Alternative Fuels and Their Effects on Portland Cement

by

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Abstract

The production of portland cement is a complex process involving several materials, complex systems, and temperatures on the order of 1500 °C. Non-renewable fossil fuels such as coal, petroleum coke, and natural gas have traditionally been used to generate these temperatures, but recent economic and environmental concerns have encouraged the cement industry to investigate alternative waste fuels as a viable replacement option.

Forest trimmings, railway crossties, and liquid glycerin were the alternative fuels evaluated in this study. These industrial by-products were individually employed at a full-scale, cement production facility as a partial replacement of conventional fuels. Though the alternative fuels had lower heating value as compared to coal and petroleum coke, they supplied as much as 30 percent of the energy required for cement production when combined with waste tires and plastics. Cement was successfully produced during three- to four-day burn periods while maintaining target production rates. All primary emission (NO_x, SO_2, VOC, and CO) levels remained within the allowable limits set forth by the Alabama Department of Environmental Management. Carbon monoxide emissions were reduced by 40 percent during the forest trimmings trial burn relative to the baseline condition. VOC emissions were increased for all burns utilizing alternative fuels.

Chemical analyses showed high variability in several process materials, which led to variations in cement compositions from each burn. However, many changes were of little practical significance and were primarily the result of variable plant conditions.

Cement produced from the forest trimmings burn experienced low early-age but high long-term strength development. Cement produced from the glycerin burn experienced delayed setting times and low strengths at all ages, which may have been partially due to the large percentage of P_2O_5 in the glycerin fuel. Several additional physical properties of the cement produced from the alternative fuels also showed a significant difference relative to the baseline condition. However, plant conditions were highly variable throughout the study, which made it difficult to relate these effects to the addition of alternative fuels.

Overall, the cement plant was able to utilize alternative fuels to produce high-quality, relatively consistent cement with little impact on emission levels and cement performance. Therefore, it is concluded from the study that forest trimmings, railway crossties, and liquid glycerin are all viable alternative fuel options for the production of portland cement pending consideration of local availability, associated costs, and compatibility with the local facility’s production operations.

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Chapter 1

Research Introduction

1.1 Project Background

Portland cement concrete is the most widely used construction material in the world today (Aïtcin 2000; Chen and Juenger 2009). Several structures, such as roads, bridges, dams, and buildings are typically built of concrete. The key ingredient of concrete, portland cement has been used for centuries, but advancements in the manufacturing process have led to the material it is today. The modern day production of portland cement requires a vast number of materials and complex systems working in tandem through a closely monitored process. Any alterations within the process can result in drastic changes to the final product, which may yield unacceptable performance in concreting applications.

Portland cement is manufactured by combining several raw minerals found within the earth. They are heated to temperatures approaching 1500 °C, which chemically fuse the materials together to form a product known as clinker. Clinker is then ground with sulfates to produce a fine powder known as portland cement. Upon the addition of water, portland cement forms a hydraulic binder. This binder is proportioned with fine and coarse aggregate to produce concrete. An image of a full-scale cement production facility is shown in Figure 1.1.

The intense heat required during the manufacturing process has traditionally been generated by the use of fossil fuels, such as coal, petroleum coke, and natural gas. Their

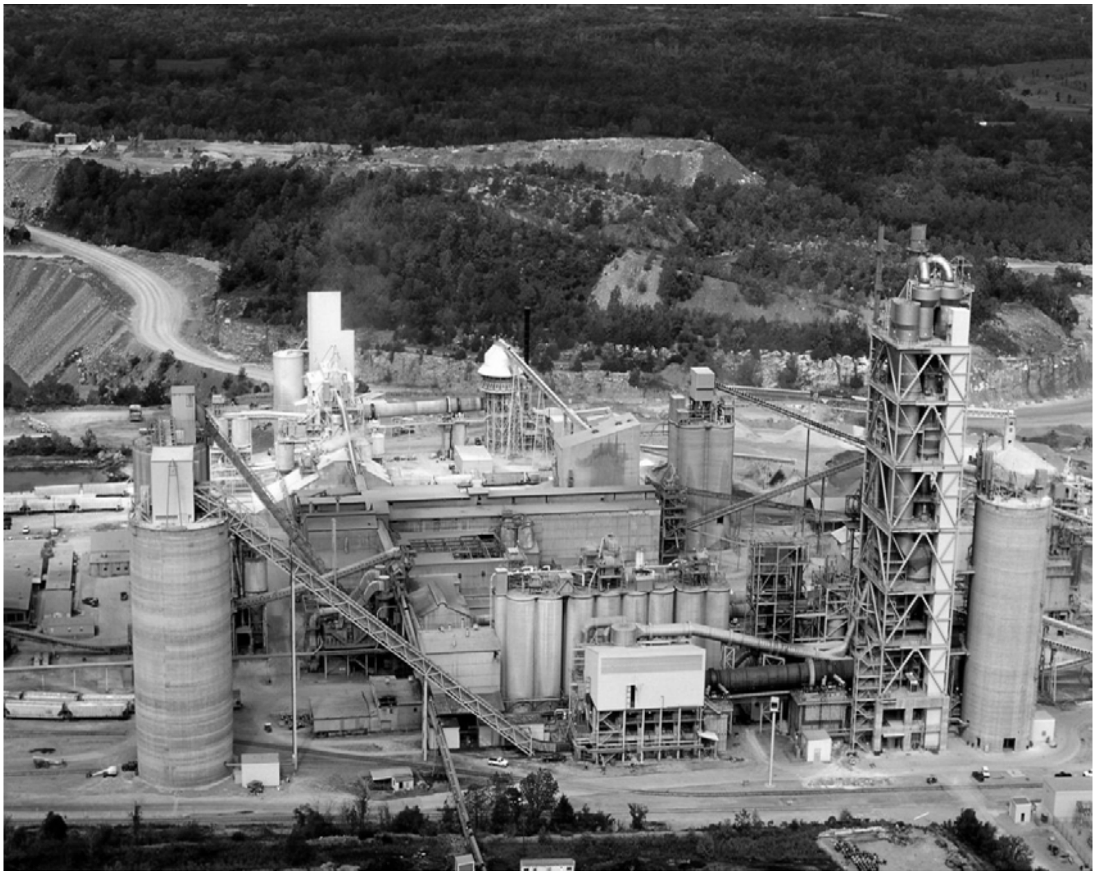


Figure 1.1: Full-scale portland cement production facility

abundance throughout the world has made these conventional fuels an ideal source of heat. However, fossil fuel resources are limited, and energy demands are continuously increasing. The cost associated with firing these fuels is also increasing, and accounts for more than 40% of production (Jackson 1998). Considering these and other concerns, fuel-dependent industries have been forced to research and implement alternative fueling options to supplement these conventional fuels.

Alternative waste fuels have been used in portland cement production since the early 1970's. Today, alternative fuels fulfill 20-70% of the world's energy demands (PCA 2009). Oil, tires, industrial and municipal solid wastes, and several other fuels have been successfully implemented in the portland cement manufacturing process. These fuels have not only lowered production costs for the industry, but several environmental benefits have resulted as well (Mokrzycki and Uliasz-Bocheńczyk 2003). Many of these wastes are typically disposed of in landfills, and are routinely incinerated to prevent congestion. Waste incineration releases toxic pollutants into the atmosphere, and incidentally, requires fossil fuels to generate the heat source. Utilizing waste products for cement product not only reduces landfill congestion, but also provides a productive means of incineration without excess pollutants disturbing the environment. Though many benefits result from the utilization of alternative fuels, it is necessary to evaluate all aspects of the operation to address any potential concerns.

Incorporating alternative waste fuels into operation often requires a facility to make appropriate modifications. Several fuels must be conditioned prior to combustion to ensure consistency and efficiency. The installation of mechanical equipment is typically necessary and can become extremely costly. In addition, facilities must be aware of a waste's continued availability. If a source is depleted or becomes difficult to obtain, the need for any or all equipment may become obsolete.

Another potential concern regarding the use alternative fuels is the performance implications on the final product. All materials input into the system will collectively determine the final chemical composition of the cement. Therefore, any alterations to the operation can result in drastic changes to cement and concrete performance.

During the combustion of raw materials and fuels, several toxic chemicals are volatized within the kiln and emitted into the atmosphere. Many emissions pose serious ecological and human health risks, so are closely regulated by governmental agencies.

The chemical and physical properties of a fuel will partially determine the amount of each emission that a facility releases. Therefore, the environmental implications of alternative fuels must also be considered before they are deemed acceptable.

Previous results have shown that the use of alternative fuels in cement production are justified both economically and ecologically (Mokrzycki and Uliasz-Bocheńczyk 2003). Regardless, each new fuel must be evaluated individually regarding all aspects of the cement manufacturing operation before it can be considered a viable fueling option. During this study, three alternative fuels were considered. The remaining sections of this chapter will introduce these fuels as well as the steps taken to evaluate their use in the industry.

1.2 Statement of Objectives

Three alternative fuels were considered during this study: forest trimmings, railway ties, and liquid glycerin. Each was evaluated individually to determine its viability as a fuel for portland cement production. The key objectives of this study are to determine the effects of alternative fuels on the following:

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

These objectives were fulfilled by three primary parties: a cement production facility, an external laboratory, and Auburn University. The first objective was primarily determined by the cement plant's operating personnel. It was important to realize any complication pertaining to the utilization of each fuel, to determine its consideration for possible use in the future.

