9

Notes:

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

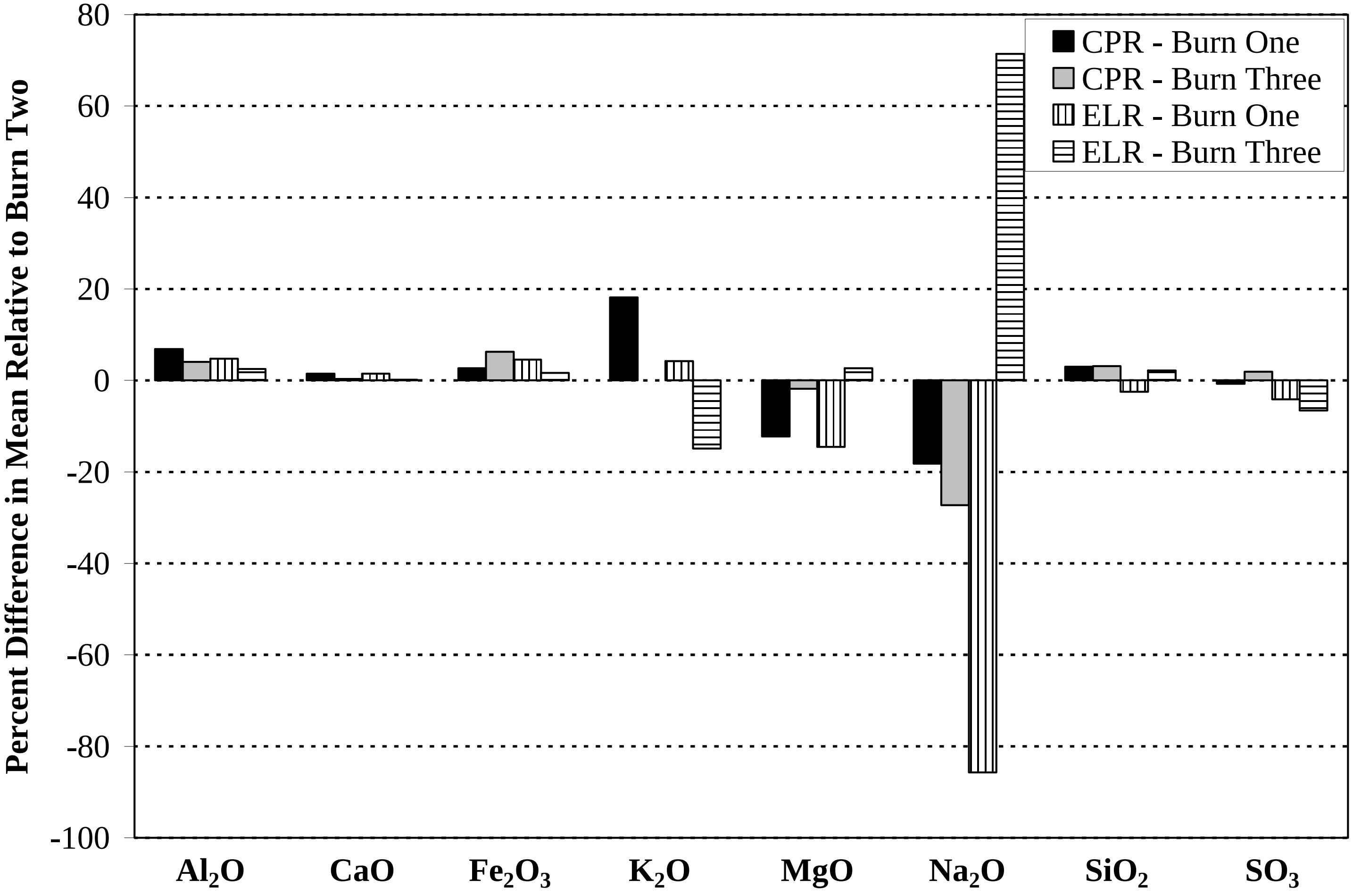


Figure 4.6: Percent Difference in Chemical Composition Means for Cement

The final chemical composition of cement that was determined was the Bogue compounds by Rietveld Analysis. This test was conducted by the cement plant specialty laboratory. The results of this test are shown in Table 4.29. Along with the results, the percent differences relative to Burn Two are also shown. The results for Burn Three had not been received by the time of the completion of this document.

Table 4.29: SLR - Rietveld Analysis on Cement

Parameter	Burn One		Burn Two	Burn Three	
	Value (wt. %)	% Diff.	Value (wt. %)	Value (wt. %)	% Diff.
Alite	65.11	12.4	57.94	CIP	NA
Belite	17.12	-6.6	18.33	CIP	NA
Ferrite	6.36	-37.9	10.24	CIP	NA
Aluminate	5.67	35.2	4.20	CIP	NA

Notes:

CIP - Collection in Progress
NR - Not Reported
NA - Not Applicable

4.3.7 Physical Properties of Cement

The physical properties of the cement were determined by personnel at the cement plant and at Auburn University. Both testing entities conducted the same tests; the one exception was that Auburn determined the drying shrinkage development of paste prisms. The results of the physical properties conducted by the cement plant are shown in Table 4.30.

Table 4.31 shows the results from the physical property tests conducted by Auburn University.

A graphical representation of selected results can be seen in Figure 4.7. Just as with the chemical composition plots of this nature, the percent differences for each of the testing agencies are relative to Burn Two data as determined by that testing agency. Some of the percent differences are not shown in Figure 4.7. Notably, the compressive strength and drying shrinkage results were plotted on their own, and are discussed later in this section.

Figure 4.7 shows that a major change was seen in the autoclave expansion. Burn Three showed an 83 percent increase, and Burn One showed a 40 percent decrease relative to Burn Two as reported by the cement plant. Auburn University reported an increase of 67 and 33 percent for Burn One and Three respectively, for the same property.

Another interesting result to note from Figure 4.7 is that Burn Three showed an acceleration in setting times, both initial and final, in the Gillmore and Vicat setting test, at both testing agencies. This result may suggest that the cement produced during Burn Three has a tendency to set more quickly than the cement produced during Burns One and Two. The setting time results for Burn One relative to Burn Two do not show results that allow for any conclusive results to be made. However, six of the eight results did show a dramatic retardation in setting times.

The final property that showed large changes for Burns One and Three, relative to Burn Two, is the air content in mortar, as shown in Table 4.30. This test was only conducted by the cement plant. Both burns showed an increase in air content relative to Burn Two. 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 cement, and is not practically significant to this study.

Table 4.30: CPR - Physical Properties and Percent Change for Cement

Property	Burn One		Burn	Burn Three	
	Value	% Diff.	Value	Value	% Diff.
Air in Mortar (%)	6.7	15.5	5.8	6.6	13.8
Blaine Specific Surface Area (m^2/kg)	366	-3.9	381	374	-1.8
Autoclave Expansion (% Exp.)	0.06	-40.0	0.10	0.18	80.0
Cube Flow (%)	125.7	2.2	123.0	122.5	-0.4
Compressive Strength (MPa)					
1 day	15.3	-0.6	15.4	13.6	-11.7
3 days	24.3	-2.8	25.0	22.2	-11.2
7 days	31.9	-2.1	32.6	30.7	-5.8
28 days	42.7	-3.0	44.0	42.8	-2.7
Normal Consistency (%)	25.6	-0.4	25.7	25.9	0.8
Gillmore Initial Set (Min.)	105	-8.7	115	98	-15.2
Gillmore Final Set (Min.)	275	3.0	267	263	-1.5
Vicat Initial Set (Min.)	80	9.6	73	62	-15.1
Vicat Final Set (Min.)	180	-23.4	235	225	-4.3

Table 4.31: AUR - Physical Properties and Percent Change for Cement

Property	**Burn One**		**Burn**	**Burn Three**	
	Value	**% Diff.**	**Value**	**Value**	**% Diff.**
Autoclave Expansion (% Exp.)	0.05	66.7	0.03	0.04	33.3
Cube Flow (%)	91	-7.1	98	111	13.3
Compressive Strength (MPa)					
1 day	9.30	-15.5	11.0	11.5	4.5
3 days	17.2	-25.5	23.1	17.1	-26.0
7 days	25.8	-13.4	29.8	24.8	-16.8
28 days	35.1	-11.1	39.5	38.8	-1.8
Normal Consistency (%)	25.4	-3.1	26.2	26.2	0.0
Gillmore Initial Set (Min.)	150	108.3	72	72	0.0
Gillmore Final Set (Min.)	238	64.1	145	105	-27.6
Vicat Initial Set (Min.)	106	53.6	69	66	-4.3
Vicat Final Set (Min.)	236	72.3	137	115	-16.1
Drying Shrinkage (%)					
7 days	-0.042	-17.6	-0.051	-0.045	-11.8
14 days	-0.068	-5.6	-0.072	-0.069	-4.2
21 days	-0.079	-4.8	-0.083	-0.081	-2.4
28 days	-0.087	-7.4	-0.094	-0.089	-5.3

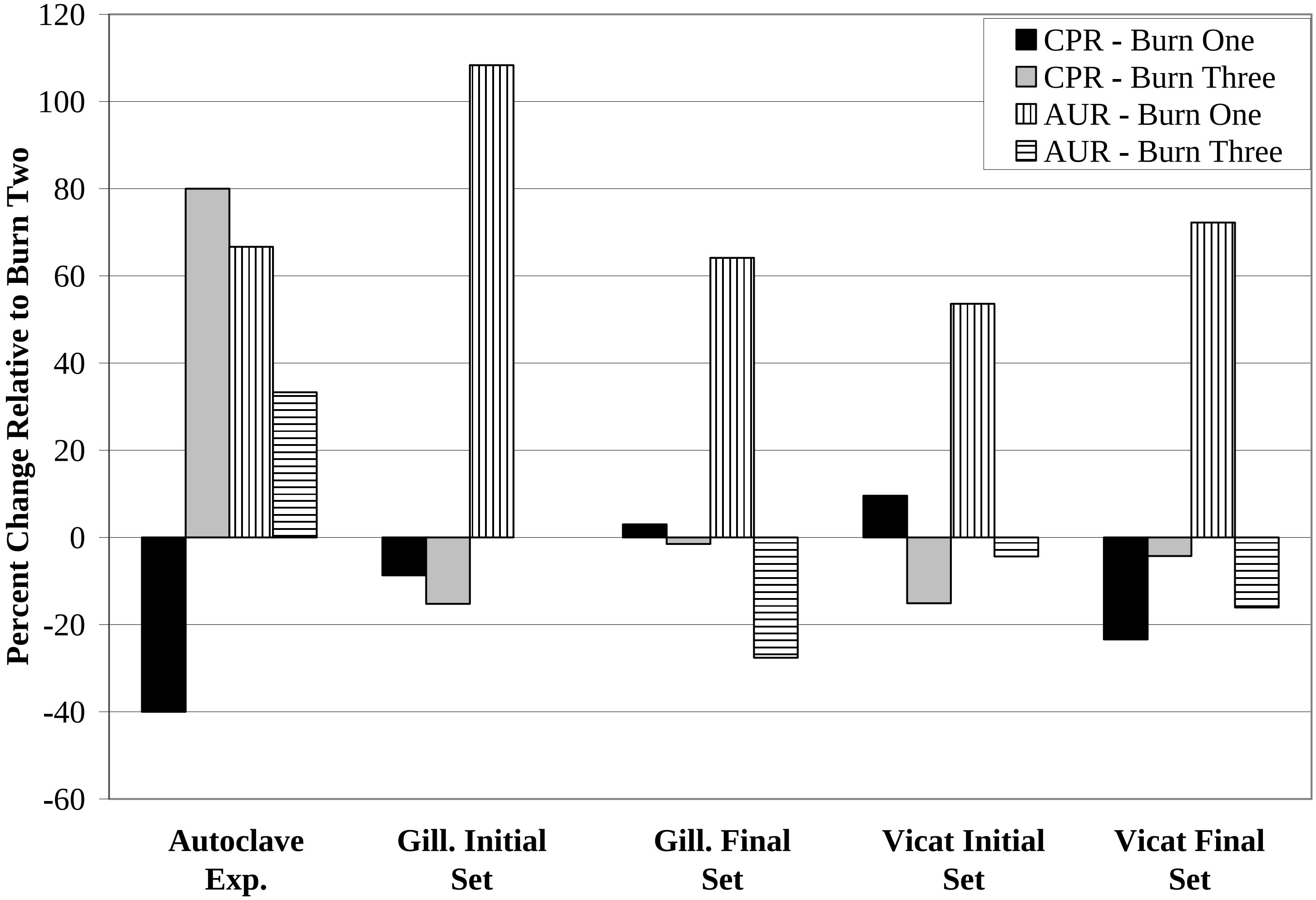


Figure 4.7: Percent Difference in Physical Properties of Cement

The results from both the cement plant and Auburn University for mortar cube compressive strengths are presented graphically in Figure 4.8. The most notable aspect of these results is that the numbers presented by the cement plant are all higher than those presented by Auburn. 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. Based on those criteria, none of the results presented by the cement plant are significantly different between burns. However, the results presented by Auburn University show that the compressive strength of the three- and seven-day cubes for Burn Two are significantly stronger than those of either of the other burns. These results will be compared with the compressive strength results associated with concrete in Section 4.3.8.

The final test of the physical properties of cement, which was conducted only at Auburn University, was drying shrinkage of paste prisms. The results of this test are shown graphically in Figure 4.9. The ages associated with these results are cement ages. The specimens were cured for three days prior to exposure to drying conditions. These results are presented with a shrinkage value reported as a positive percentage of the original length. From Figure 4.9 one can see that the trend of the results is reasonably definitive, although not too different. At all ages, Burn One showed the least shrinkage, and Burn Two showed the most shrinkage, while Burn Three was consistently in the middle. These results will be compared with the drying shrinkage results exhibited by concrete in Section 4.3.8.

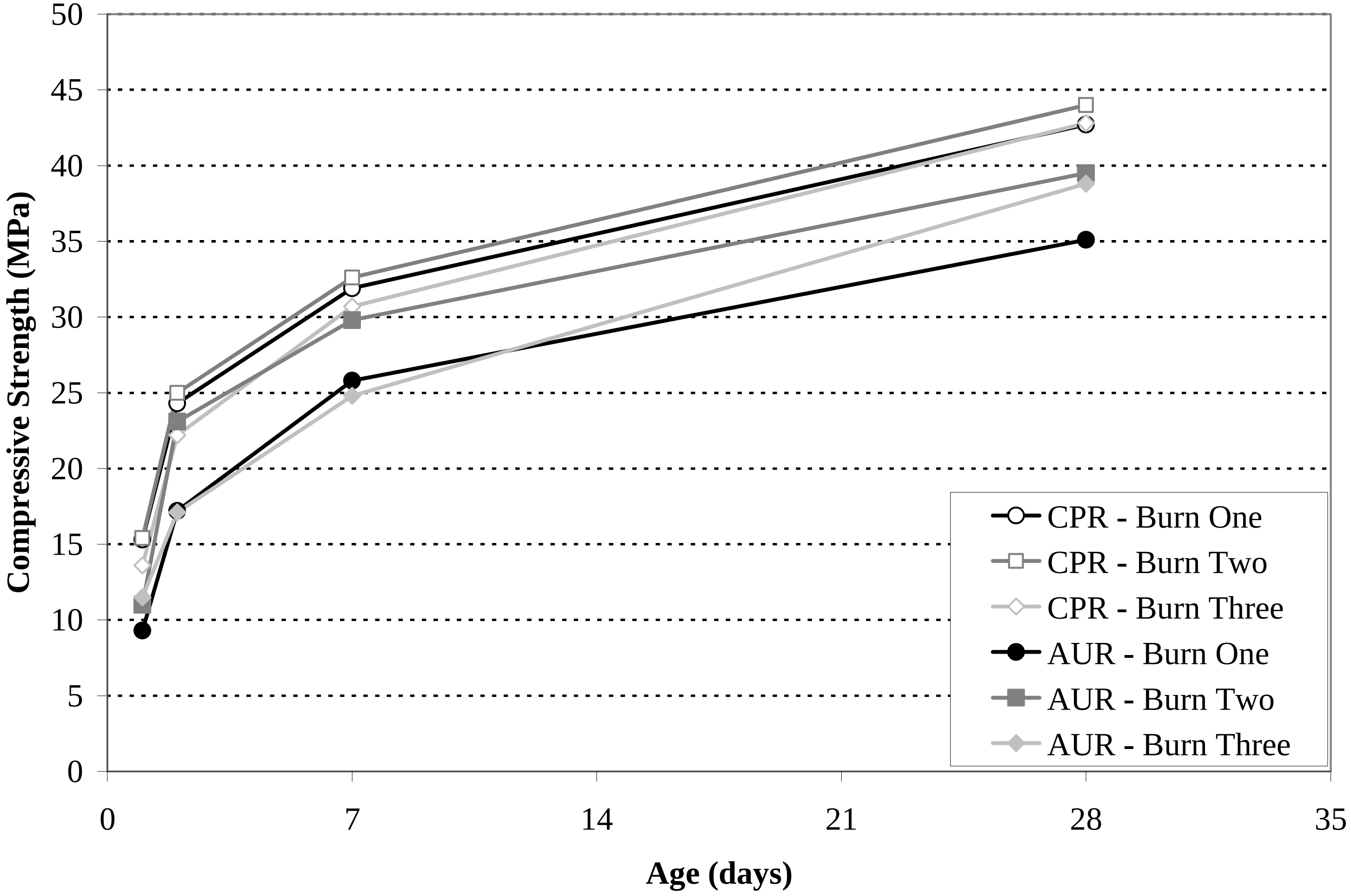


Figure 4.8: Compressive Strength Development of Mortar Cubes from Both Testing Agencies

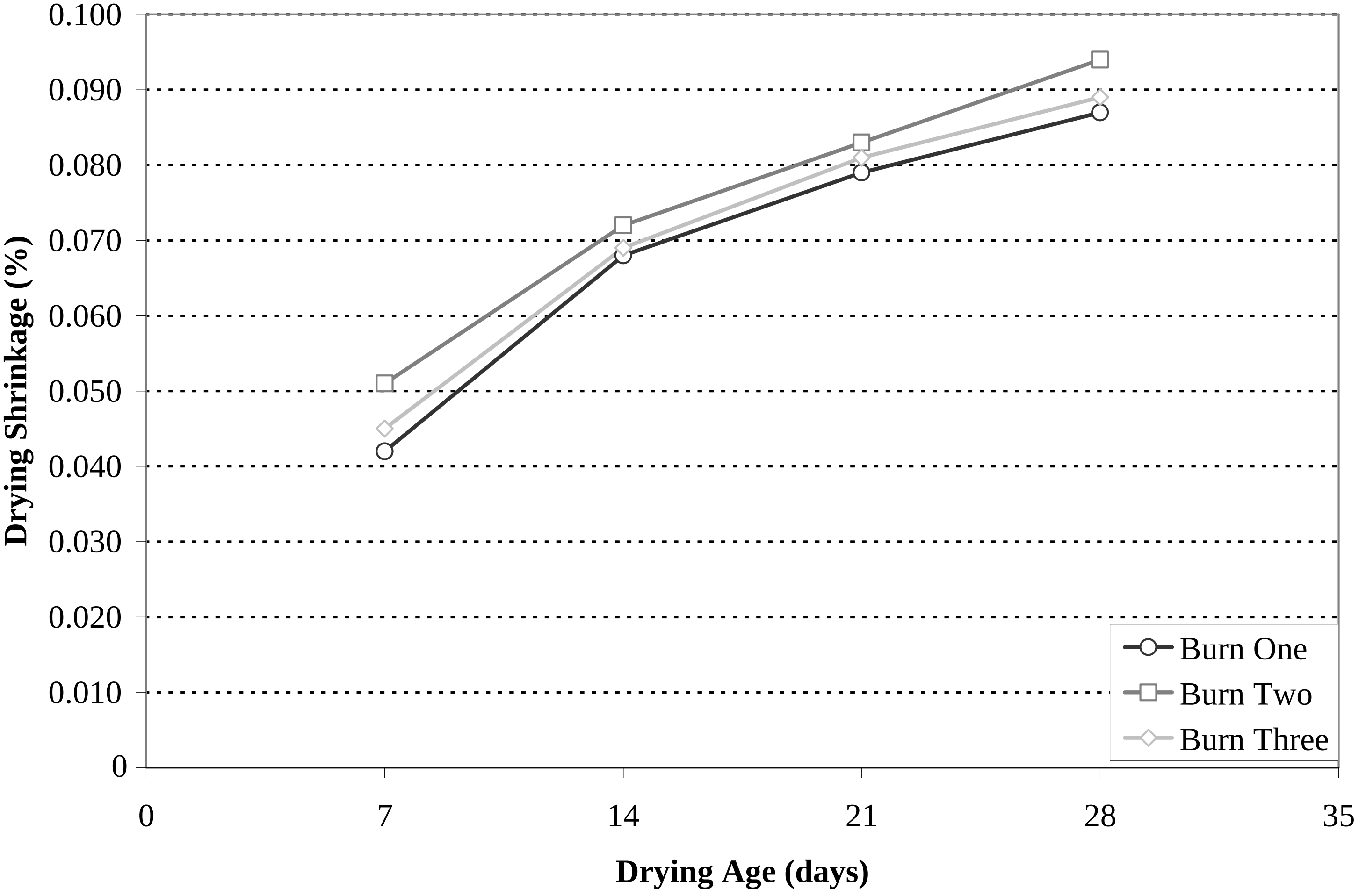


Figure 4.9: AUR - Drying Shrinkage Development of Mortar Prisms

Another physical property of the cement is the heat of hydration. This is the amount of heat generated by the cement as the hydration process progresses. This test was conducted by the specialty laboratory, and the results can be seen in Table 4.32. This table also shows the difference between Burns One and Two. The results for Burn Three had not been received by Auburn personnel at the time of the completion of this document. The heat of hydration data are very similar between Burns One and Two.

Table 4.32: SLR - Heat of Hydration of Cement

Age	**Burn One**		**Burn Two**	**Burn Three**	
	Value (kJ/kg)	**% Diff.**	**Value (kJ/kg)**	**Value (kJ/kg)**	**% Diff.**
7 days	359	-2.2	367	CIP	NA
28 days	395	-0.4	397	CIP	NA

Notes:

CIP - Collection in Progress
NA - Not Applicable

The final physical property of cement that was determined 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, this result may help to explain some of the differences in some of the physical properties of the cement and concrete. The results of this test are shown in Figure 4.10. From this result, one can see that the particle distribution of Burn One was somewhat finer that of Burn Two.

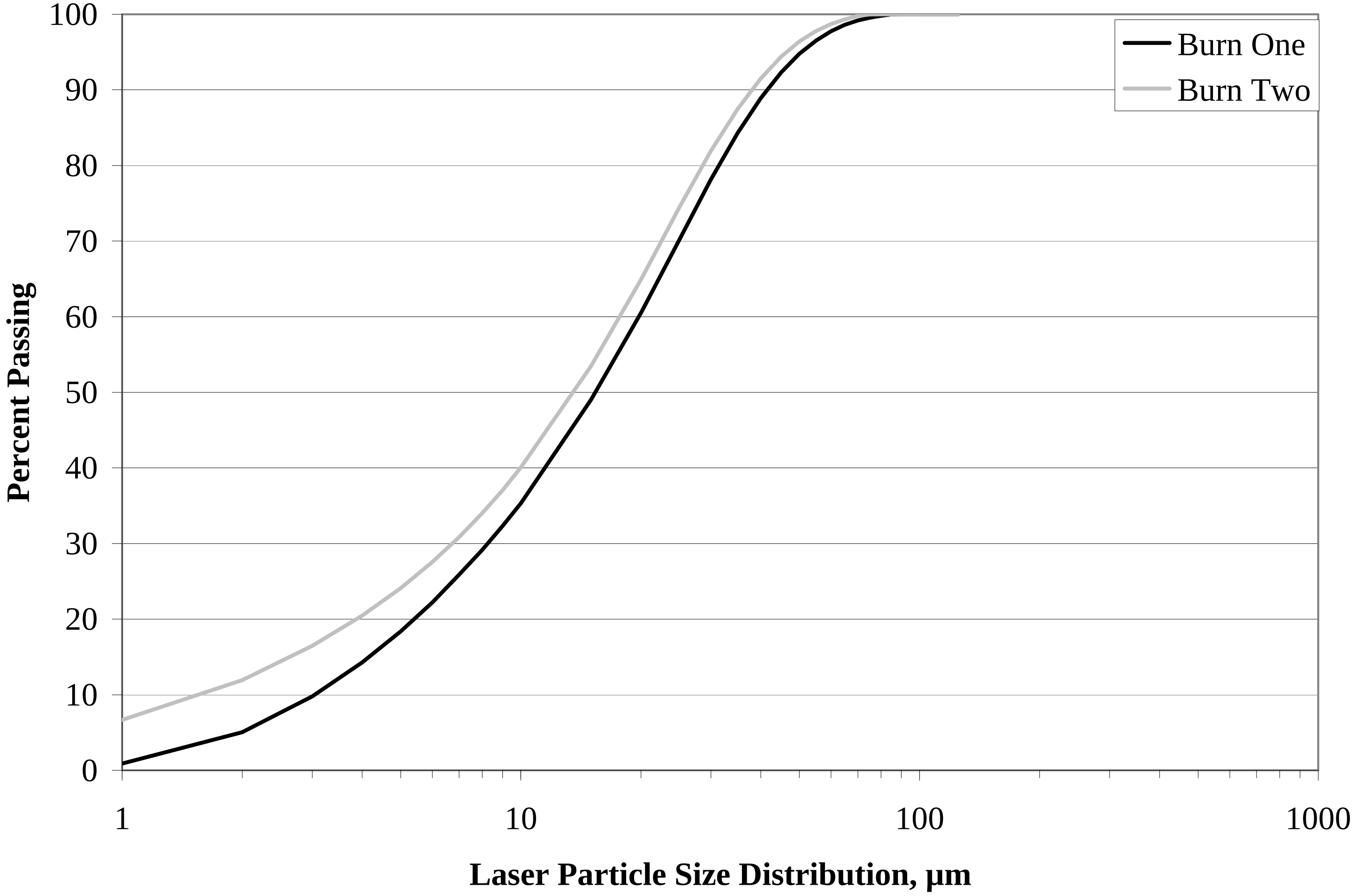


Figure 4.10: SLR - Particle Size Distribution of Cement

4.3.8 Properties of Concrete

Concrete was produced using the cement collected during each of the burn phases. There were two different concrete mixtures that were produced relative to each burn phase. The results for each type of mixture are discussed individually due to the fact that proportions of the mixtures were different, and cannot be compared with one another.

The first mixture, Mix A, was a conventional mixture with a water-to-cement ratio of 0.44, and utilized only an air-entraining admixture. This mixture was made at Auburn University and at the concrete laboratory of the cement plant. Table 4.33 shows the concrete property results of Mix A. Burn Three does not show any results from the laboratory of the cement plant because this mixture had not been produced by the completion of this document. Additionally, setting time and splitting tensile strength data were not determined by the cement plant.

The percent difference for each concrete property reported in Table 4.33 is calculated relative to the concrete mixture produced at Auburn University using cement from Burn Two. These differences for all properties except for compressive strength and splitting tensile strength are shown in Figure 4.11. It is obvious from this figure that the most dramatic change was in the slump. The results concerning slump from the cement plant showed a decrease of 64 and 71 percent for Burns One and Two, respectively. This difference can most likely be attributed to differences in laboratory practices and/or conditions between the cement plant and Auburn University. Therefore, it is not a property attributable to the cement used, and is only significant relative to the strengths of the concrete.

It is important to note that the 91-day permeability results are similar, especially after considering that the within-test repeatability for ASTM C 1202 is on the order of 1000 Coulombs. From this data it may thus be concluded that the concrete made from each of these cements should have similar permeability.