The second objective was determined by a combined effort of the cement plant and external laboratory. It was necessary to determine the chemical characteristic of the clinker and cement to link any changes to a change in fuel. This also provides explanation of various performance related effects.

The third and fourth objectives were the primary objectives in this study. It is necessary to compare the effects of alternative fuels on the performance of the cement and concrete. The cement plant and Auburn University were involved in evaluating these objectives. Various physical properties would determine if cement produced from alternative fuels was comparable to cement produced from conventional fuels. These results were used to establish a link between the chemical properties and performance of the cement.

The final objective was to monitor the emissions produced during the production process. This was done by the cement plant with a Continuous Emissions Monitoring System (CEMS). Again, results were compared to determine the environmental implications of utilizing alternative fuels.

1.3 Research Plan

Forest trimmings, railway ties, and liquid glycerin were each co-fired with conventional fuels during this study. Cement was produced during a 3- to 4-day trial period within the *Lafarge North American Roberta cement plant*, a full-scale, cement-manufacturing facility located in Calera, AL. A thorough sampling and testing plan was developed in order to carry out the objectives listed above. This plan included five distinct collection and testing periods referred to as burns. Each burn was unique in the fuels utilized. Much effort was made to maintain consistency in all other aspects of the operation.

Forest trimmings were utilized as the alterative fuel during the first burn, referred to as the 'FT burn'. Coal, petroleum coke (coke), waste tires, and waste plastics were also co-fired during the process. Waste tires and plastics are typically referred to as alternative fuels. However, they are used during normal plant operation at this particular facility, and will therefore be considered conventional fuels for the purposes of this study. This 3-day trial burn took place in January of 2009. A second burn was conducted in March of 2009 to serve as a baseline for relating the effects from the FT burn. This 3-day burn was referred to as the 'B-CCTP burn', implying a baseline burn (B), in which coal (C), coke (C), tires (T), and plastics (P) were the fuels utilized. Aside from the fueling scenario, all other aspects were consistent during these two burns. The intentions were to isolate the alternative fuel as the only variable, thus providing an explanation for any changes noticed throughout the cement production process.

A second baseline burn was conducted in July of 2009 during a 3-day period. This baseline burn (B) utilized coal (C), coke (C), and waste plastics (P) during production, so was titled the 'B-CCP burn'. This burn was conducted to serve as a baseline for the fourth and fifth burns. Railway crossties were co-fired with coal, coke, and waste plastics during the fourth burn. This 4-day trial burn, titled the 'RR burn' was also conducted in July of 2009. Liquid glycerin was the final alternative fuel investigated during this study.

This 3-day trial burn, referred to as the ‘GL burn’ took place in November of 2009. Again, all aspects of the operation remained consistent during the B-CCP, RR, and GL burns to isolate the alternative fuels as the only variable, with intentions of correlating any effects to their use.

Modifications were made at the cement plant to accommodate each of the fuels burned. During each burn, samples were collected by the cement plant staff, and chemical compositions were determined on all materials other than the fuels. Various physical properties were also determined by the cement plant. The final job of the cement plant was to monitor the primary emission components during each burn.

Testing specimens were prepared from each sample and shipped to an external laboratory for additional testing. Chemical compositions were determined for all materials. In addition, proximate, ultimate, and combustion analyses were conducted on all fuels.

All samples were collected from the cement plant and shipped to the external laboratory by Auburn University. Several physical properties were determined by Auburn University. In addition, researchers at Auburn University mixed concrete and performed associated tests. Results from all parties were collected and analyzed by Auburn University in order to present them 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 importance of alternative fuels, as well as potential concerns regarding their use in portland cement production. The alternative fuels are introduced, in addition to the primary objectives of this work. Chapter 1 also provides a brief explanation of the steps taken to satisfy the objectives of this project.

A review of previous literature related to the subjects covered throughout this study is provided in Chapter 2. A detailed explanation of each stage of the production process is presented, as well as the materials involved. The importance of alternative fuels, and the potential concerns associated with their involvement are then discussed. Background information of the alternative fuels utilized during this project is presented in addition to previous studies that have evaluated their effects. The chemistry involved during the production process will be discussed, in addition to how the chemical composition of portland cement relates to its performance. Finally, a discussion of the hydration process of portland cement and how chemical admixtures are used to alter this process will be presented.

The experimental plan previously mentioned is detailed in Chapter 3. The procedures involved in sampling all materials will be explained. In addition, all tests and testing procedures will be discussed as they were carried out to satisfy the objectives of this project.

A summary and analysis of all results gathered throughout the study are presented in Chapter 4. Data are first presented, then analyzed and discussed as they pertain to the objectives of this study. Comparisons are made in relation to the results discussed in Chapter 2. Conclusions are drawn based on supporting evidence, and the performance of each alternative fuel is evaluated.

The final chapter of this document contains summaries, conclusions, and recommendations related to this study. The importance of this study is provided as well as the methods chosen to carry out its objectives. The objectives are restated, and conclusions are drawn as they pertain to each. In the case that definitive conclusions could not be reached, reasoning is provided. Finally, recommendations on several aspects related to this study are presented with the intent of improving future testing to better satisfy the objectives.

A set of appendices follows Chapter 5. Each appendix, A through E, provides the raw data collected during each burn, which was summarized in Chapter 4.

Chapter 2

Literature Review

2.1 Introduction

Portland cement is the most widely used and manufactured construction material in the world (Aïtcin 2000; Chen and Juenger 2009). In 2007, 2.7 billion tons of cement was produced globally (Schneider 2009). The U.S. is home to 113 cement plants throughout 36 states, and ranks third in cement production behind China and India (PCA 2010). Figure 2.1 shows U.S. cement consumption from 1996 through 2008. Note that domestic production consumes the largest portion of portland cement. Though overall consumption shows a steady decline from 2005 through 2008, domestic production continues to increase.

When mixed with water, portland cement undergoes a chemical reaction to form a hydraulic binder. This binder is mixed with fine and coarse aggregates such as sand and gravel, to form a solid mass known as concrete. Though the basic concepts of concrete remain the same, modifications to portland cement manufacturing have been made to perfect this material into what it is today.

Science and industry have investigated various alterations in cement mixtures throughout the ages, but the universal product used today is generally accredited to an English mason by the name of Joseph Aspin. In 1824, Aspin was the first to prescribe a formula and obtain a patent on his cement mixture that he named portland cement due to

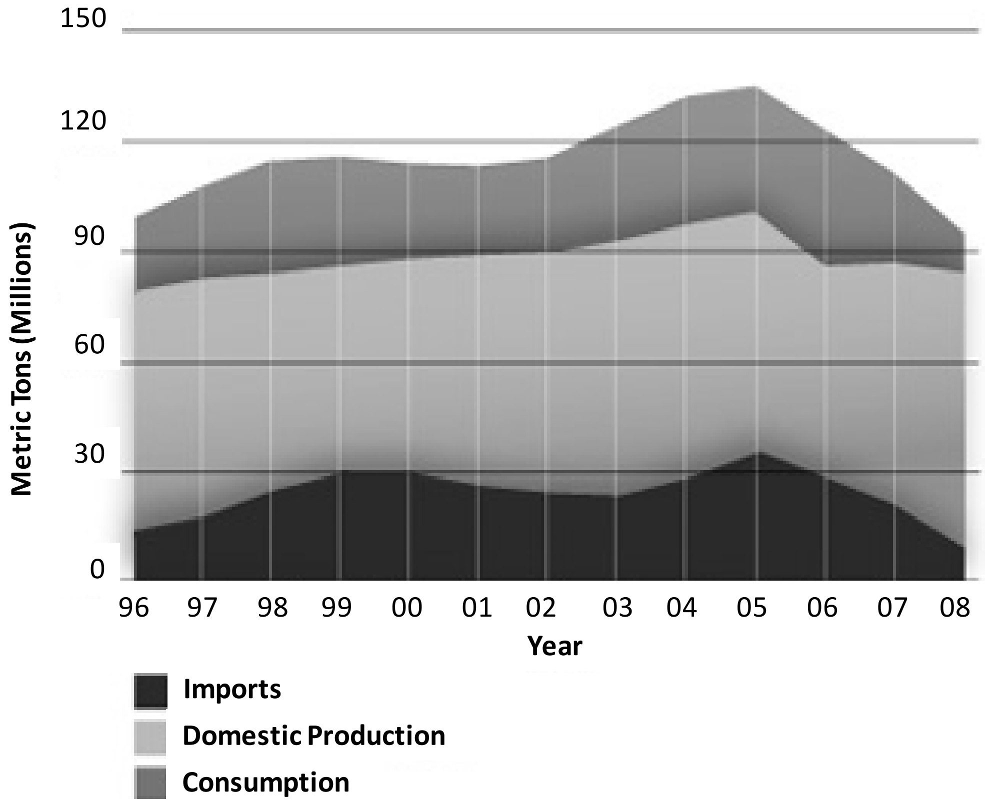


Figure 2.1: U.S. cement consumption by year (PCA 2009)

its resemblance in color to the natural limestone quarried on the Isle of Portland in the English Channel (Kosmatka et al. 2002). Though dramatic improvements have been made through its production, the general principle remains the same, and Aspin's portland cement has become the colloquial reference for hydraulic cements used all over the world.