Table 4.33: AUR and CPR - Concrete Mix A Results

Property	Burn One				Burn Two			Burn Three	
	AUR	**% Diff.**	**CPR**	**% Diff.**	**AUR**	**CPR**	**% Diff.**	**AUR**	**% Diff.**
Total Air Content (%)	4.0	-5.9	3.6	-15.3	4.25	3.2	-24.71	4.0	-5.9
Slump (mm)	100	11.1	30	-66.7	90	30	-66.67	90	0.0
Unit Weight (kg/m^3)	2394	-1.8	2450	0.5	2439	2448	0.37	2464	1.0
Initial Set (Min.)	211	-3.2	218	0.0	218	247	13.30	216	-0.9
Final Set (Min.)	298	9.2	322	17.9	273	NC	NA	266	-2.6
Compressive Strength (MPa)									
1 day	12.3	-11.5	15.8	13.7	13.9	15.1	8.63	14.0	0.7
3 days	22.7	9.7	23.3	12.6	20.7	21.9	5.80	23.1	11.6
7 days	25.2	-11.3	33.3	17.3	28.4	32.8	15.49	28.5	0.4
28 days	35.0	-5.7	43.3	16.7	37.1	42.2	13.75	39.0	5.1
91 days	41.6	0.5	48.2	16.4	41.4	49.6	19.81	CIP	NA
Splitting Tensile Strength (MPa)									
1 day	1.7	-15.0	NC	NA	2.0	NC	NA	1.7	-15.0
3 days	2.4	4.3	NC	NA	2.3	NC	NA	2.3	0.0
7 days	2.6	-7.1	NC	NA	2.8	NC	NA	2.8	0.0
28 days	3.2	-3.0	NC	NA	3.3	NC	NA	3.5	6.1
91 days	3.7	-7.5	NC	NA	4.0	NC	NA	CIP	NA
Permeability @ 91 days (Coulombs)	2650	-9.6	2530	-13.7	2930	2660	-9.22	CIP	NA

Notes:

CIP - Collection in Progress
NC - Not Collected
NA - Not Applicable

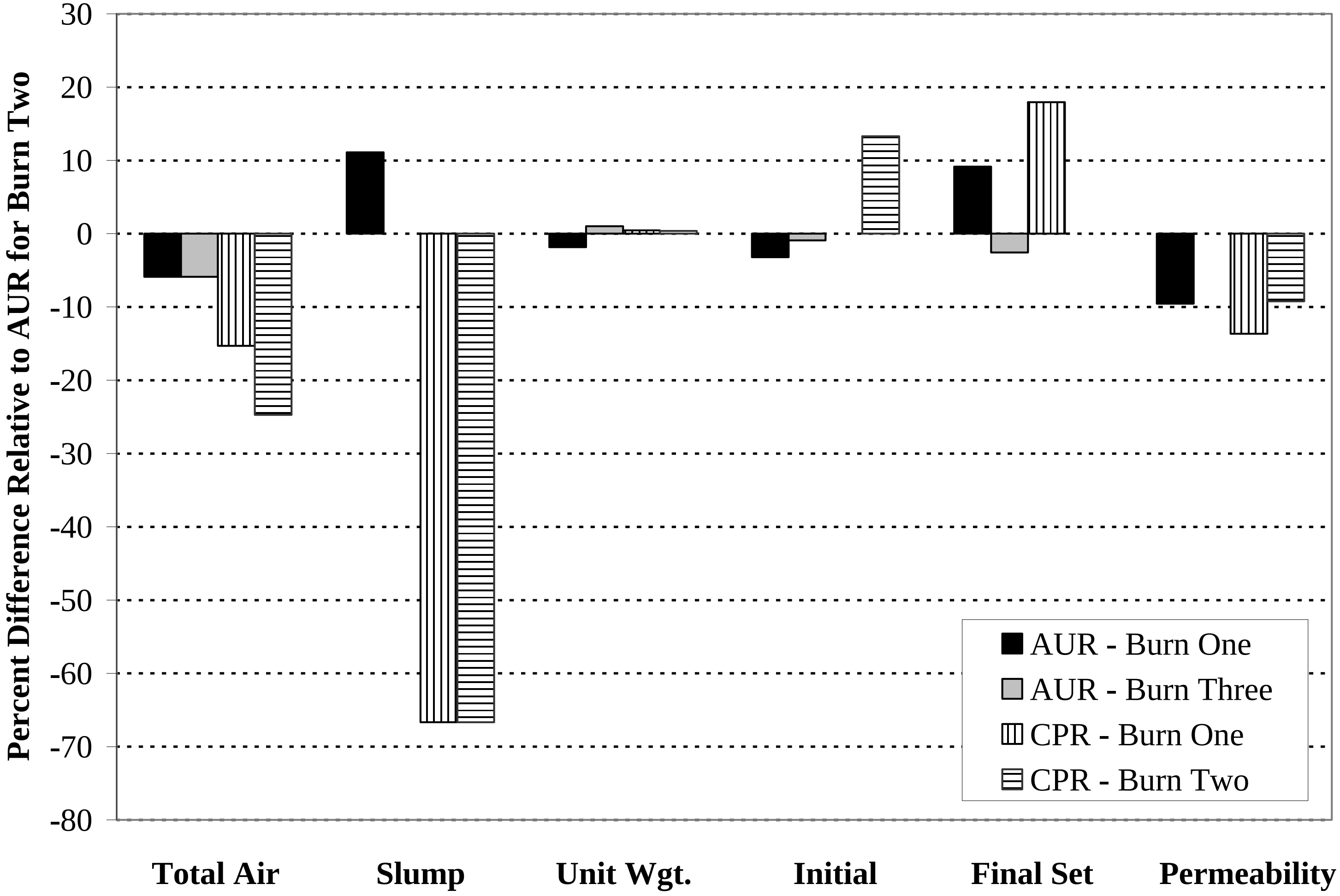


Figure 4.11: Percent Difference in Mix A Concrete Results Relative to AUR Burn Two

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 results of Mix A are shown in Table 4.33. These results are plotted relative to one another in Figure 4.12.

The most noticeable difference in compressive strength is that both of the mixtures conducted by the cement plant produced higher compressive strengths. This result was also shown in the compressive strength of mortar cubes. The fact that the slumps of the cement plant mixtures were considerably lower than that for those produced at Auburn University indicates that the fresh concrete had a lower consistency at the time of placement. This may indicate that less free mixing water was available; these concretes were thus made with a slightly lower water-to-cement ratio. This result is most likely the primary reason for the difference in strengths between the two testing entities. However, the value that is more meaningful is the relative difference between the concrete strengths for each burn. The results from the cement plant show very little difference at all ages between the concrete from Burns One and Two.

The compressive strength results reported by Auburn University show a meaningful difference at ages of seven and 28 days. The acceptable range of results, as specified by ASTM C 39, for a single operator, is 7 percent. Based on this criteria, Burn One showed a significant change relative to Burn Two at 1, 3, and 7 days. However, because two results decreased, and one increased, these results are inconclusive. Burn Three showed a significant increase over Burn Two only at a concrete age of 3 days.

Because the results at other ages were so similar, these results are once again inconclusive. There was a significant difference between Burns One and Three at concrete ages of 1, 7, and 28 days. This may suggest that the concrete produced from Burn Two cement is significantly stronger than that produced from Burn One cement. These results will be compared with those of Mix B in the following sections.

Results from splitting tensile strength tests of concrete produced from portland cement from Burns One, Two, and Three can be seen in Figure 4.13. According to ASTM C 496, the acceptable range of results within a single laboratory is 14 percent. Based on this criteria, there were no significant changes in splitting tensile strength between any of the burns. The greatest difference occurred at a concrete age of one day, and was only one percent above the acceptable range of results. This suggests that there were no significant changes in splitting tensile strength for Mix A.

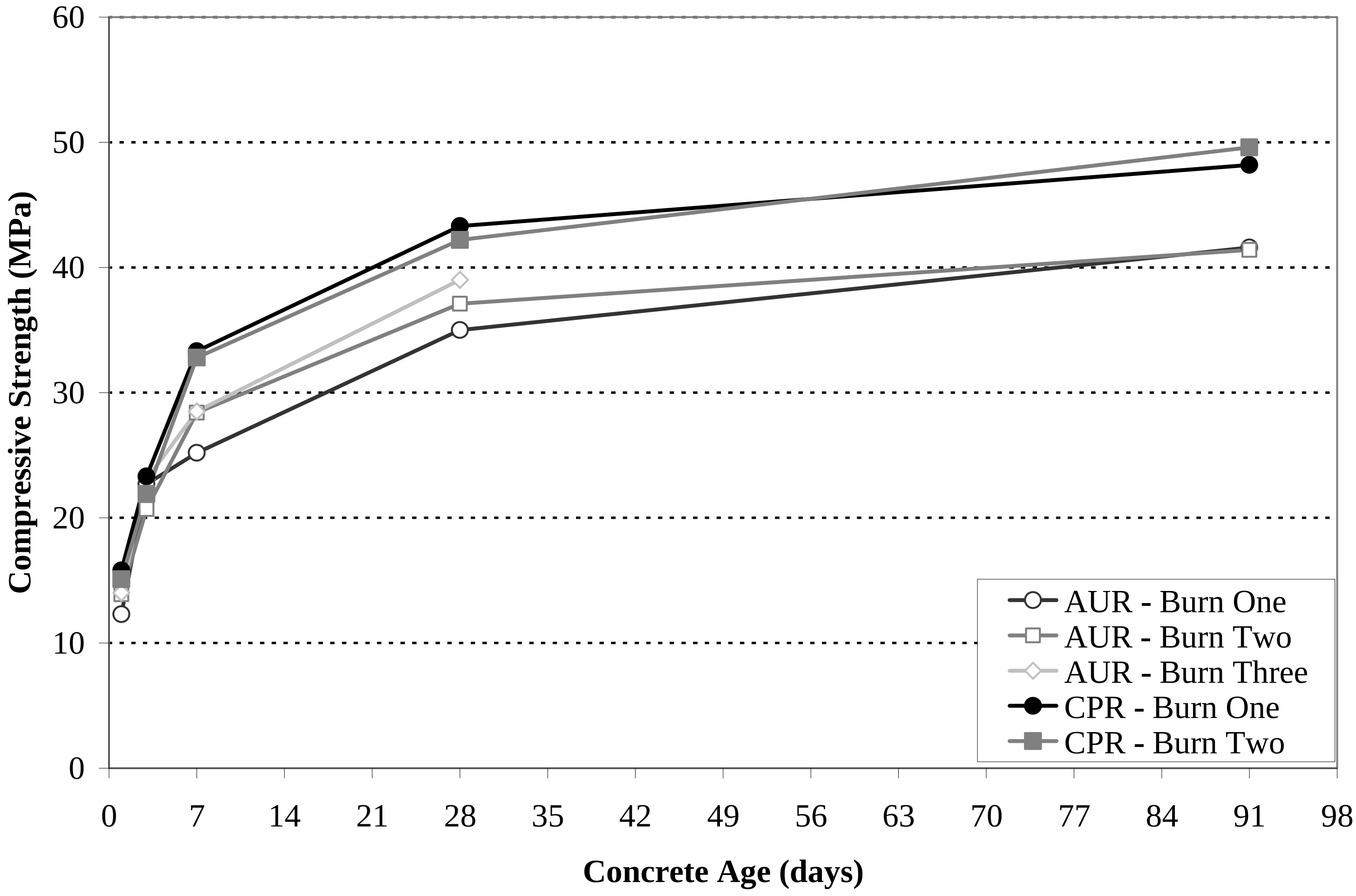


Figure 4.12: Compressive Strength for Mix A Concrete

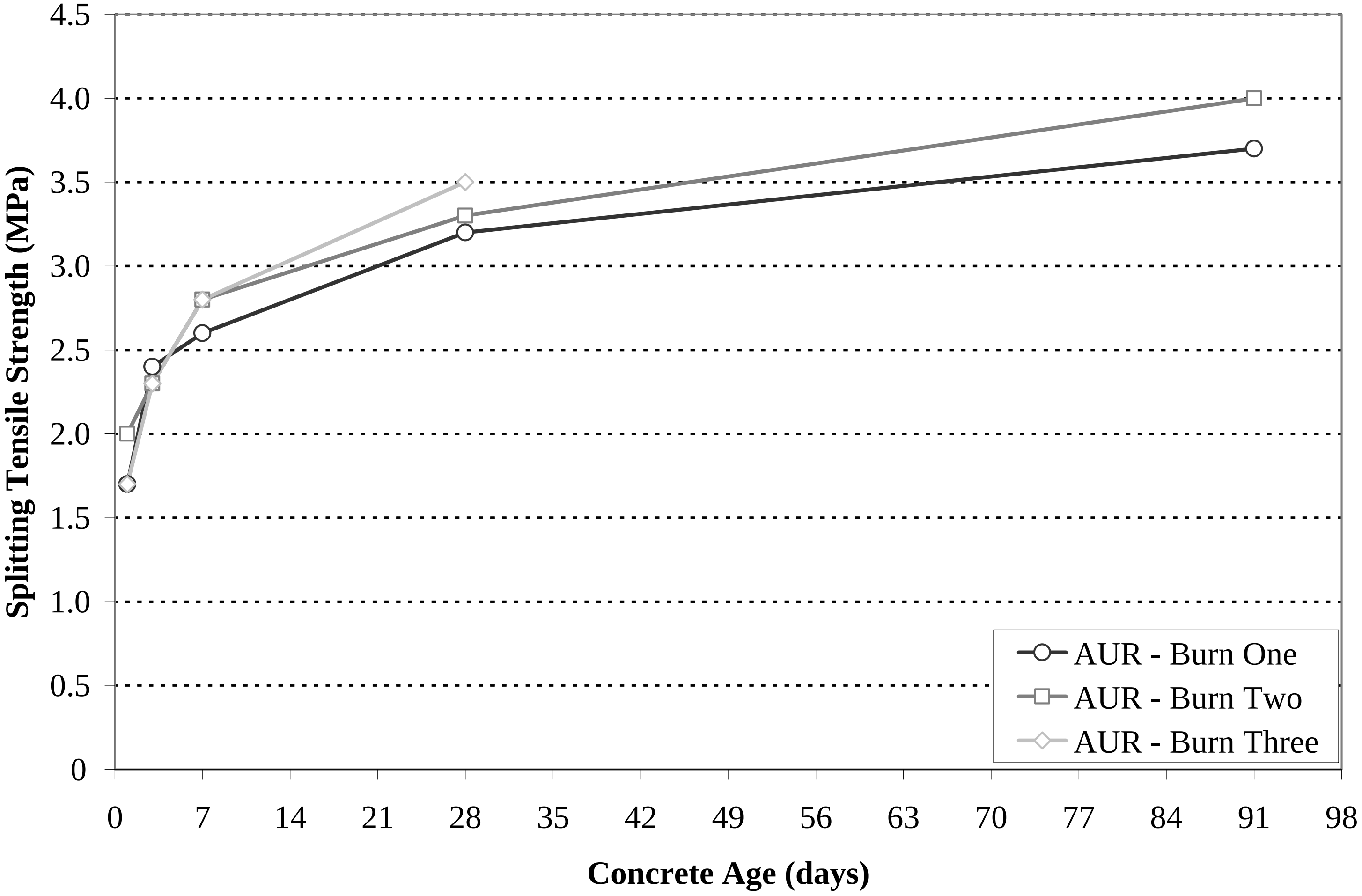


Figure 4.13: AUR - Splitting Tensile Strength for Mix A Concrete

The drying shrinkage development of concrete Mix A is shown in Table 4.34. The results are presented with shrinkage values reported as positive numbers. All values are given as a percent length change relative to the original length. In addition to the length change value, the percent difference of Burns One and Three relative to Burn Two are also presented. The concrete was exposed to drying conditions after seven days of saturated curing after concrete placement. Due to the timing of the burn, shrinkage results for the concrete from Burn Three are only reported up to a concrete age of 28 days.