The production of portland cement is an extremely energy-intensive process traditionally carried out by consuming large quantities of fossil fuels, such as coal, petroleum coke, and natural gas. These fuels can account for more than 40% of the total production costs (Jackson 1998). As energy demands increase, concerns of fossil fuel depletion, environmental and health hazards, and rising production costs also develop. This has forced the cement industry to explore other options to resolve these issues.

In the early 1970's, cement plants began utilizing industrial byproducts as an alternative to traditional fuels in the cement production process, and their popularity has continually grown since (Karstensen 2008). These waste-derived fuels consist of oils, tires, industrial and municipal solid waste, among many others. Today, alternative fuels fulfill 20-70% of the energy demands for many facilities around the world, and results have shown their use in cement production to be justified both economically and ecologically (Mokrzycki and Uliasz-Bocheńczyk 2003; PCA 2009). Alternative fuels have proven to preserve fossil fuel resources, reduce the volume of wastes that must be landfilled or incinerated, and decrease the global greenhouse effect (Greco et al. 2004). However, there is still much debate regarding sustainability, product quality, and other potential concerns that encourage further investigation of alternative fuels as a sufficient replacement option and their effects on the industry.

The remainder of this chapter focuses on the effects of alternative or waste-derived fuels as they pertain to the cement and concrete industries. A review of past literature provides background information as well as former research results to help understand the implications of utilizing alternative fuel for the production of portland cement.

2.2 Portland Cement Production

The portland cement manufacturing process is generally continuous for 330 days out of the year (Cahn 1998). From 1900 to 1998, global cement production rose from about 10 million tons to over 1.6 billion tons annually (Aïtcin 2000). Assuming one cubic meter of concrete requires about 250 kg of cement, this amounts to 2.5 tons of concrete per person per year (Aïtcin 2000). Only fresh water is consumed in larger amounts. This tremendous growth has brought much attention to the industry's efficiency, as well as its effects on society.

The manufacturing of today's portland cement is performed by combining predetermined quantities of raw materials containing calcium, silica, alumina, and iron (Miller 2004; PCA 2009). These materials are crushed, blended, and heated to temperatures upwards of 1500 °C, which chemically fuse the materials into a single product known as clinker. Once cooled, the clinker is ground with sulfates to form the fine powder that is portland cement. The quantity and chemical composition of these raw materials are dependent on outside industrial conditions and geologic availability, and thus vary among facilities. Facilities will either employ a wet or dry process through production, but the dry-process is generally more efficient, so it is more commonly used (Manias 2004). Whichever process is selected, the finished cement is packaged, stored, and sold to consumers.

Figure 2.2 depicts a schematic of a typical cement production facility exhibiting a dry process. Appropriate quantities of raw materials enter the roller mill where they are crushed to desirable sizes and blended together. The raw mix is then fed through a series of preheaters to partially calcinate the blend. The calcination process is detailed in later sections. The raw mix then makes its way through the rotary kiln where high temperatures chemically fuse the materials together. The molten mass is then rapidly cooled to form clinker. The clinker is then sent to the grinding mill where it is finely

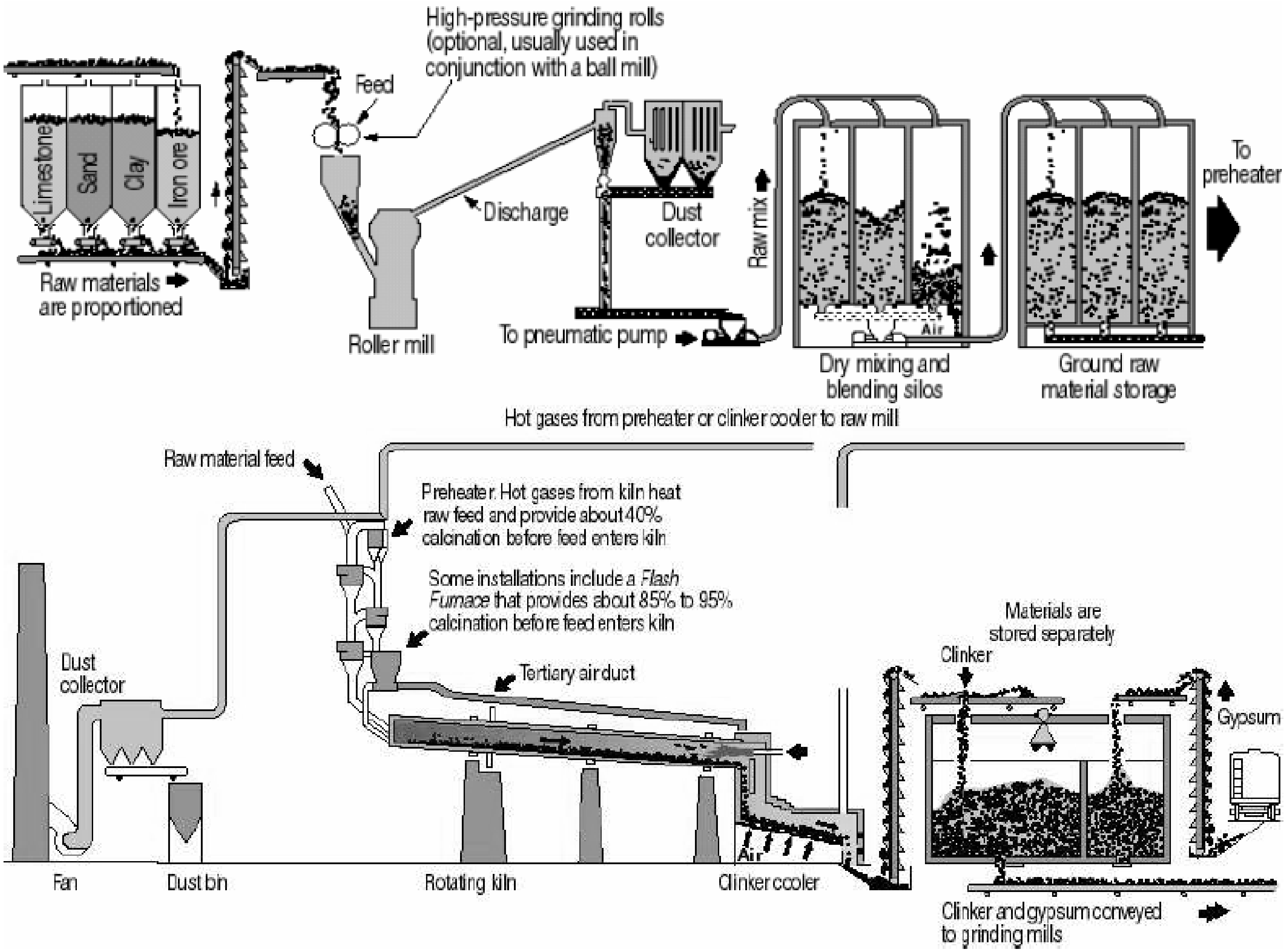


Figure 2.2: Layout of a typical dry-process portland cement production facility (Kosmatka et al. 2002)

ground with sulfate to form portland cement. Dust is collected throughout the process and is recycled back into the system.

This entire manufacturing process is highly energy intensive. With several methods of achieving each step in production, a facility's energy consumption will highly depend on the methods chosen. On average, 3.2 to 6.3 GJ of thermal energy is needed to produce 1 ton of portland cement (Hendrik and Padovani 2003). Table 2.1 shows various methods of achieving each stage of production and the approximate energies associated with each. Notice that the only direct use of fuel occurs in the clinker kiln. This is where the raw materials are heated by the fuels to produce clinker. It can be seen that a wet-process kiln consumes the most fuel energy. This is because additional energy is required to dry the materials. A large portion of electricity is also needed to rotate the kiln, but the grinding stage of production consumes the most electricity. Although cement manufacturing is an energy-intensive process, development of new production methods have improved energy efficiency by more than 37% since 1972 (PCA 2010).

2.2.1 Raw Materials

The principal raw materials in cement manufacturing are calcareous materials (containing calcium carbonates), siliceous materials (containing silica), and argillaceous materials (containing alumina and silica) (Bhatty 2004). Some of the most common sources of raw materials are listed in Table 2.2. About 1.7 tons of raw materials are needed to produce 1 ton of cement (Hendrik and Padovani 2003). These materials are needed to provide the clinker with appropriate quantities of four primary oxides: calcium oxide or lime (CaO = 65%), silica oxide (SiO_2 = 22%), alumina oxide (Al_2O_3 = 6%), and iron oxide (Fe_2O_3 = 3%) (Hendrik and Padovani 2003). The remaining 4% is a mixture of

Table 2.1: Approximate energy consumption in cement making processes and process types (Adapted from Worrell et al. 2001)

Process Step	**Fuel use** (GJ/t of cement)	**Electricity use** (kWh/t of cement)	**Primary energy** (GJ/t of cement)
Crushing			
Jaw crusher	-	0.3 - 1.4	0.02
Gyratory crusher	-	0.3 - 0.7	0.02
Roller crusher	-	0.4 - 0.5	0.02
Hammer crusher	-	1.5 - 1.6	0.03
Impact crusher	-	0.4 - 1.0	0.02
Raw meal grinding			
Ball mill	-	22	0.39
Vertical mill	-	16	0.28
Hybrid systems	-	18 - 20	0.32 - 0.35
Roller Press-			
Integral	-	12	0.21
Pregrinding	-	18	0.32
Clinker kiln			
Wet	5.9 - 7.0	25	6.2 - 7.3
Lepol	3.6	30	3.9
Long dry	4.2	25	4.5
Short dry-			
Suspension preheating	3.3 - 3.4	22	3.6 - 3.7
Preheater & precalciner	2.9 - 3.2	26	3.2 - 3.5
Shaft	3.7 - 6.6	NA	3.7 - 6.6
Finishing grinding			
Ball mill	-	55	0.60
Ball mill/separator	-	47	0.51
Roller press/ball mill/separator	-	41	0.45
Roller press/separator/ ball mill	-	39	0.43
Roller press/ separator	-	28	0.31

Table 2.2: Sources of raw materials (Kosmatka 2002)

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

*Most common sources

magnesium, potassium, sodium, sulfur, and other oxides. Though these elements within the raw materials are generally present as various minerals rather than oxides, they will be oxidized through calcination during the pyro-process in the kiln. The blend of raw materials will determine the composition, and thus, the quality of the clinker, so their preparation is essential in producing acceptable cement (Miller 2004).

According to Miller (2004), two main factors must be considered when developing a raw material mixture. First, the mix must be able to achieve acceptable free lime content in the clinker within reasonable heating temperatures. This must also be done in a timely manner so to not significantly slow production rates. Second, the composition of the raw blend must be carefully controlled to ensure a consistent cement behavior necessary for design and construction applications. Prearranged limits are set on several of the cement's primary compounds, which further dictate the blend of raw materials (Miller 2004).

Calcium oxide (CaO), also known as lime, will represent approximately two-thirds of the clinker by mass (Miller 2004). Limestone is the most typical source of calcium and is therefore the predominant raw material used during the cement making process. Many cement manufacturing facilities are located near limestone quarries to cut down on transportation costs (EPA 1995). Once transported from the quarry, the chemical composition of the limestone is first analyzed to determine the CaO content and other compositional factors that will dictate the selection and quantities of remaining raw materials. These factors are heavily dependent on the source of the limestone (Miller 2004). Some of these factors can be viewed in Table 2.3 with four typical limestone sources arranged into categories according to their CaO content.

The pure limestone source shown in Table 2.3 can be seen to contain the largest CaO content. A lesser amount of this type limestone would be needed in a raw blend, but an increased quantity of other materials would be required. A "Cement Rock" type limestone contains the lowest CaO content, but the abundance of other compounds may allow it to represent nearly all of the raw mixture. A limestone that falls into the intermediate or siliceous categories will most likely represent about 80% of the raw mixture (Miller 2004).

In the presence of high temperatures, limestone is decomposed into its mineral constituents through the removal of carbon dioxide (CO_2) gas in a process known as calcination. CO_2 is a greenhouse gas that is extremely harmful to the environment, and much effort is made to reduce quantities released into the atmosphere. Cement plants often add a fraction of the required limestone during the grinding stage of production (Hendrik et al. 2003). This results in less limestone being calcinated, thus less CO_2

Table 2.3: Typical limestone compositions, mass % (Miller 2004)

Elements, as oxides	**Pure Limestone**	**Intermediate Limestone**	**Siliceous Limestone**	**Cement Rock**
SiO_2	0.25	6.83	9.05	13.19
Al_2O_3	0.15	2.67	1.03	4.87
Fe_2O_3	0.13	1.14	0.42	1.75
CaO	55.31	48.83	48.83	41.96
MgO	0.40	0.70	0.85	2.00
SO_3	0.02	0.58	0.52	0.83
Na_2O	0.03	0.09	0.11	0.36
K_2O	0.04	0.30	0.35	0.78
Loss on Ignition	43.66	38.85	38.76	34.20
Silica Ratio, S/R	0.89	1.78	6.24	1.99

emissions released. However, this increases the CO_2 content of the cement, which typically alters primary compounds in the cement.

Once the aforementioned factors of the limestone (or calcareous materials) have been determined, the argillaceous materials may be selected. The primary purpose of these materials is to achieve a particular silica ratio, the ratio of the silica content to the sum of the alumina and iron contents (Miller 2004). A higher silica ratio will allow the raw mixture to be easily burned and visa versa (Young and Miller 2004). An optimum silica ratio depends on the diameter and length of the kiln, but values of around 2.62 will typically provide sufficient burnability and quality of the raw mixture throughout the clinkering process (Miller 2004; Young and Miller 2004).

In few circumstances, the calcareous and argillaceous materials are sufficient in providing the stoichiometric needs to form the desired clinker phase compositions (Miller

2004). Typically, corrective materials are necessary to adjust the C_3S (alite) or lime saturation factor, silica ratio, and the C_3A or A/F ratio (Miller 2004). These corrective materials, such as sand, iron ore, and bauxite, often contribute only one element in order to “fine tune” the raw blend.

Once the type and quantity of raw materials have been chosen, they must be crushed and blended prior to entering the kiln. The primary goal of the crushing stage is to achieve the targeted particle size distribution, average particle size, and specific surface with least amount of energy consumption (Chatterjee 2004). By crushing each material to its appropriate fineness, kiln temperatures may be minimized to lower energy consumption. Material characteristics such as crushability and burnability are dependent on the material’s source, so the degree of comminution of each material will vary among facilities. Once the appropriate fineness has been obtained, the raw materials are mixed together to form a homogenized mixture with the predetermined chemical composition (Chatterjee 2004). This mixture of raw materials is often referred to as kiln feed.

2.2.2 Pyro-processing

The next stage of the cement manufacturing operation is known as pyro-processing. Upon the introduction of heat, the kiln feed will undergo a series of endothermic and exothermic reactions that will essentially fuse the raw blend into a single product known as clinker. The raw material composition and mineralogy, as well as the time and temperature profile of these materials in the kiln will determine the chemical makeup of the clinker which, in turn, determines the performance of the cement being produced (Manias 2004).

There are two main processes that a facility may employ: wet and dry. During the wet process, the materials are suspended in water during clinkering. However, this requires more energy to remove the moisture prior to combustion. Therefore, keeping the raw materials dry throughout clinkering by use of the dry process is generally more efficient, so it is more commonly used (Manias 2004). There are actually several configurations of both the wet and dry processes, but all processes fall into one of these two categories.

In 1990, several cement plants in Poland decided to modernize their facilities from a wet to a dry method of clinker production. As a result, Mokrzycki et al. (2003) reports the average heat energy used during clinker production decreased from 5720 kJ/kg in 1990, to 4100 kJ/kg in 2000. Therefore, a wet process requires more than 28% additional energy to produce clinker than a dry process. This decrease in energy means a reduction in production costs, which is why most facilities find it advantageous to employ a dry process for clinker production.

As mentioned earlier, the raw materials provide the clinker with its four primary oxides: calcium oxide or lime (CaO), silica oxide (SiO_2), alumina oxide (Al_2O_3), and iron oxide (Fe_2O_3) (Hendrik and Padovani 2003). These elements are generally present as various minerals within the kiln feed but become oxides through a process known as calcination. Calcination is a thermal process which removes a portion of the carbon within the raw materials as carbon dioxide (CO_2), essentially increasing their presence as oxides (Jackson 1998). This oxidation process prepares the raw materials for reaction, and makes the clinkerization process much more fuel and cost efficient (Young and Miller 2004). Many facilities utilizing a dry process often benefit from installing a preheater or precalciner which heats the kiln feed to approximately 850 °C, partially calcining the blend prior to entering the kiln. The kiln feed is fed into the preheater or precalciner through a series of hoppers, each being fed from the one above with an increase in temperature as the blend approaches the kiln. The number of hoppers or stages will determine the systems heat efficiency as well as the emission quantities of dioxin and furans (D/F) and nitrogen oxides (NO_x) (Bech and Mishulovich 2004). These emissions are discussed in greater detail in Section 2.4. Some precalciners are fit with their own source of heat while others exploit excess heat from the kiln (Bech and Mishulovich 2004). Precalciners containing their own combustion chamber can nearly complete the calcination process before the raw feed even enters the kiln (Karstensen 2004). Benefits of installing a precalciner include reducing energy consumption, reducing NO_x emissions, and reducing kiln length requirements thus increasing production (Worrell et al. 2001).

Regardless of the process or design configuration, the kiln feed passes through the kiln at a rate determined by the slope and rotational speed of the kiln (Kosmatka et al. 2002). With the heat source at the lower end or exiting end of the kiln, the kiln feed enters at the free end and increases in temperature as it approaches the lower end. During its travel through the kiln, the raw blend undergoes a sequence of extremely complicated chemical reactions through which the following material transformation takes place, in order from the free end (Manias 2004):

1. Evaporating of 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

During this process, the calcium and other components of the raw mix, combine to form the four major clinker phases; namely: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminoferrite (C_4AF) which are commonly referred to as the Bogue compounds (Tennis and Kosmatka 2004). These compounds are often called alite (C_3S), belite (C_2S), aluminate (C_3A), and ferrite (C_4AF), respectively. These compounds are composed of microscopic crystals whose size and quantity are determined by the rate at which the raw feed completes the temperature profile listed above (Glasser 2004). Typically, longer heating times yield larger crystals which make grinding of the clinker difficult and can adversely affect the strength characteristics of the cement produced from this clinker (Young and Miller 2004). The Bogue compounds typically account for over 90% of the cement by mass, with the remainder being a calcium sulfate source that is added during the grinding stage later explained (Tennis and Kosmatka 2004). Alite and belite constitute about 75% of the clinker weight and are the primary contributors to cement performance (Hendrik and Padovani 2003). Alite contributes to short-term strength gain of concrete and is typically desired in larger concentrations than belite, which is responsible for long-term gains (Ylmén et al. 2009). These compounds are discussed in greater detail in Section 2.6.