Table 4.34: Drying Shrinkage Development of Mix A Concrete

Drying Age (days)	Burn One		Burn Two	Burn Three	
	Length Chage (%)	% Diff	Length Chage (%)	Length Chage (%)	% Diff
4	0.009	-50.0	0.018	0.008	-55.6
7	0.018	-33.3	0.027	0.011	-59.3
14	0.028	-17.6	0.034	0.020	-41.2
28	0.029	-17.1	0.035	0.029	-17.1
56	0.038	5.6	0.036	CIP	NA
112	0.045	2.3	0.044	CIP	NA
224	0.049	4.3	0.047	CIP	NA
448	CIP	NA	CIP	CIP	NA

Notes:

CIP - Collection in Process
NA - Not Applicable

The results in Table 4.34 are presented graphically in Figure 4.14, 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 determination of the heat of hydration produced under semi-adiabatic conditions. The results of this test for concrete Mix A can be seen in Figure 4.15. 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 based on temperature. The equivalent age is shown on a logarithmic scale. As one can see from Figure 4.15, there was essentially no difference in degree of hydration between the three burns. The concrete from Burn Three reached a slightly higher degree of hydration at an equivalent age of 10,000 hours, but the difference is still very small. Based on this result, there was very little difference in hydration progression between the three burns.

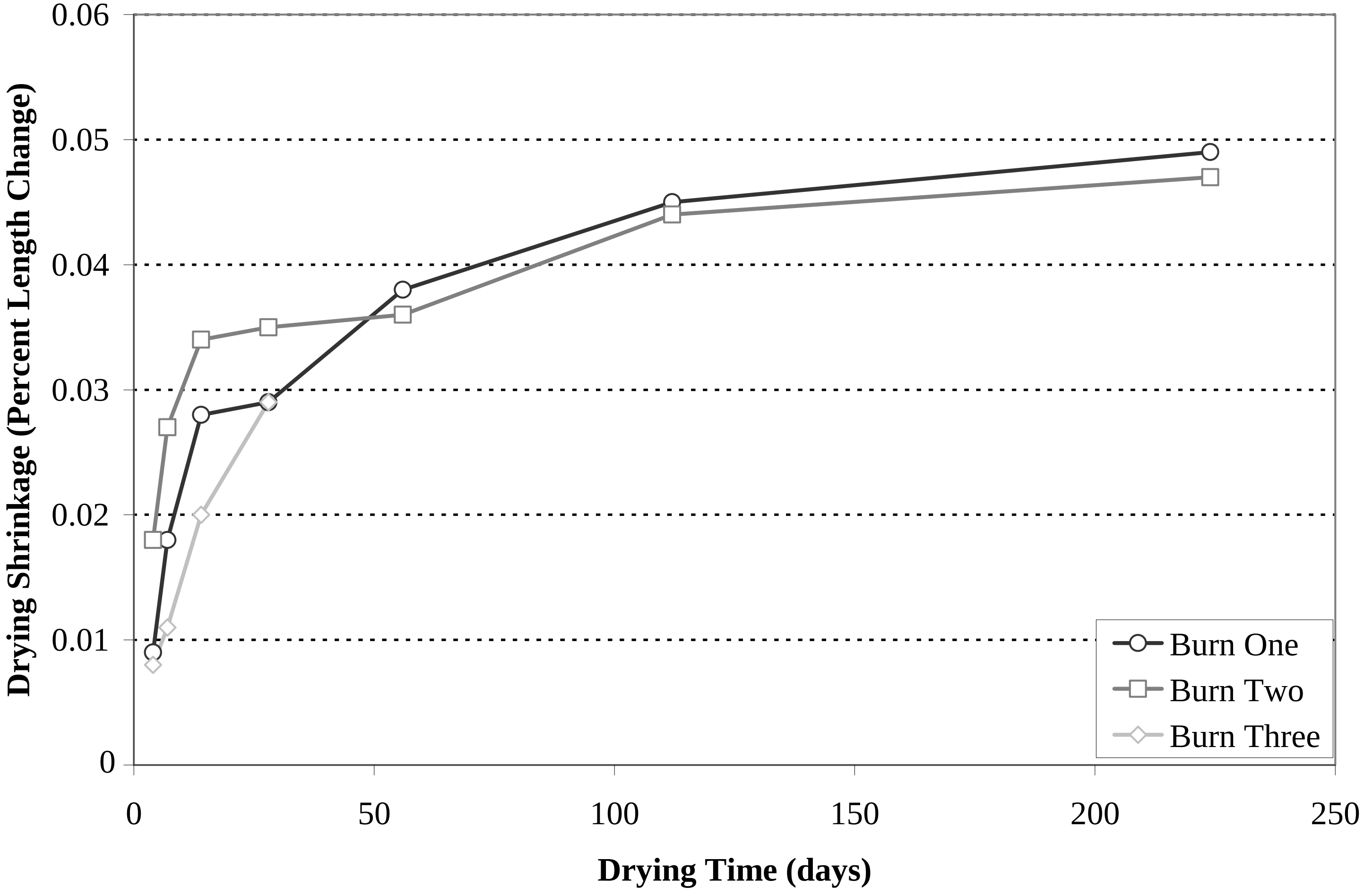


Figure 4.14: AUR - Drying Shrinkage Development for Mix A

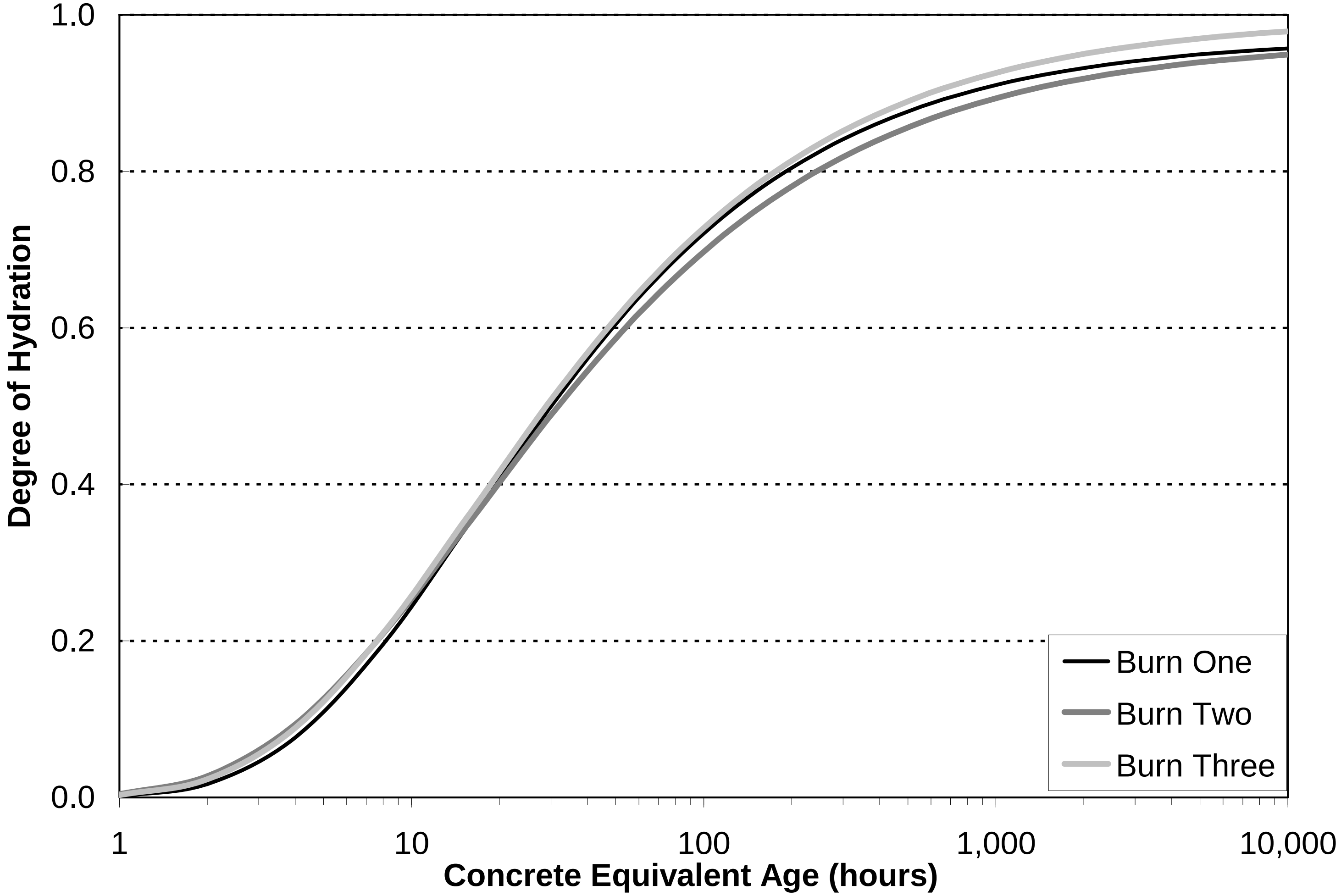


Figure 4.15: AUR - Semi Adiabatic Degree of Hydration Development for Mix A

The second mixture, Mix B, was a high-strength mixture with a water-to-cement ratio of 0.37. This mixture utilized both an air-entraining admixture and a water-reducing admixture. Mix B was only prepared by personnel at Auburn University. The results of tests on Mix B are shown in Table 4.35. Once again Burn Two was considered the baseline, and therefore is used as the reference for the percent differences. These changes, for all properties except compressive strength and splitting tensile strength, are presented graphically in Figure 4.16.

Mix B showed an increase in total air content for both Burns One and Three. In fact, Burn One showed a 50 percent increase in this property over Burn Two, and these differences are also slightly reflected in the unit weight. The unit weight showed a maximum change of 2.2 percent, which occurred in Burn One.

The slumps from Burns One and Three were both 152 millimeters. This was a decrease of approximately eight percent relative to Burn Two. The final property was setting time, which showed a similar change in both initial and final times for the Coal Only burn. This burn showed an increase in initial setting time of 33 percent, and an increase in final setting time of 39 percent. Burn Three showed an acceleration in initial set, which is the same result that was seen in mortar setting times and in Mix A. The final set time for Burn Three showed practically no change.

Table 4.35: AUR - Concrete Results for Mix B

Property	Burn One		Burn Two	Burn Three	
	Value	% Diff.	Value	Value	% Diff.
Total Air Content (%)	6.0	50.0	4.0	5.0	25.0
Slump (mm)	150	-6.3	160	150	-6.3
Unit Weight (kg/m^3)	2374	-2.2	2427	2413	-0.6
Initial Set (Min.)	318	33.1	239	229	-4.2
Final Set (Min.)	405	39.7	290	291	0.3
Compressive Strength (MPa)					
1 day	20.8	-19.7	25.9	22.3	-13.9
3 days	31.9	-11.6	36.1	33.1	-8.3
7 days	37.7	-5.7	40.0	38.0	-5.0
28 days	44.3	-10.9	49.7	51.0	2.6
91 days	51.5	-12.9	59	CIP	NA
Splitting Tensile Strength (MPa)					
1 day	2.5	-16.7	3.0	2.7	-10.0
3 days	3.3	-10.8	3.7	3.4	-8.1
7 days	3.7	-5.1	3.9	3.5	-10.3
28 days	4.1	-4.7	4.3	4.0	-7.0
91 days	4.3	-12.2	4.9	CIP	NA
Permeability @ 91 days (Coulombs)	2650	3.9	2550	CIP	NA

Notes:

CIP - Collection in Process
NA - Not Applicable

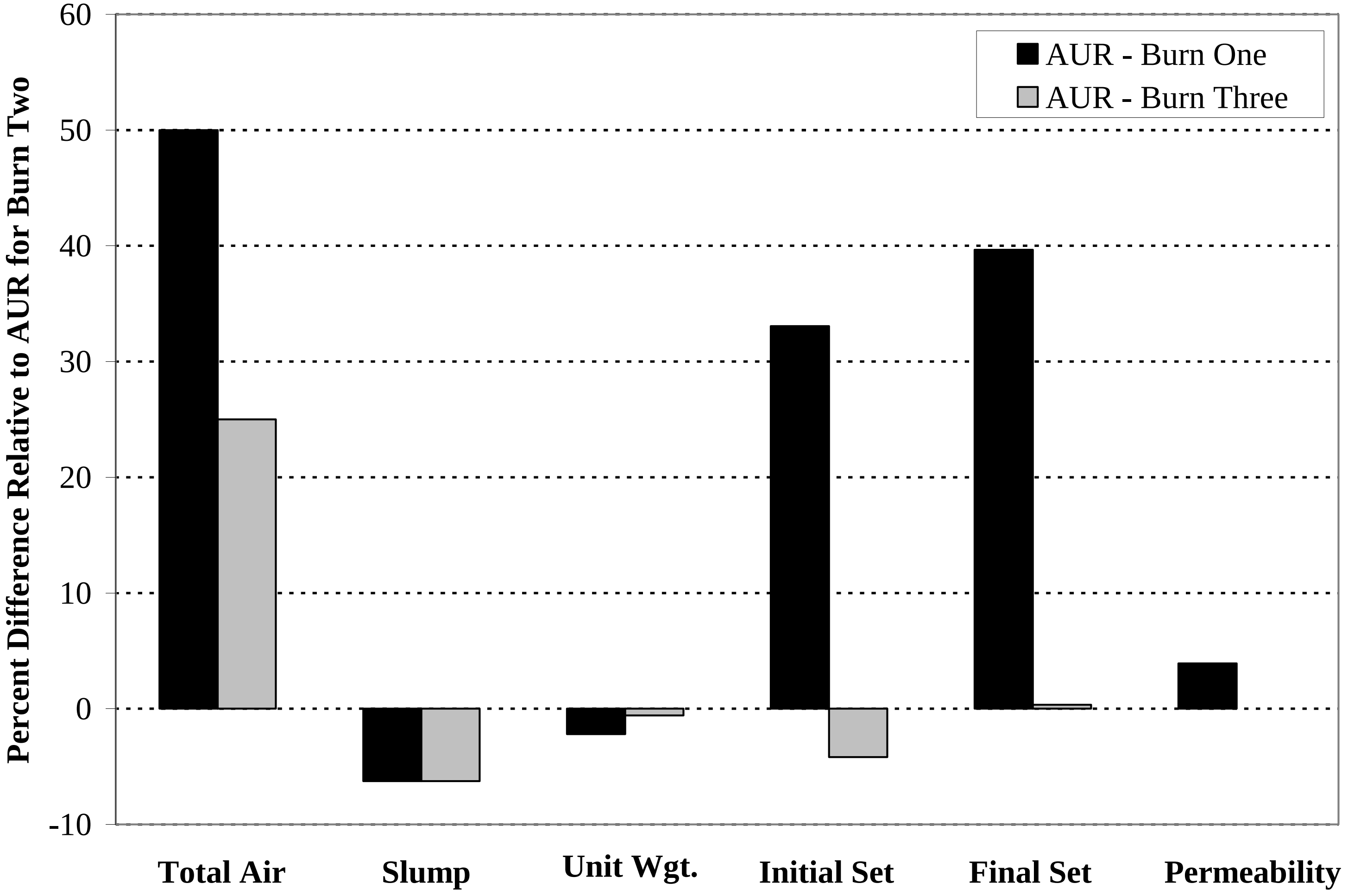


Figure 4.16: AUR - Percent Difference in Concrete Properties for Mix B

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 Burn One was significantly weaker than the concrete made from Burns Two and Three at all ages except for seven days. Based on this result, it is fairly conclusive that Burn One produced concrete with significantly 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.

A graphical presentation of the splitting tensile strength of Mix B, conducted by Auburn University, can be seen in Figure 4.18. Just as with the splitting tensile strength results presented in Mix A, Burn One produced lower strengths than Burn Two, but at no ages did this difference surpass the acceptable range of results provided by ASTM C 496. Based on these results, there is no significant change in splitting tensile strength for Mix B.

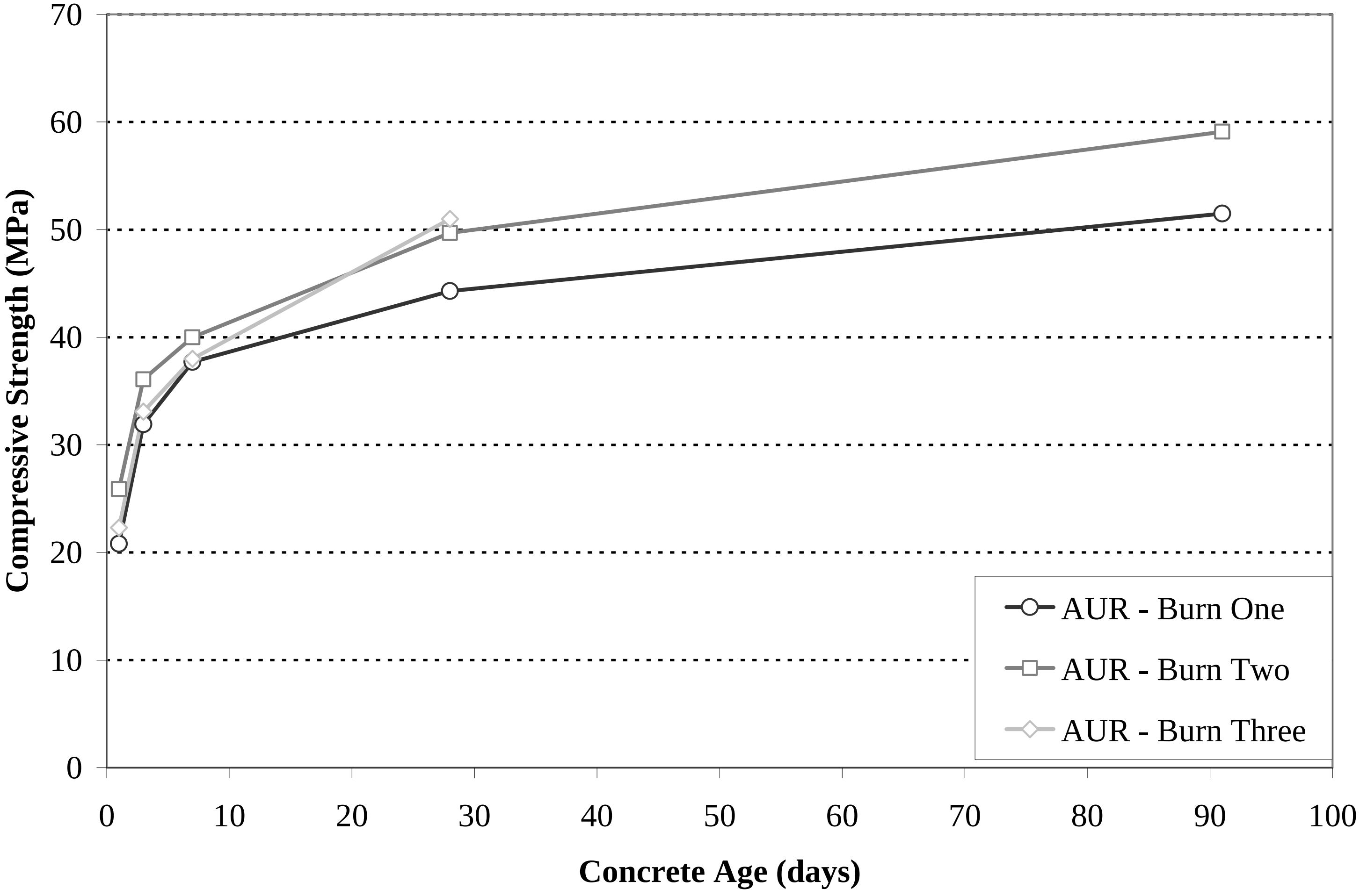


Figure 4.17: AUR - Compressive Strength for Mix B Concrete

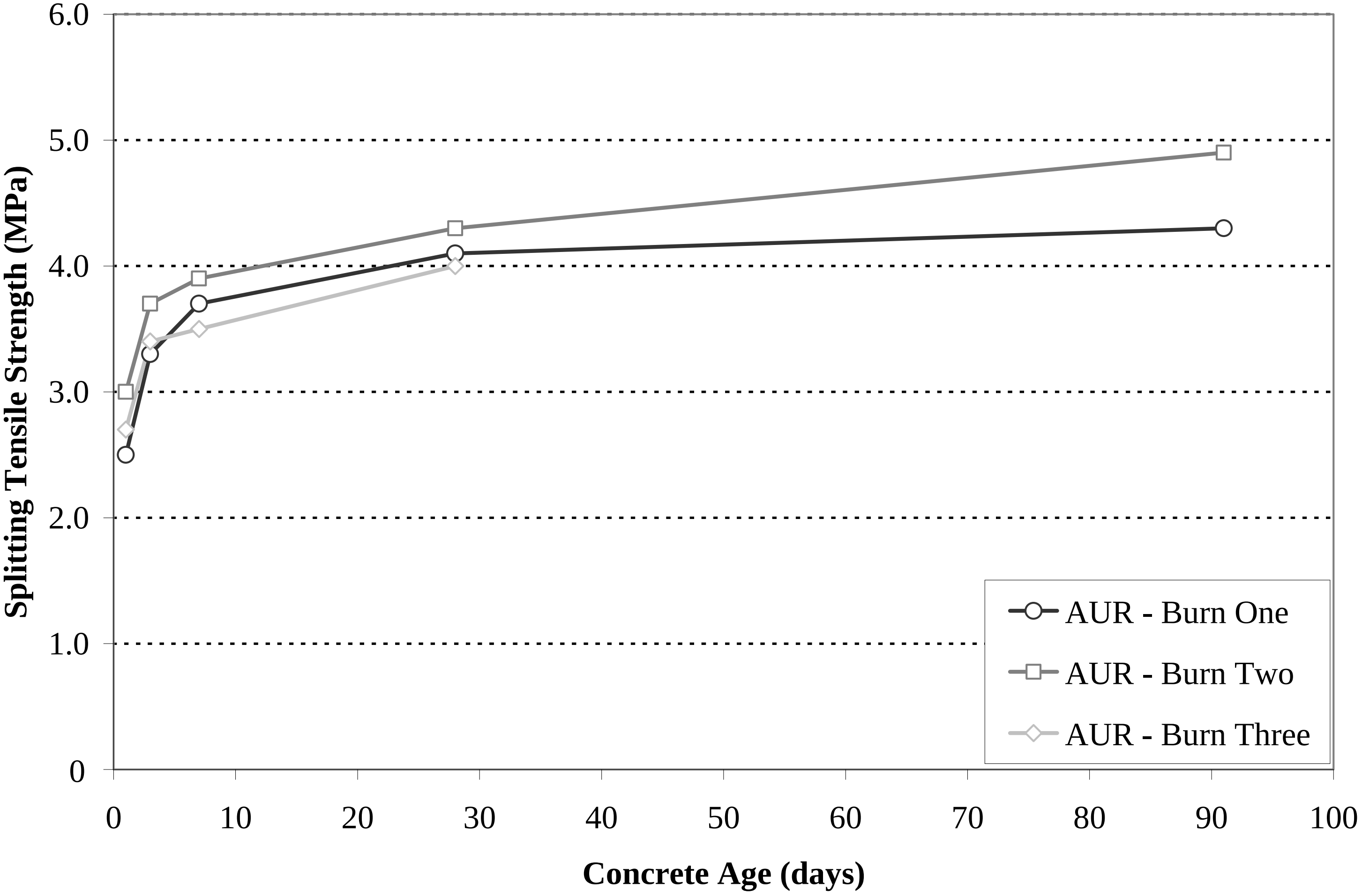


Figure 4.18: AUR - Splitting Tensile Strength for Mix B Concrete

The results of the drying shrinkage development test conducted at Auburn University on Mix B concrete can be seen in Table 4.36. Just as with the Mix A results, shrinkage values are reported as a positive percentage length change. Due to the timing of the burn phases, many of the long term results are yet to be collected.

Table 4.36: AUR - Drying Shrinkage Development of Mix B Concrete

Drying Age	Burn One		Burn Two	Burn Three	
(days)	Length Chage (%)	% Diff	Length Chage (%)	Length Chage (%)	% Diff
4	0.013	18.2	0.011	0.016	45.5
7	0.019	-5.0	0.020	0.018	-10.0
14	0.032	28.0	0.025	0.023	-8.0
28	0.037	23.3	0.030	0.036	NA
56	0.043	10.3	0.039	CIP	NA
112	0.051	NA	CIP	CIP	NA
224	CIP	NA	CIP	CIP	NA
448	CIP	NA	CIP	CIP	NA

Notes:

CIP - Collection in Process
NA - Not Applicable

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 appears as though the drying shrinkage properties of the concrete were not significantly altered.

Figure 4.20 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 Burns Two and Three are basically the same. Burn One, however, experienced lower hydration between equivalent ages of 10 and 1,000 hours. This result could explain the slightly lower compressive strengths for Burn One at one and three days.