Gases are generated from fuel combustion and exothermic reactions that occur during clinkering. These gases provide the kiln feed with the energy necessary to undergo this clinkering process. The excess gas released from the kiln entry contributes to the precalcining process discussed previously. Gas and raw material temperatures can be seen in Figure 2.3 as they progress through a typical rotary kiln. The retention times of both the gases and material are also shown.

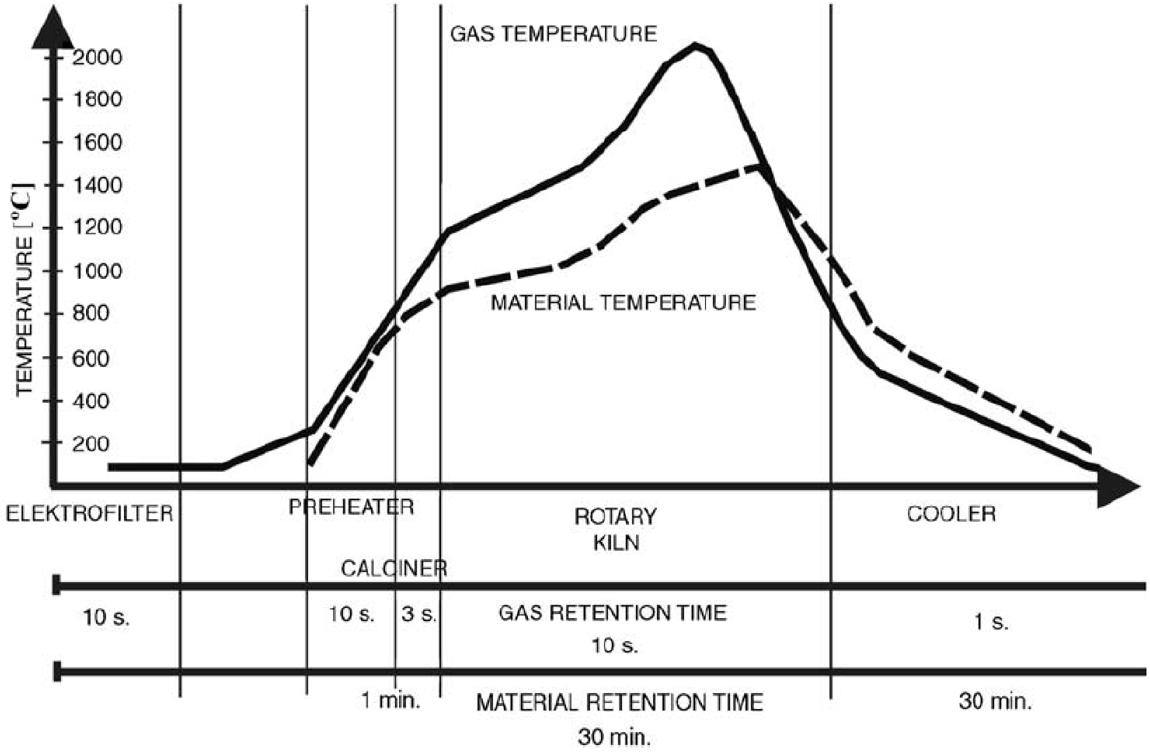


Figure 2.3: Gas and material temperature inside a typical cement kiln (Mokrzycki and Uliasz-Bocheńczyk 2003)

2.2.3 Clinker Cooling

Just as the rate of heating effects many properties of the clinker, the rate of cooling is of equal importance. It is during this cooling process where the final chemical composition and quality of the clinker is determined. According to Jackson (1998), if the clinker is cooled too slowly, the C_3A exhibits a tendency to crystallize in a form which is more reactive and may lead to setting problems or insufficient strength-gaining properties. Coolers are also necessary to enable handling of the clinker, which is essential during the remaining stages of manufacturing.

Another purpose of the clinker cooler is to recoup a portion of the excess heat from the clinker and recycle it back into the kiln system to preheat the combustion air (Manias 2004). The rate of cooling as well as the amount of heat that can be recycled is dependent on the type of cooler utilized.

Clinker coolers have undergone significant development over the past years, and there is a wide selection to accommodate any facility's needs. Some of them include planetary, rotary, shaft, grate, and traveling grate coolers. The grate cooler, shown in Figure 2.4, is by far the most commonly used clinker cooler in North America today (Steuch 2004). The clinker enters the cooler in the liquid phase and solidifies as cool air is rushed either through grates from beneath or through ducts connected to the assembly. The clinker travels through the cooler by way of reciprocating grates until exiting into a crusher, which breaks up large clumps to ensure efficient cooling.

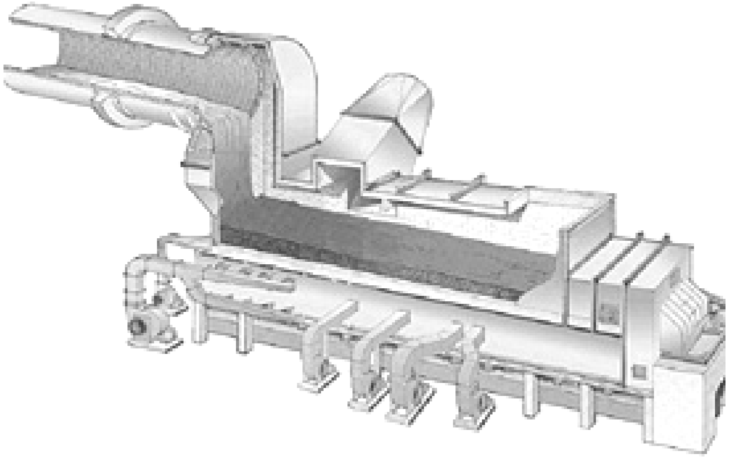


Figure 2.4: Grate cooler for cooling clinker
(Network Solutions 2010)

2.2.4 Grinding and Finishing

Once the clinker is cooled, it is typically stored as it awaits the final stage of production: grinding and finishing. The clinker is generally clumped in masses as large as several centimeters in diameter. It is necessary to reduce the size of these clumps to a uniform fineness that will ensure a consistent chemistry throughout. This is obtained by use of a finish mill system. Incidentally, the finishing mill consumes the most electric power of all other stages during the manufacturing process (Strohman 2004).

There are several methods used for grinding the clinker. The most common method used today is the ball mill, but others include a roller mill, roll press, or some combination of these (Strohman 2004). The ball mill is composed of a cylindrical tube which rotates about a horizontal axis. There are at least two chambers separated by slotted diaphragms. As the clinker enters the rotating mill, large steel grinding balls impact the clinker clusters until they are small enough to enter the second chamber where smaller steel balls grind the clinker to an optimum fineness. The size of the balls depends on the hardness of the clinker, but typical diameters range from 13 to 100 millimeters (Jackson 1998). The final, desired gradation of the clinker is dependent on several parameters which dictate how the finished product will perform.

Ground clinker alone will in fact react with water to exhibit cementing properties, but this reaction occurs quickly, rendering it insufficient as a construction material. To counter this rapid hardening, calcium sulfate, typically gypsum is blended with the clinker during the grinding process. The sulfate, in amounts normally between 3 and 8 percent, retards the hydration of the tricalcium aluminate (C_3A) and optimizes the strength-giving properties of the calcium silicates (C_3S and C_2S) (Jackson 1998).

Once the calcium sulfate is ground with the clinker, the finished product is portland cement. Samples are taken frequently and analyzed for quality assurance purposes. Several parameters previously mentioned, such as the Bogue compounds, silica ratio, and free lime content are examined to ensure the cement will possess its intended properties. The addition of secondary materials may be necessary if the cement’s chemistry is not adequate. Once the manufacturer is satisfied with the cement, it is then ready to be packaged, sold, and shipped to consumers.

2.3 Alternative Fuels and Portland Cement Production

As previously mentioned, the clinkering process of portland cement production requires the raw materials be heated to temperatures upwards of 1500 °C within the kiln system. Maintaining this high output of thermal energy requires the consumption of immense quantities of fuel. Since fuel can account for more than 40% of the overall production costs, it is apparent that a facility’s selection and use of a fuel source will be of upmost concern (Jackson 1998). This selection will not only play a major role in a facility's efficiency, but also impact the environment and quality of the finished product. For nearly four decades, industrial waste has been used in the cement industry as an alternative to traditional fuels. Today, these alternative fuels fulfill 20-70% of the energy demands for many facilities around the world (PCA 2009). While there are many benefits to these waste-derived fuels, several potential concerns must be addressed to explore their use as a sufficient replacement option. It should be noted that the terms 'alternative fuels' and 'waste fuels' may be used interchangeably as they both refer to fuels which substitute traditional fuels.

Coal, petroleum coke, and natural gas are the traditional fossil fuels used in portland cement production, but coal is the most predominant. Incidentally, coal is used to meet nearly 25% of the world's energy demands (Greco et al. 2004). Its worldwide abundance, sustainability, and high energy output per unit mass have made coal a versatile and popular source of fuel (Greco et al. 2004). Its popularity has also made it a costly one. Costs vary depending on several factors but have nearly tripled in the past decade, and prices are continuing to rise (Shafiee and Topal 2010). As much as 150 kg of coal is required to produce 1 ton of cement (Ayala 2006). With some facilities producing 10,000 tons of cement per day, more than 1,600 tons of coal may be consumed by a facility per day (Manias 2004).

Though all fossil fuels are abundant throughout most of the world, they are not renewable sources of energy. With the increasing energy demand and conservation of our limited fossil fuel reserves in mind, fuel-dependent industries have been forced to research and implement alternative options to supplement conventional fuels (Mokrzycki and Uliasz-Bocheńczyk 2003).

A fuel, as defined by Greco et al. (2004), is any substance that gives rise to a chemical reaction of oxidation that is exothermic, self-sustainable, and very rapid when introduced to a sufficient amount of heat and air. Many substances may be classified as fuels according to this definition. More specifically, a fuel used to produce portland cement must meet additional criteria. According to Lechtenberg (2009), the four basic principles for the use of alternative fuels in cement production are as follows:

1. The chemical quality of the fuel has to meet regulatory standards to ensure environmental protection.
2. The calorific value of the fuel must be stable enough to allow a controlled supply of energy to the kiln to produce a homogeneous clinker.
3. The physical form of the fuel has to permit easy handling for transportation and a controlled flow into the kiln.
4. The fuels must not introduce any chemical compounds into the clinker that might be deleterious to the stability of the production process or the performance of the product.

The use of alternative fuels in cement production began in the early 1970's and quickly became popular through the world (Karstensen 2004). Several alternative fuels have been utilized in the past. Figure 2.5 shows many of these fuels categorized by their origin. Cost, availability, and environmental implications will collectively dictate a facility's alternative fuel selection.

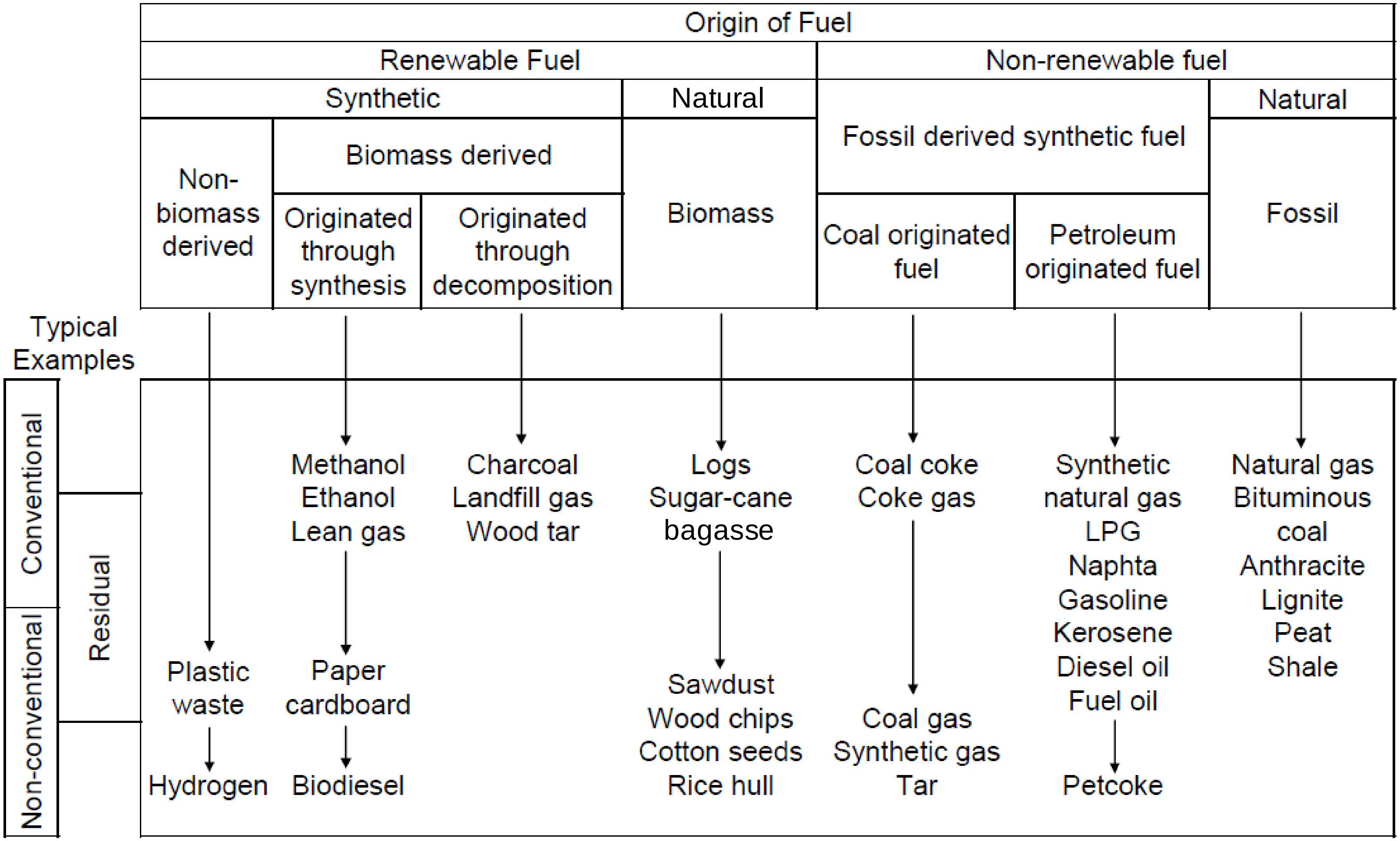


Figure 2.5: Various fuels and their origin (adapted from Greco et al. 2004)

Perhaps it is best to divide alternative fuels into three basic groups: solid, liquid, and gaseous fuels (Mokrzycki et al. 2003). Each group requires unique facility modifications to facilitate preliminary conditioning, dosing methods, and fuel firing equipment. Table 2.4 shows examples of fuels from each group utilized in the past.

Alternative fuels generally serve as only a partial replacement to traditional fuels. The rate of replacement depends on the physical and chemical properties of the alternative fuel being used, but could feasibly represent 80% or even 100% of the fuels required for production (Skjeggerud 2009; Willitsch and Sturm 2002). However, there are replacement limits that exist for alternative fuels, and they vary from country to country. For instance, Spain is limited to 15% replacement, while Switzerland has no limit (Conesa et al. 2007).

Alternative fuels have been used in many countries for decades, and results have shown their use in cement production to be justified both economically and ecologically (Mokrzycki and Uliasz-Bochenczyk 2003). Each facility must weigh the expected advantages against the preliminary costs and potential adversities associated with firing these fuels.

Table 2.4: Typical waste fired in cement kilns (adapted from 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 waste	Farming residues (rice husk, peanut husk, etc.)
	Municipal waste
	Plastic shavings
	Residual sludge from pulp and paper production
	Rubber shavings
	Sawdust and woodchips
	Sewage treatment plant sludge
	Tannery waste
	Tars and bitumens
	Used catalyst
	Used tires

2.3.1 Alternative Fuels in Cement Kilns

When burning alternative fuels, it is most important to ensure sufficient temperature, oxygen, retention time, and proper mixing conditions (Karstensen 2008). Few modifications must be made to rotary kiln systems to permit proper combustion of alternative fuels. Their existing environment renders sufficient conditions due to the following characteristics (Greco et al. 2004; Karstensen 2004):

1. Temperature and retention time exceeds the environmental agency’s minimum required for waste incineration,

2. Alkaline environment absorbs a majority of the acidic gases that result from oxidation of sulfur and chlorine,
3. Most metals are trapped by dedusting systems and are recycled back into the system as cement kiln dust, and
4. Most metallic oxides and other non-combustible compounds within the waste will not compromise the quality of the clinker.

The pyro-process is considered the heart of the cement-making process, and the kiln's design and functionality will largely dictate cement performance. Each kiln responds differently to the introduction of alternative fuels, and these facilities may require additional quality assurance measures to ensure total efficiency of combustion and total parameter control (Greco et al. 2004). Undesirable chemical elements in the fuels or raw materials can lead to the formation of kiln rings or subsequent build-ups and may cause kiln shut-downs (Manias 2004). Some of these elements include alkalies, sulfates, and chlorides, and their effects are discussed more in Section 2.5. For this reason, it is essential that the kiln inputs are properly conditioned and their chemical compositions are known (Greco et al. 2004). Monitoring emission output is also necessary to ensure compliance with environmental regulations. If these issues are not within the tolerance of acceptability, any and all economic gains may be considered void.

2.3.2 Advantages of Alternative Fuels

There are several advantages for cement manufacturers to employ alternative fuels as a substitute for traditional fuels. Four notable gains may occur simultaneously (Greco et al. 2004):

1. Preservation of fossil fuel reserves,
2. Reduction of cement production costs,
3. Reduction in the volume of waste disposed of through landfill and incineration, and
4. Decrease in the global greenhouse effect.

The traditional fuels mentioned are commonly known as fossil fuels, and their supply is limited and their resources non-renewable. At current consumption rates, global depletion of coal is expected in the next 122 years (WCI 2010). Though these fuels are fired for applications other than cement production, partial replacement or co-processing of various alternative fuels could significantly reduce this industry's footprint on fossil fuel consumption.

Although coal is the most predominant fossil fuel used in cement production, natural gas and oil are also traditionally used. As production demands rise, so do the costs of these fuels. Figure 2.6 shows yearly trends of fossil fuel prices from 1950 to 2008. According to Schneider (2009), 2.7 billion tons of cement was produced globally in 2007. In two years since, cement production costs have nearly doubled due to an increase in energy and electricity costs. Though the cost of waste varies, the price for each unit of energy released while firing a waste fuel is far below that of a traditional fuel (Greco et al. 2004). An increase in alternative fuel replacement may not be enough to counter this trend, but it certainly contributes in reducing production costs.