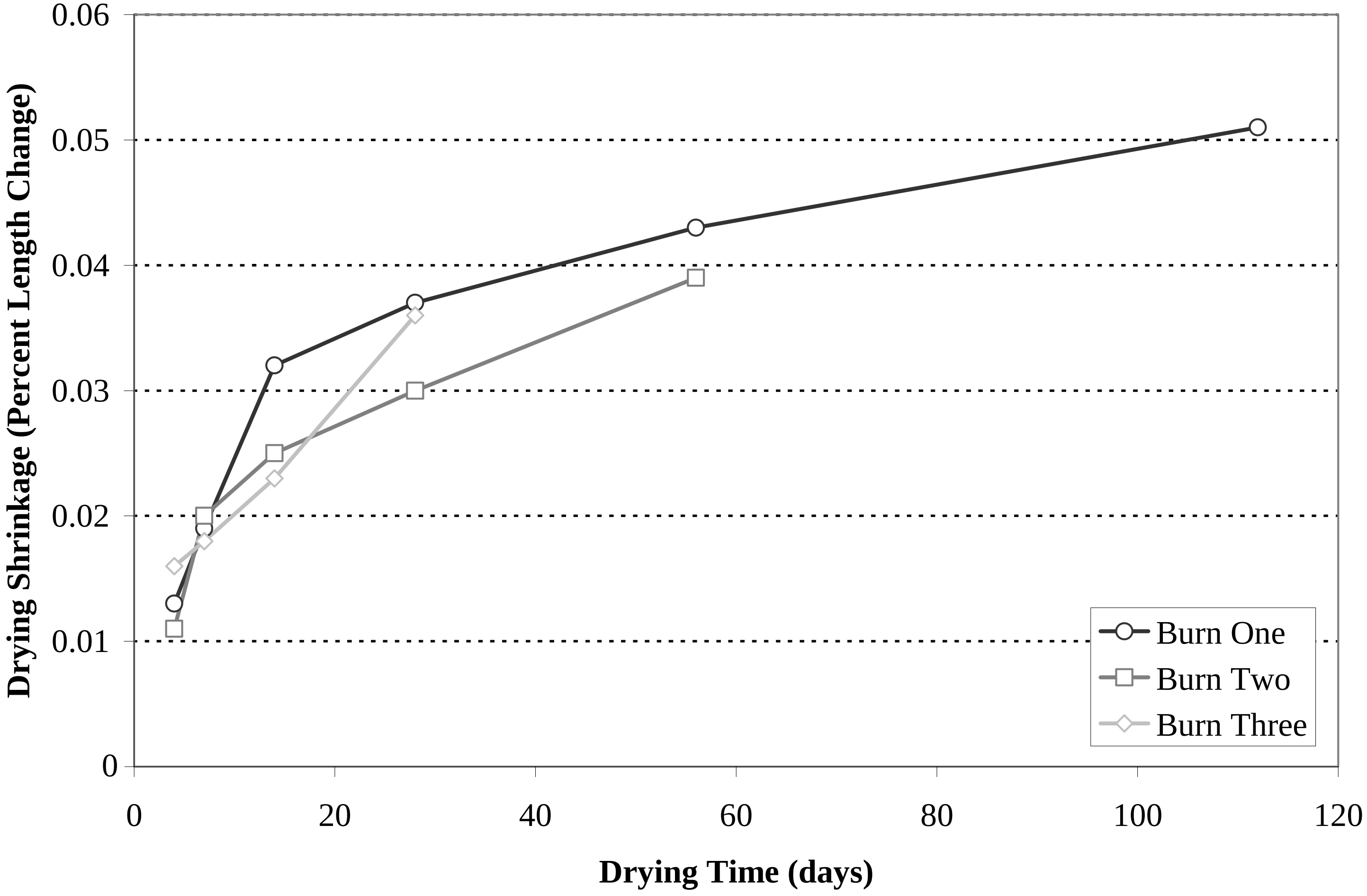


Figure 4.19: AUR - Drying Shrinkage Development for Mix B Concrete

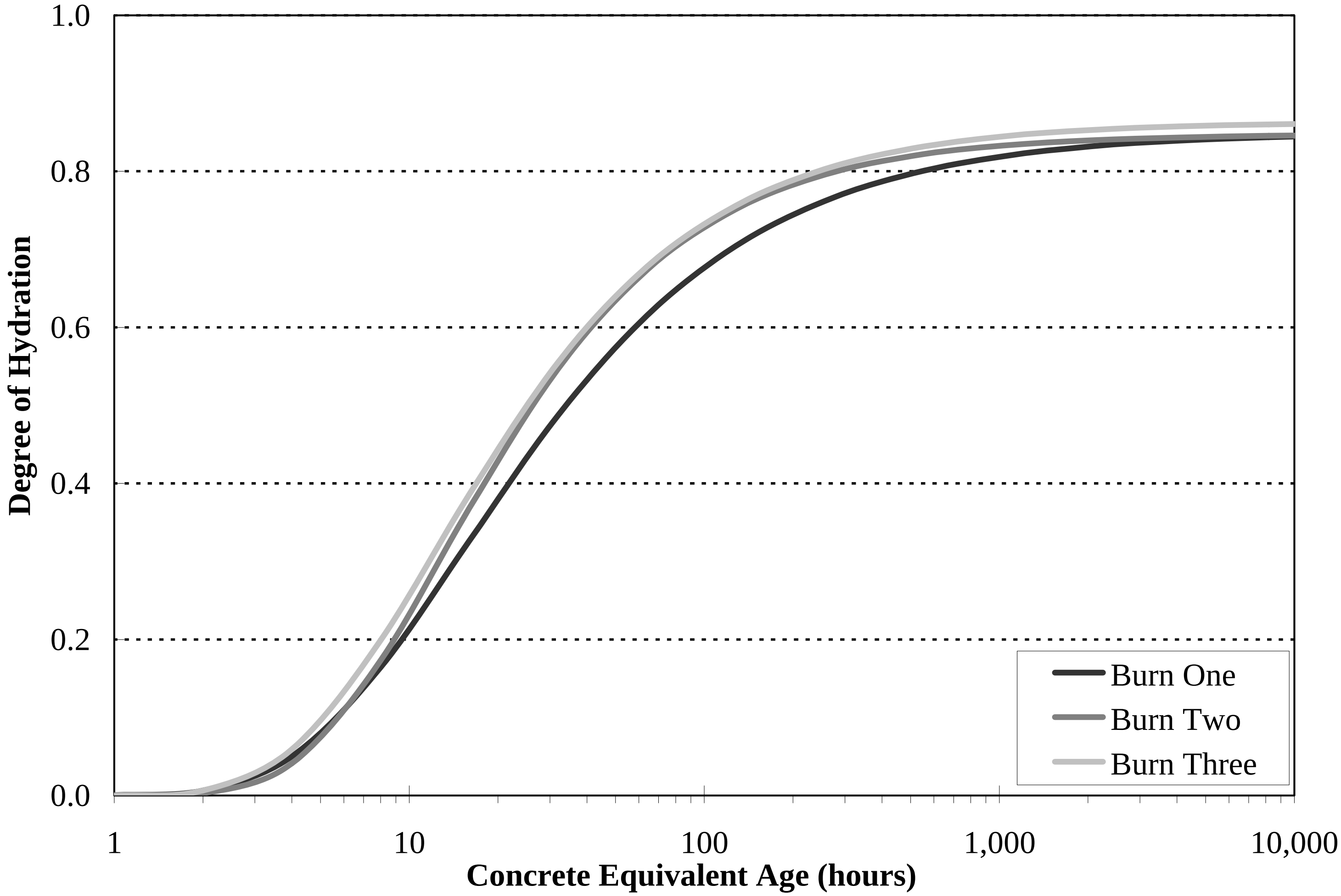


Figure 4.20: AUR - Semi Adiabatic Degree of Hydration Development for Mix B

4.3.9 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 4.37 shows the summary statistics for these data. 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 now presented in terms of tons per ton of clinker produced. Figure 4.21 through Figure 4.24 show the time-history plot of each of the emissions relative to time. In addition, the average for each emission is given in the key.

Table 4.37: CPR - Summary Statistics for Emissions

		Burn One	Burn Two	Burn Three
NO_x (tons/ton clinker)	**Average (10^{-3})**	0.82	1.21	1.05
	Coefficient of Variation (%)	8.3	8.0	9.4
	P-Value[1]	0.064 [2]	0.015 [2]	0.035 [2]
SO_2 (tons/ton clinker)	**Average (10^{-6})**	0.40	11.24	0.41
	Coefficient of Variation (%)	218.9	145.6	163.7
	P-Value[1]	<0.005 [2]	<0.005 [2]	<0.005 [2]
VOC (tons/ton clinker)	**Average (10^{-5})**	2.31	3.42	2.61
	Coefficient of Variation (%)	64.5	35.8	22.4
	P-Value[1]	<0.005 [2]	0.008 [2]	0.023 [2]
CO (tons/ton clinker)	**Average (10^{-4})**	7.68	5.41	5.67
	Coefficient of Variation (%)	9.9	10.8	22.0
	P-Value[1]	0.060 [2]	0.214	0.375

Notes:

[1] Based on Anderson-Darling Statistics

[2] Not Normally Distributed

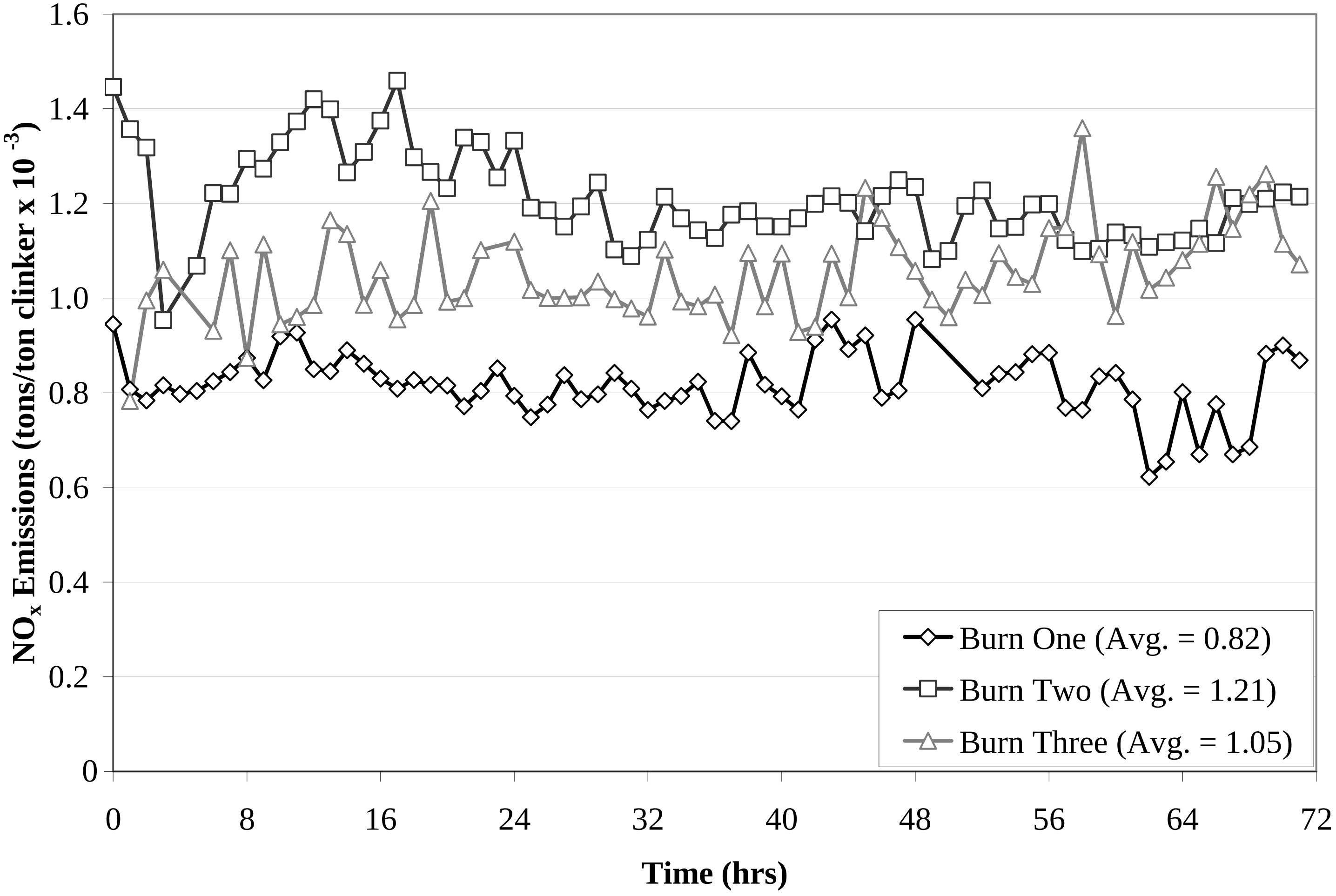


Figure 4.21: CPR - Time History Plot of NO_x Emissions

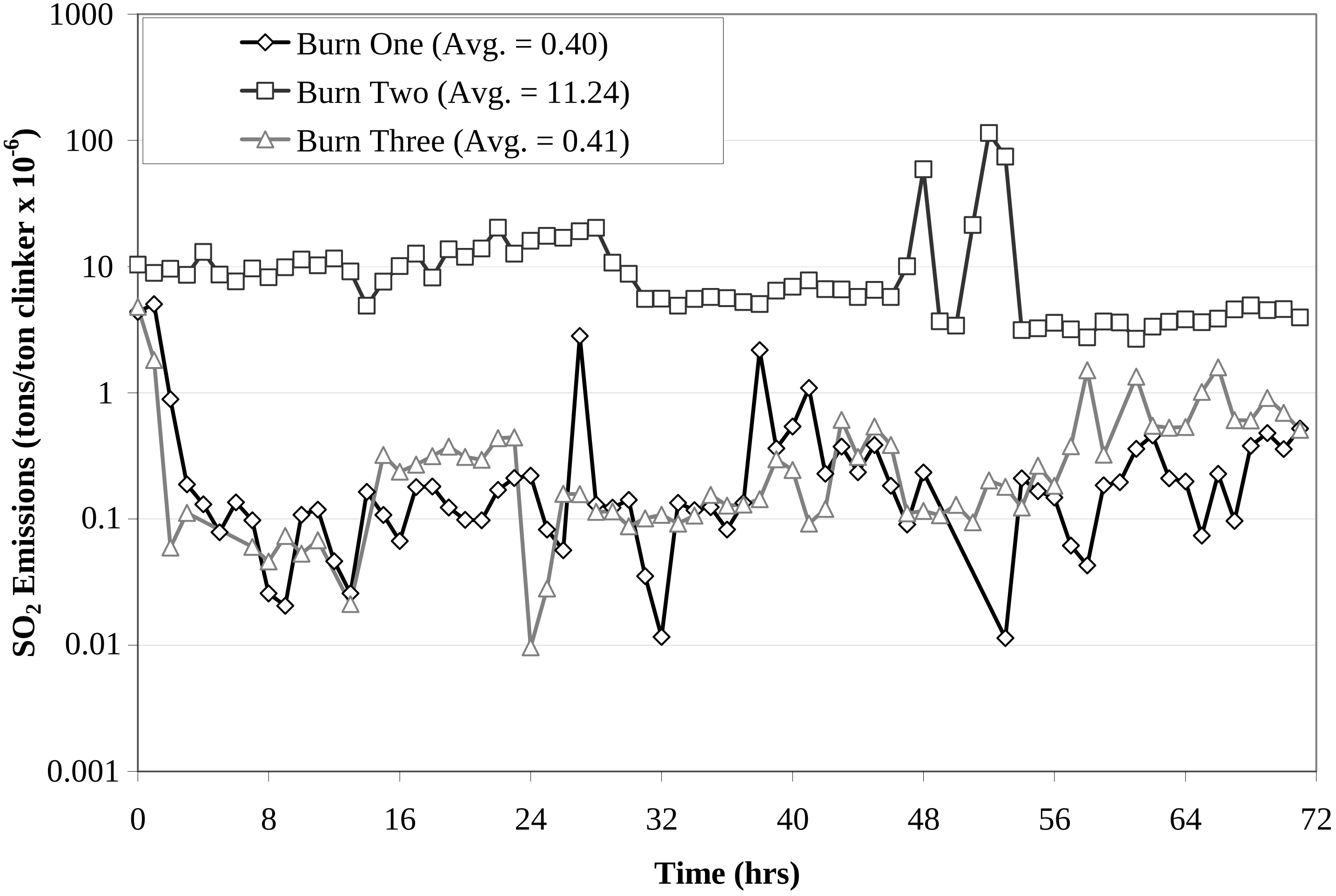


Figure 4.22: CPR - Time History Plot of SO_2 Emissions

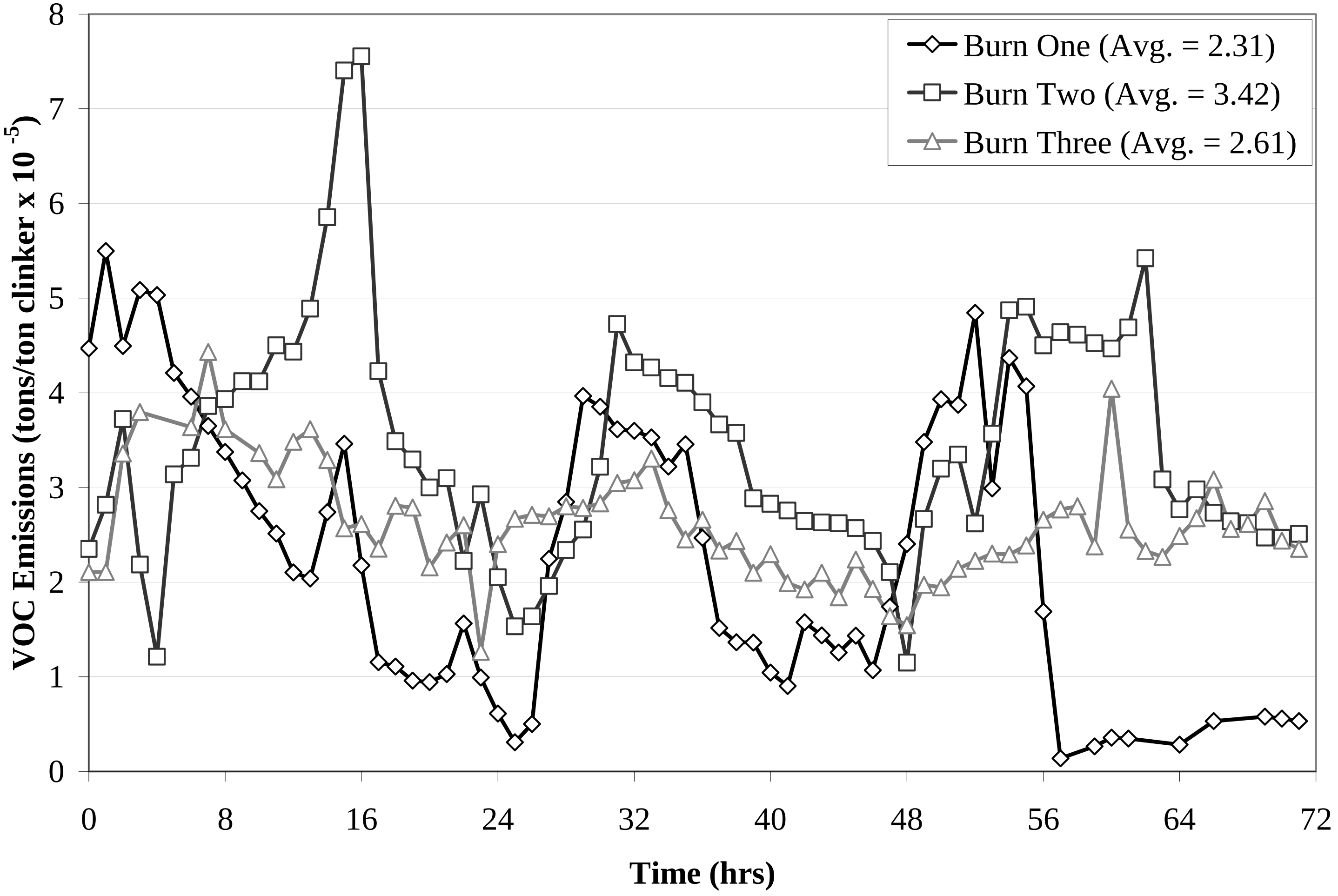


Figure 4.23: CPR - Time History Plot of VOC Emissions

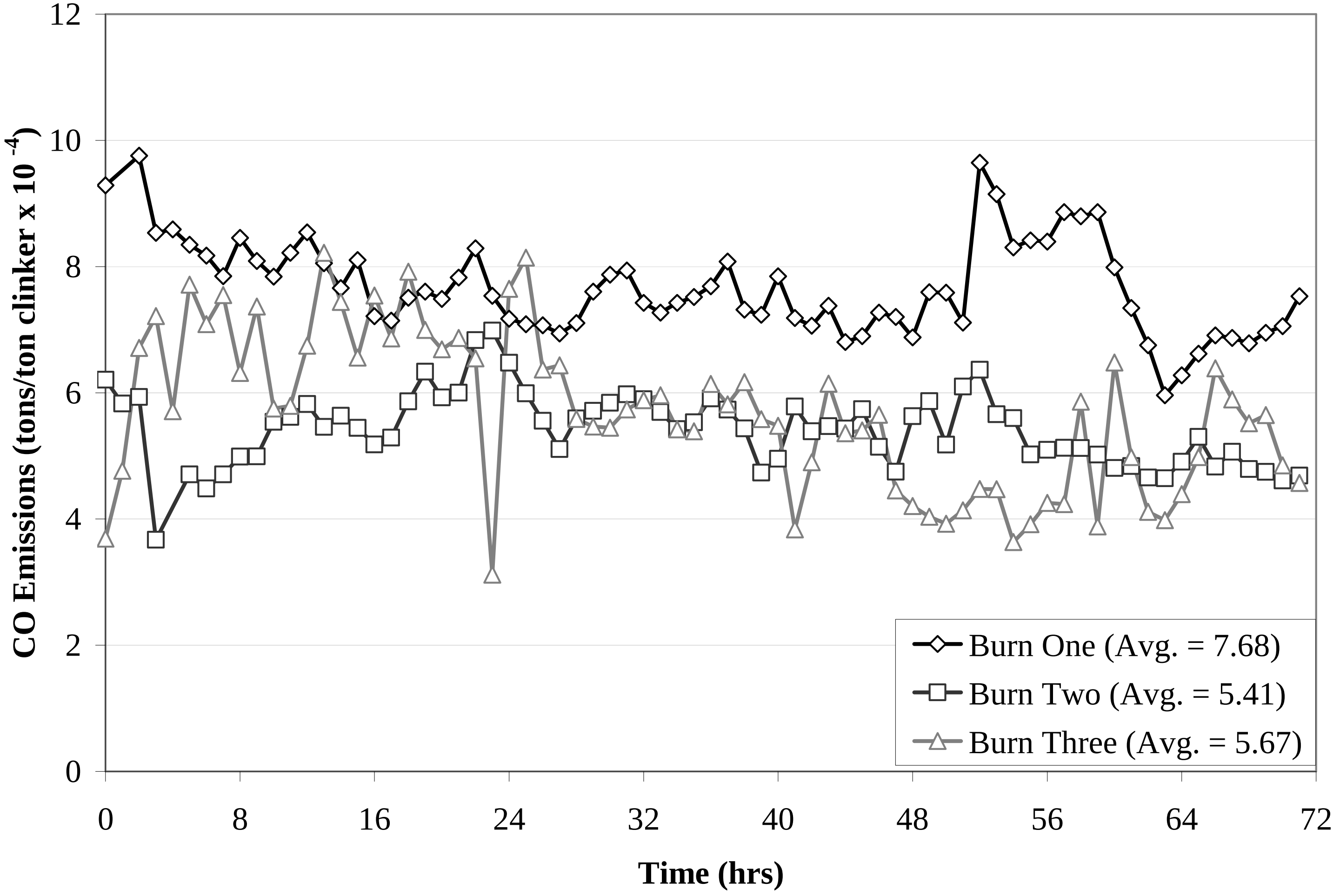


Figure 4.24: CPR - Time History Plot of CO Emissions

Table 4.38 shows the percent differences between Burns One and Three relative to Burn Two. It also shows whether these results were statistically different, along with the corresponding P-values. Figure 4.25 shows these results graphically. The most striking difference is the one that applies to the SO_2 data. This SO_2 emissions data showed almost a 100 percent decrease for both Burns One and Three. After discussion with personnel at the cement plant, the consensus was that there was some type of anomaly with this emission during Burn Two. Although differences did occur in most of the other emissions, the cement plant personnel could offer no plausible explanation for these high SO_2 readings for Burn Two. The results shown in Figure 4.25 indicate that the NO_x and VOC were reduced in Burns One and Three relative to Burn Two, whereas the CO emissions were increased. It is important to notice that the average CO levels were the lowest when alternative fuels were used.

Table 4.38: CPR - Percent Difference and Significance of Emissions

		Burn One	**Burn Three**
NO_x	**Percent Difference**	-32.4	-13.1
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
SO_2	**Percent Difference**	-96.4	-96.4
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
VOC	**Percent Difference**	-32.5	-23.8
	Statistically Different	Yes	Yes
	P-Value	0.000	0.000
CO	**Percent Difference**	41.8	4.8
	Statistically Different	Yes	No
	P-Value	0.000	0.115

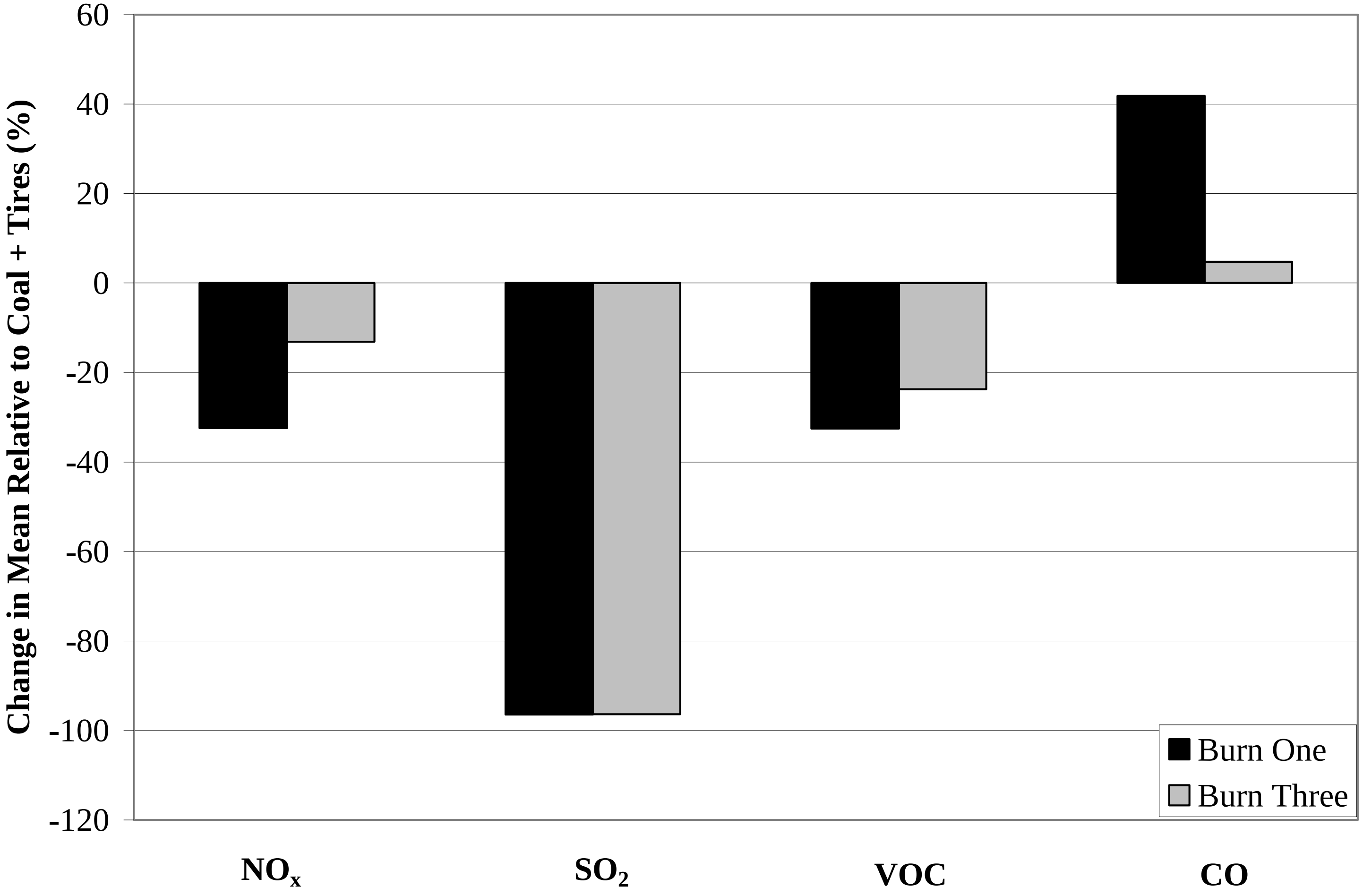


Figure 4.25: CPR - Percent Change in Means of Emissions Relative to Burn Two

4.4 Conclusion

The production of portland cement utilizes many complex materials, facilities, and processes. The nature of the production process results in countless 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 implementation 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 build-ups inside 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 rate of the plastics was also limited by the equipment used. In this case, the injection system was limited in the quantity of the low-density plastic fuels that were being used. In spite of the limitations associated with these fuels, the results shown in Section 4.3.3 showed some positive results as well. The most prominent of these was the energy content of the alternative fuels. The heat value of each of the fuels was determined to be as follows:

1. Coal: 11,157 to 12,476 BTU/lb,
2. Tires: 14,467 to 14,687 BTU/lb, and

3. Plastics: 11,327 to 14,446 BTU/lb.

These results indicate that the tires and plastics have good combustion properties as they produce more heat per pound than the coal. These combustion properties, along with the costs associated with acquisition, mean that the cement plant will continue to use these fuels for the foreseeable 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 burn periods. 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. 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 by 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 impact 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 significant change between burn periods.

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 significantly affected by the cement from which it was made.

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 seen between each of the burns. This shows conclusively that each of the cements used in this study were significantly similar in their drying shrinkage properties.

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 showed an increase relative to Burn Two in all cases but one. However, because of the one inconsistent result, no definitive conclusion could be drawn. The setting times for cement and concrete showed some significant changes. In the Gillmore and Vicat setting tests of cement pastes, the cement of Burn Three showed significant acceleration relative to that of Burns One and Two. The concrete made from Burn Three did not show a similar acceleration for either Mix A or Mix B. The setting time of Mix B concrete showed significant retardation for cement from Burn One. Again, however, this result was not corroborated by either the cement paste results or the Mix A results.

Perhaps the most prominent result was the compressive strength of Burn One. In the mortar cube test, as well as both concrete mixtures, Burn One showed a trend in that it consistently produced the lowest compressive strengths. At various ages, Burn One was, at best, significantly similar to the other results, but in many cases, it was significantly weaker.

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 with the chemical composition of the cement, it is difficult to say that the fuels used were directly responsible for any changes that may 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 burn periods. The following list summarizes the emissions collected for each burn based on the averages:

1. NO_x (Burn Two) > NO_x (Burn Three) > NO_x (Burn One),
2. SO_2 (Burn Two) > SO_2 (Burn Three) > SO_2 (Burn One),
3. VOC (Burn Two) > VOC (Burn Three) > VOC (Burn One), and
4. CO (Burn One) > CO (Burn Three) > CO (Burn Two).

Based on these results, Burn Two showed the highest emissions for NO_x, SO_2, and VOC. This could possibly be attributed to the higher rate of tire use during Burn Two relative to Burn Three, and the lack of tire use in Burn One. However, CO, the primary greenhouse gas emitted by the cement plant, was the highest when only coal was used.

Unfortunately, the variable nature of the cement production process makes it very difficult to conclusively say 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 burn periods, further research is necessary to determine whether these changes are a direct result of the use of 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 is both profitable for the portland cement industry, and beneficial to the environment.

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, recycled industrial plastics, and broiler litter were examined as viable alternatives to traditional fuels. Tires have been used in the cement industry for many 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. The use of broiler litter as fuel in a cement plant releases some of the pressure that the environment may feel from land application.

In this study, a full-scale, operational cement plant was used as the test venue. During normal production, the aforementioned alternative fuels were burned in four different test periods. Each of these test periods was called a burn period, and each utilized different combinations of these fuels. The first burn period that was conducted used only coal. The second burn period utilized coal and whole tires. Based on previous research conducted by the cement plant, standard operation at this specific facility uses this combination of fuels. For this reason, the coal plus tires burn was considered the baseline in this study. The third burn period utilized coal, tires, and plastics. The final burn period implemented coal, tires, and broiler litter. Due to the timing of the last burn period, the results had not been collected and are not reported in this document. These results will be presented in future work.

Within each burn period, 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 burn periods. 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 out of the cement from each burn, and various concrete properties were tested. These physical properties of cement and concrete were then compared between burn periods in order to determine if the fuels had any impact. Finally, the emissions released by the cement plant were monitored during each burn period. These emissions were then compared between burn periods 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 the cement plant to maintain productive operation. 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 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 equipment to move the low-density material into the kiln. Despite these limiting factors, both of these fuels showed potential, in that they both had higher energy content than the coal. The average energy content for the coal was approximately 11,700 BTU/lb. The average energy content of the tires was approximately 14,500 BTU/lb. The average energy content of the plastics was approximately 12,800 BTU/lb. Based on the energy content, as well as the cost of acquisition relative to the coal, the cement plant will continue to burn these fuels in the foreseeable future.