The global population is ever increasing, meaning more consumers to produce more waste. As the congestion of landfills brings rise to environmental and aesthetic concern, incineration has served as an obvious means of waste disposal. Incinerators not only contribute to environmental hazards by emitting dioxins, furans, and other toxins into the atmosphere, they actually require fossil fuel ignition to source the heat, contributing further to these hazards. Recent modifications to incinerators have reduced their emission output, but not to a level that the high-temperature kiln processes can provide (Cordwell 2006). Most incinerators are also inefficient as they do not utilize the heat generated. Using these wastes as alternative fuels for cement production not only provide a productive means of incineration, they eliminate emissions from the fossil fuels they replace. Incidentally, it is cheaper to modify a kiln to accommodate waste combustion than to build a new incineration plant (Mokrzycki and Uliasz-Bocheńczyk 2003).

During cement production, carbon dioxide (CO_2) gases are emitted through both the decarbonization of limestone in the calcination process and through the combustion of carbon-based fuels. Due to both CO_2 sources, and considering those from electricity consumed during production, the cement industry is a major contributor to CO_2 emissions (Worrell et al. 2001). This greenhouse gas, among others, essentially traps radiation within the earth's atmosphere. While several of these greenhouse gases occur naturally, others are primarily manmade, and their abundance is undesirable as they are thought to be the source of climate change, formerly known as global warming (EPA 2010). The amount of CO_2 emitted during the clinkerization process is highly dependent on the fuel being used. According to Worrell et al. (2001), by utilizing waste fuels as a substitute to fossil fuels, CO_2 emissions may be reduced by 0.1 to 0.5 kg per kg of cement produced. Assuming alternative or waste derived fuels will inevitably undergo incineration, it only seems logical to utilize their energy towards cement production or other practical

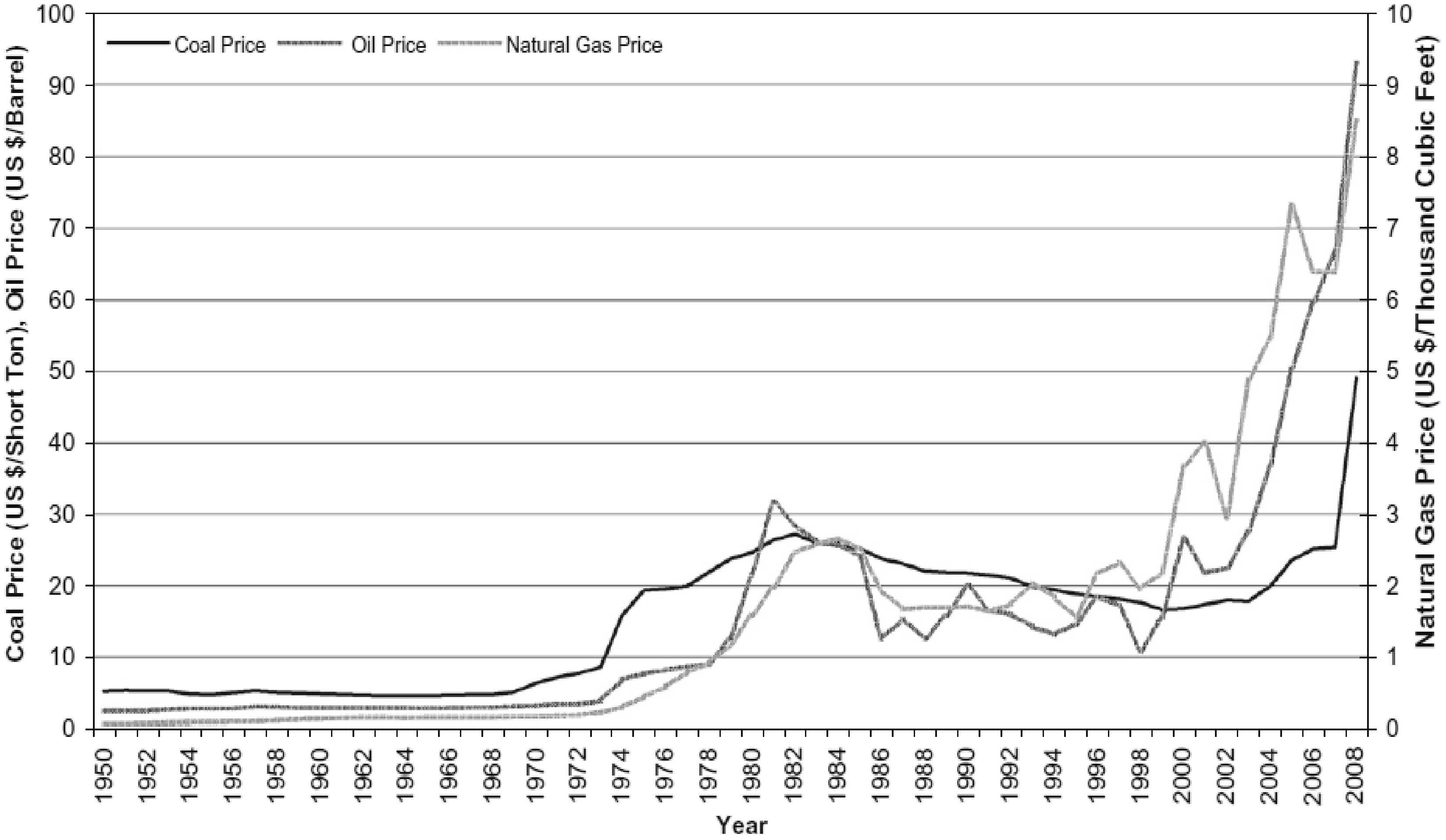


Figure 2.6: Average yearly trend of fossil fuel prices (Shafiee and Topal 2010)

purposes. Otherwise, their contribution to CO_2 and other greenhouse gases will serve no benefit other than freeing landfill space for additional waste disposal.

Japan generates approximately 480 million tons of waste each year; 400 million tons from industrial waste, and the remainder from general, consumer waste (Taniguchi 2001). By utilizing 25 million tons annually as alternative fuels and raw materials, Japan's cement industry has seen a 14% reduction in carbon dioxide emissions. Taniguchi (2001) also reports that every ton of cement produced represents an equivalent of more than 188 kg of waste diverted from landfills.

Another, indirect advantage of utilizing waste-derived fuels is their potential to replace portions of various raw materials. For instance, the steel belts found within used tires provide a source of iron, reducing the amount of indigenous iron needed in kiln feed. (Pipilikaki et al. 2005).

2.3.3 Disadvantages of Alternative Fuels

In order for a facility to make a decision regarding whether or not to implement alternative fuels into their production process, many factors must be considered. It is pertinent to weigh the potential benefits against the predicted drawbacks in order to approach an educated solution. Ultimately, the economical aspect will prevail as the deciding factor (Kääntee et al. 2004). Consequently, the product quality must not be sacrificed. Alterations in any stage of the cement production process may alter the chemical make-up, thus the performance of the cement. In an industry such as portland cement production, sales depend on the buyer's confidence in a consistent and quality product, so their reputation may not be compromised.

The alternative fuel selection of most cement plants is governed by chance, based on the local availability of wastes (Lechtenberg 2009). Most waste materials require some degree of processing or conditioning prior to kiln entry, such as shredding to obtain workability and consistency, removal of detrimental contents, and/or drying to an optimum moisture content to increase its overall energy output. This requires the installation of mechanical equipment which can become extremely cost-intensive. The degree of conditioning is dependent on the material, and will ultimately determine the maximum replacement rate of the fuel. In addition, there is no way of knowing the duration of a particular waste's availability. If a source is depleted or becomes unavailable, the need for any or all equipment may become obsolete.

Feeding and metering systems must also be installed to convey the fuels to the kiln and monitor their rates of entry. According to Lechtenberg (2009), a number of these systems are available on the market for capital costs ranging from \$600,000 to over \$6,000,000 (USD) depending on their capacity and precision. Precise metering and constant feeding is critical, yet difficult to maintain, as some material mixtures are often bulky with densities of 200 kg/m^3 (Willitsch and Sturm 2002). Another cost associated with such equipment is the operating personnel. Training and monitoring are necessary to ensure continuous conveyance and proper functionality of equipment.

Another potential constraint on utilizing alternative fuels is their chemical composition, which can affect many stages of the operation. The chlorine present in many fuels reacts with sodium and potassium to form NaCl and KCl. In the presence of excess chlorine, these reactions tend to form blockages in the cyclone pipes which may result in kiln shutdown (Lechtenberg 2009). Since production rates reflect profits, any kiln shutdown is a costly one. Most elements either exit the kiln through the stack emissions or are incorporated into the clinker, both of which are of great concern. Any undesirable compounds deposited into the cement may adversely affect product performance. Emissions are regulated by governmental agencies and must be closely monitored.

2.3.4 Alternative Fuel Options

As seen in Figure 2.5 and Table 2.4, there are numerous possibilities for alternative fuels, and options are available within reach of nearly any geographic location. Several factors are used to validate a waste's potential as a sufficient alternative fuel. According to Mokrzycki and Uliasz-Bocheńczyk (2003), the following properties should be examined prior to burning alternative fuels:

1. Physical state of fuel (solid, liquid, gaseous),
2. Content of circulating elements (Na, K, Cl, S),
3. Toxicity (organic compounds, heavy metals),
4. Composition and content of ash,
5. Volatile content,
6. Calorific, or heating value,
7. Physical properties (particle size, density, homogeneity), and
8. Moisture content.