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 a significant difference between each of the burn periods 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 fuels that were used.

The most significant results concerning 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 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 is used to produce. Many of the physical properties of cement that were tested did not show a significant difference between burn periods. Autoclave expansion and drying shrinkage of paste prisms were the most prominent results that showed no practically significant change. From these results, it appeared as though the susceptibility to length change under various conditions was not altered between the burn periods.

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 setting times of as much as 27 percent relative to the cement produced using coal plus tires. The majority of the results did not show a significant difference in setting times between the cement produced during the other burn periods. The final result that showed a significant change was the mortar cube compressive strength. The cement produced using coal plus tires showed a trend of higher strengths than the other two burns, at all ages. This result was most significant at mortar ages of three and seven days, and was as much as 26 percent. The difference in compressive strength of mortar from the coal only burn and the coal, tires, and plastics burn was not significant. Although differences were found in the physical properties of cement between the burn periods, it was not possible to conclude that they were a direct result of the fuels that were used.

The fourth objective of this study was to determine if the utilization of alternative fuels directly impacted the properties of concrete made from this portland cement. Two different concrete mixtures were made from the cement produced during each burn period. 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 results from both concrete mixtures showed no significant change in permeability between any of the burn periods. Additionally, the drying shrinkage development of both concrete mixtures did not show any significant changes between each burn period. This result agreed with that for the drying shrinkage development of paste prisms. The splitting tensile strength of both concrete mixtures also showed no significant change between burn periods. A few results showed significant changes at certain ages, but no significant trends were shown.

Some concrete properties did show significant trends, one of which was the setting time. In one of the concrete mixtures produced from the cement using coal only, a significant retardation in setting time occurred. This retardation was as much as 40 percent relative to the Coal plus Tires burn period, and the Coal, Tires, and Plastics burn period. However, this result was not corroborated in the other concrete mix. Besides this result, there were no significant changes in concrete setting time. The compressive strength of concrete cylinders is the primary property used to indicate the performance of concrete. This property did show a significant trend for the concrete made using the Coal Only cement. The concrete produced from this cement was significantly weaker, at most ages, than the concrete made from the cement produced during the Coal plus Tires burn. The difference in compressive strength between these two burns was as much as 20 percent. The concrete made from this cement was also significantly weaker, at many ages, than the concrete made from the cement produced by using Coal, Tires, and Plastics. The difference in these concretes was as much as 14 percent. Based on these results, the concrete made from the cement that was produced using Coal Only was significantly weaker than concrete made from either of the other burn periods.

The final objective of this study was to determine if the utilization of alternative fuels directly impacted the 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 relative changes in the means of each emission were as follows:

1. NO_x (Coal plus Tires) > NO_x (Coal, Tires, and Plastics) > NO_x (Coal),
2. SO_2 (Coal plus Tires) > SO_2 (Coal, Tires, and Plastics) > SO_2 (Coal),
3. VOC (Coal plus Tires) > VOC (Coal, Tires, and Plastics) > VOC (Coal),
4. CO (Coal) > CO (Coal, Tires, and Plastics) > CO (Coal plus Tires).

However, the variable nature of the production process once again minimized the ability of the researcher to say conclusively that the fuels used were directly responsible for any changes that were seen in the emissions.

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 satisfying those 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. These obstacles resulted in a number of delays in the timing of the burn periods. Now that the facilities are in place to handle these alternative fuels, it would be beneficial to conduct a number of burn periods using similar fuels within close proximity (time wise) to one another. Due to the delays experienced in this study, the burn periods were too far apart. These extended breaks between burn periods required 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 burn periods.

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 burn period 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 burn periods. Other parameters of the production process, which were not monitored by this project, were also likely altered between burn periods. Once again, these changes that were made rendered it impossible to determine if the chemical composition of the fuels had any effect on the chemical composition of the clinker and/or cement.

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.

The emphasis of this project was the effect that alternative fuels had on everything from the production process 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.10)[1]	1 / burn	Discrete	During Each Burn Period	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.12)	1 / burn	Discrete	During Each Burn Period	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.10)[2]	2 / day	Discrete	Standard Sampling Period (Figure A.1)	Cement Plant	Yes
12	***Kiln Feed (Raw Material Seven)***	Standard External Lab Parameters (Table A.12)	2 / day	3-Day Composites	Standard Sampling Period (Figure A.1)	External Lab	No
13	***Raw Material Six***	Standard Cement Plant Parameters (Table A.10)[1]	1 / burn	Discrete	During Each Grinding Period	Cement Plant	Yes
14	***Raw Material Six***	Standard External Lab Parameters (Table A.12)	1 / burn	3-Day Composites	During Each Grinding Period	External Lab	No

Notes:

[1] Na_2O_{eq} is not collected

[2] Moisture is not collected

[3] Moisture and LOI is not collected

Table A.2a: 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.11)	2 / day	3-Day Composites	Standard Sampling Period (Figure A.1)	Cement Plant	Yes
2	*Pulverized Coal*	Ultimate Analysis (Table A.11)				Cement Plant	Yes
3	*Pulverized Coal*	Standard Cement Plant Parameters (Table A.10) [1]				Cement Plant	Yes
4	*Pulverized Coal*	Combustion Analysis (Table A.11)				Cement Plant	Yes
5	*Pulverized Coal*	Proximate Analysis (Table A.11)	2 / day	3-Day Composites	Standard Sampling Period (Figure A.1)	External Lab	No
6	*Pulverized Coal*	Ultimate Analysis (Table A.11)				External Lab	No
7	*Pulverized Coal*	Standard External Lab Parameters (Table A.12) [2]				External Lab	No
8	*Pulverized Coal*	Combustion Analysis (Table A.11)				External Lab	No

Notes:

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

[2] Moisture is not collected

Table A.2b: 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.11)	1 / burn	One Composite Sample Prepared from 8 Discrete Radial Section Samples Removed from Random Tires	During Each Burn Period [2]	External Lab	No
2	*Tires*	Ultimate Analysis (Table A.11)				External Lab	No
3	*Tires*	Standard External Lab Parameters (Table A.12) [1]				External Lab	No
4	*Tires*	Combustion Analysis (Table A.11)				External Lab	No
5	*Plastics*	Proximate Analysis. (Table A.11)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Plastics Burn Period	External Lab	No
6	*Plastics*	Ultimate Analysis (Table A.11)				External Lab	No
7	*Plastics*	Standard External Lab Parameters (Table A.12) [1]				External Lab	No
8	*Plastics*	Combustion Analysis (Table A.11)				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.2c: 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.11)	8 / day	Discrete (Every Fourth Sample Analyzed in Duplicate)	During Broiler Litter Burn Period	External Lab	No
10	*Broiler Litter*	Ultimate Analysis (Table A.11)				External Lab	No
11	*Broiler Litter*	Standard External Lab Parameters (Table A.12) [1]				External Lab	No
12	*Broiler Litter*	Combustion Analysis (Table A.11)				External Lab	No

Notes:

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

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.10) [1]	2 / day	Discrete	Standard Sampling Period (Figure A.1)	Cement Plant	Yes
2	Standard External Lab Parameters (Table A.12)	2 / day	Discrete	Standard Sampling Period (Figure A.1)	External Lab	No

Notes:

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

Table A.4: 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.10) [1]	XRF	12 / day	Discrete	Standard Sampling Period (Figure A.1)	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 (Figure A.1)	Cement Plant Specialty Lab	No
5	***Trace Element Content of Clinker:*** Standard External Lab Parameters (Table A.12)	XRF				External Lab	No

Notes:

[1] Moisture and LOI are not collected

Table A.5: 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.10)[1]	XRF	8 / day	Discrete	Standard Sampling Period (Figure A.1)	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.10)[2]	XRF	8 / day	1-Day Composites		Cement Plant	Yes
6	***Trace Element Content of Cement:*** Standard External Lab Parameters (Table A.12)	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.6: 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 (Figure A.1)	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 (Figure A.1)	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 (Figure A.1)	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 (Figure A.1)	Auburn University	No

Notes:

[1] Auburn University will conduct these tests on one three-day composite sample during each burn period

Table A.7: 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 and 365		

Notes:

[1] Test will not be conducted by the cement plant

Two standard concrete mixtures will be 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.8: 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 (Figure A.1)	Cement Plant	Yes

Table A.9: 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.10: 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.11: 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.12: 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.13: 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

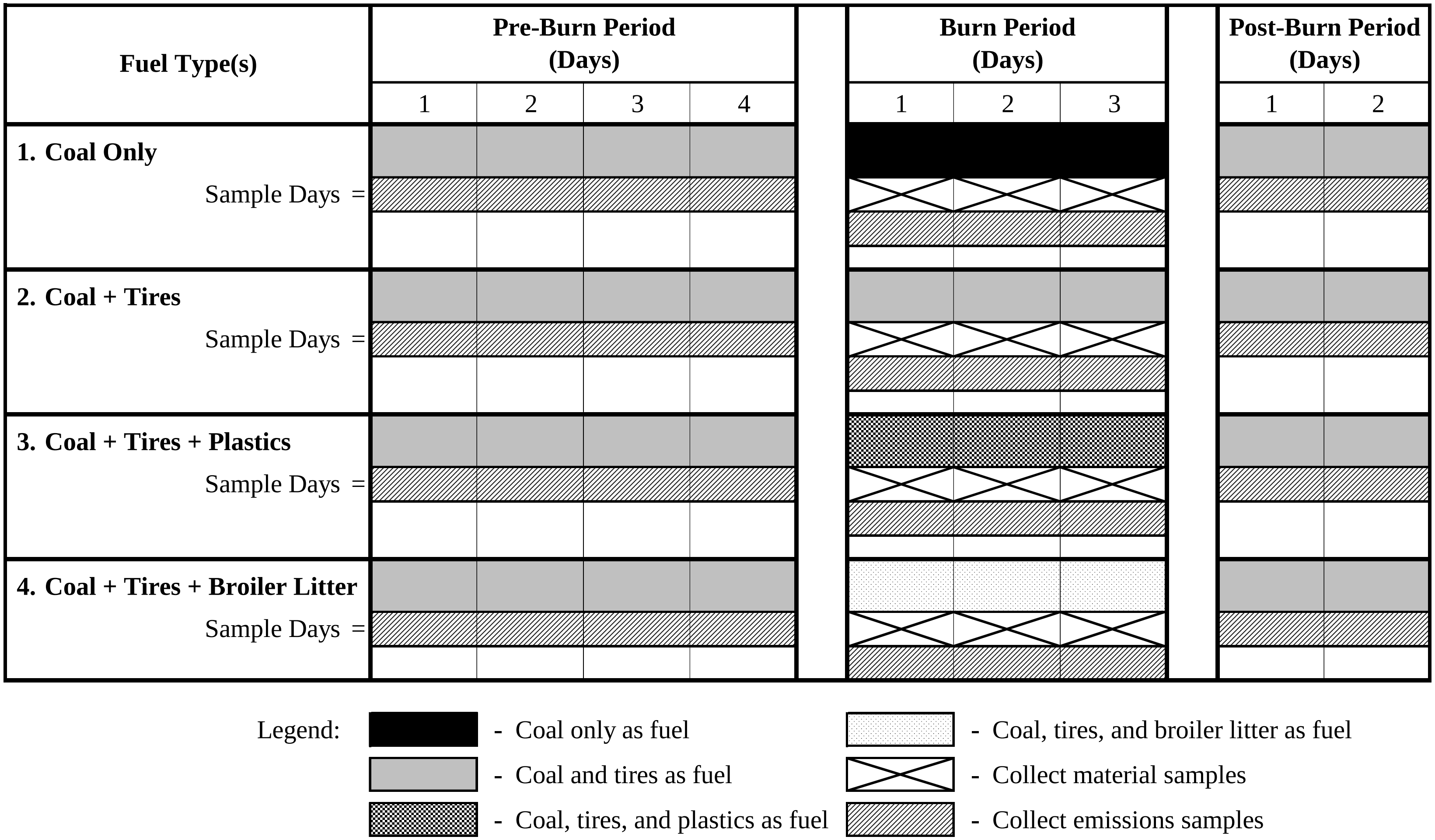

Figure A.1: Standard Sampling Period Timeline

Appendix B.1

Raw Data for Coal Only Burn Period

B.1.1. GENERAL COMMENTS

- The raw data from the Coal Only Burn Period are presented in this appendix.
- The burn period 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
NA - Not Applicable

[1] Based on Anderson-Darling Normality Test
[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	3.6
Slump (mm)	100	150	30
Unit Weight (kg/m^3)	2393.7	2373.9	2449.8
Setting Time (Min.)			
Initial Set	211	318	218
Final Set	298	405	322
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)			
7 days	-0.018	-0.019	NC
28 days	-0.029	-0.037	NC
448 days	CIP	CIP	NC
Rapid Chloride Ion Penetration Test Electrical Conductance (Coulombs)			
91 days	2651	2650	2528
365 days	CIP	CIP	CIP

Notes:

CIP - Collection in Progress
NC - Not Collected

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 Coal Plus Tires Burn Period

B.2.1. GENERAL COMMENTS

- The raw data from the Coal plus Tires Burn Period are presented in this appendix.
- The burn period 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 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.2.5: 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.2.6: 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.2.7: 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.2.8: 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.2.9: 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 10: 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 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: 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.2.13: 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.2.14: 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.2.15: 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.2.16: 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.2.17: 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.2.18: 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.2.19: 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.2.20: 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	4.00	3.20
Slump (mm)	90.0	160	30
Unit Weight (kg/m^3)	2439	2427	2448.0
Setting Time (Min)			
Initial Set	218	239	247
Final Set	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	32.9
28 days	37.1	49.7	42.3
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)			
7 days	-0.028	-0.021	NC
28 days	-0.035	-0.031	NC
448 days	CIP	CIP	NC
Rapid Chloride Ion Penetration Test Electrical Conductance (Coulombs)			
91 days	2930	2550	2660
365 days	CIP	CIP	CIP

Notes:

CIP - Collection in Progress	AUR - Auburn University Resul
NC - Not Collected	CPR - Cement Plant Result

B.2.11. EMISSIONS

Table B.2.21: 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.2.22: 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.3

Raw Data for Coal, Tires, and Plastics Burn Period

B.3.1. GENERAL COMMENTS

- The raw data from the Coal, Tires, and Plastics Burn Period are presented in this appendix.
- 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

NA - Not Applicable

[1] Based on Anderson-Darling Normality Test

[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	AUR - Auburn University Result
NC - Not Collected	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