The variety of elements incorporated within a fuel will collectively determine most of these factors, and consequently, the maximum rate of replacement. Therefore, it is essential to know the chemical composition of a fuel prior to it being used in production (Kääntee et al. 2004). It is common for waste fuels to be blended prior to their combustion, so they exhibit an optimum composition and the process can proceed as efficiently as possible (Mokrzycki and Uliasz-Bocheńczyk 2003). Each cement manufacturing facility or group of facilities has a unique set of standards which determine a fuel's acceptability, or how much of that fuel is permitted. For the Lafarge Cement Polska group in Poland, an alternative fuel must meet the following criteria (Al-Salem et al. 2010; Mokrzycki et al. 2003):

- Heating value > 6019 BTU/lb (weekly average),
- Chlorine content < 0.2%,
- Sulfur content < 2.5%,
- Polychlorinated Biphenyls (PCBs) content < 50 ppm, and
- Heavy metals content < 2500 ppm, out of which:
    - Hg < 10 ppm
    - Cd + Tl + Hg < 100 ppm

One valuable property among fuels is the energy output upon combustion. This property is known as the heating value or calorific value, and is commonly expressed in units of either the British Thermal Unit (*BTU*) or the calorie (*cal*), respectively. This value is partially dependent on the condition of the fuels prior to being heated. A material with a high moisture content will release less net energy as compared to one in a dry state. This is because some energy is required to remove the moisture prior to combustion. Since most materials contain some amount of moisture, the natural or moist condition is often referred to as the "As-Received (AR)" condition. Table 2.5 shows common alternative fuels used in Europe and their approximate heating values expressed in both BTU and cal for as-received and dry conditions.

Above all, cost is the predominant factor that determines whether a facility will implement alternative fuels into production. This is unfortunate due to the potential benefits that alternative fuels can provide. Even if certain alternative fuel choices are known to benefit the environment or enhance cement quality, they will not be implemented unless the net cost is reduced and the availability is sustainable.

Table 2.5: Approximate energy values of typical alternative fuels
(adapted from Lechtenberg 2009)

Alternative Fuel	**Approximate Energy Value**	
	As-Received, BTU/lb (kcal/kg)	**Dry,** BTU/lb (kcal/kg)
Wood	2700 (1500)	6300 (3500)
Cattle dung	1800 (1000)	6700 (3700)
Bagasse	4000 (2200)	7900 (4400)
Wheat and rice straw	4300 (2400)	4500 (2500)
Cane trash, rice husk, leaves, and vegetable waste	5400 (3000)	5400 (3000)
Coconut husks, dry grass and crop residues	6300 (3500)	6300 (3500)
Groundnut shells	7200 (4000)	7200 (4000)
Coffee and oil palm husks	7600 (4200)	7600 (4200)
Cotton husk	7900 (4400)	7900 (4400)
Refused Derived Fuels (RDF) fro municipal solid wastes	7200 (4000)	8100 (4500)

The alternative fuels utilized in this study were tire-derived fuels, plastic solid waste, forest trimmings, railway crossties, and liquid glycerin. A brief description of their past use as alternative fuels will be discussed in the following sections. Their results, as obtained through this study, can be found in Chapter 4. For a comprehensive discussion of other alternative fuels utilized in previous studies, much literature is available, but will not be discussed further.

2.3.4.1 Tire-Derived Fuels (TDF)

Each year, approximately 1 billion tires are generated worldwide, and about 5 million tons are disposed of as waste (Singh et al. 2009). For years, these quantities have presented serious environmental threats, and as a result, many laws have forbid tire disposal in landfills (Singh et al. 2009). Alternative technologies have recently been developed to utilize waste tires for industrial applications, such as power generation, asphaltic mixtures, and of course, cement production.

Tire-Derived Fuels (TDF) have been used as alternative fuels in cement manufacturing for decades. Like coal and pet-coke, TDF contain hydrocarbons (hydrogen and carbon), but TDF can often provide 25% more energy and emit less pollutants (PCA 2010). Table 2.6 provides several parameters of comparison among TDF, coal, and pet-coke. Note the high volatile matter content of TDF relative to the other fuels. Volatile matter, consisting of alkalies, chlorides, and others can lead to the formation of kiln rings and blockages, and will typically limit the maximum replacement of TDF (Pipilikaki et al. 2005). Although Table 2.6 does not show this trend, TDF typically have a lower sulfur content than coal; 1.3% compared to 1.5% by weight on average (Pipilikaki et al. 2005). The Lower Heating Value (LHV) shown in the table refers to the energy at which the water from the combustion products is in a gaseous phase. As a replacement to coal, every 1 ton of TDF can reduce coal usage by 1.25 tons (Pipilikaki et al. 2005). Currently, PCA (2010) estimates about 40 cement plants in 23 U.S. states use TDF as an alternative to traditional fuels. TDF may be used as whole pieces or shredded, but using whole tires is typically more economical (Cahn 1998). Conesa (2007) estimates the overall cost of utilizing 20% shredded tires is equivalent to using petroleum coke alone.

Table 2.6: Comparison analysis of pet-coke, coal, and TDF
(adapted from Pipilikaki et al. 2005)

Analysis	Pet-coke	Coal	TDF
Volatile Matter (%)	13.0	36.8	72.0
Ash (%)	7.1	14	7.0
Carbon (%)	82.6	80.6	84
Hydrogen (%)	3.4	4.6	5.0
Sulfur (%)	4.9	0.7	2.0
Nitrogen (%)	1.75	0.30	1.75
Lower Heating Value (BTU/lb)	14,000	11,800	13,500

The major drawbacks to TDF that may hinder their use in certain facilities are the high zinc and carbon content they possess (Pipilikaki et al. 2005). A large amount of zinc can adversely affect the cement during curing and lead to possible setting problems. This limits the TDF replacement rate to about 20-30% (Cahn 1998; Pipilikaki et al. 2005). Zinc will be discussed in greater detail in Section 2.5.6. In addition, the carbon content of TDF is typically higher than that of coal or pet-coke which can lead to higher carbon emissions.

In 1987, shredded car tires were used as an alternative fuel, replacing coal in the precalciner cement kiln at the Norcem Brevik Plant (Syverud et al. 1994). Emissions were recorded throughout the process, and CO, NO_2, and SO_2 showed a decreased of up to 50%, 40%, and 25%, respectively. Emissions of dioxins, furans, and heavy metals were not significantly changed during the process. Sulfur buildups were encountered in the kiln, which was quite costly, but this did not seem to affect the clinker quality.

2.3.4.2 Plastic Solid Waste (PSW) as Fuel

Over the past seventy years, the plastics industry has seen tremendous growth, and each year, production levels exceed the last (Al-Salem et al. 2010). In 2007, global production was estimated at 260 million tons, more than three times the production in 1990. Siddique et al. (2008) estimates that nearly 85% of these plastics are discarded as Plastic Solid Waste (PSW) in open spaces and landfills. Approximately 8% are incinerated and only 7% are recycled. Synthetic polymers represent the majority of these plastics, with low-density polyethylene (LDPE) being the most predominant (Siddique et al. 2008). PSW can be generated from several applications, such as automotive, industrial, and healthcare, but the majority comes from used packaging.

Several recovery methods have been developed to divert PSW from landfills and recycle them for productive applications (Al-Salem et al. 2010). These methods fall into one of four major categories: re-extrusion, mechanical, chemical, and energy recovery. One application within the energy recovery category is, of course, cement production.

Prior to combustion, PSW must be conditioned (Willitsch and Sturm 2002). It is often advantageous for plastics to be transported by a conveyor belt towards the burners, and then into the burners by compressed air. For this reason, shredding of PSW is necessary. A maximum edge length of 10 *mm* has been proven as the best particle size for adequate feeding into primary firing systems (Willitsch and Sturm 2002). Processing also involves removal of glass, metal, and mineral impurities to ensure both personnel and equipment protection, as well as to control emissions and cement quality. With the diverse availability of PSW, it is common to create a "blend" of several sources to achieve an optimum feed composition (Greco et al. 2004). Of course, it is first necessary to analyze the composition of each source. Table 2.7 shows a comparison of compositional data between a typical coal and polyethylene sample.

Table 2.7: Comparison analysis of coal and polyethylene (adapted from Al-Salem et al. 2010)

Analysis (wt. %)	Coal	Polyethylene
Volatile Matter	33.32	99.87
Ash	7.40	0.13
Fixed Carbon	59.28	–
Carbon	76.76	84.83
Hydrogen	4.70	14.08
Oxygen	8.65	–
Density (kg/m^3)	1300	920
Heating Value (BTU/lb)	11,700	19,300

The high volatile matter shown in the table may adversely affect kiln functionality. This was also the case with TDF and may limit the replacement rate of PSW in production. According to Willitsch and Sturm (2002), the main impurities found within PSW are chlorine, cadmium, lead, and zinc. These impurities and their effects will be detailed in Section 2.5. It should be noted that the heating value shown in the table is for pure polyethylene and is not indicative of a typical PSW blend. An average household

PSW mixture would be closer to 14,000 BTU/lb (Al-Salem et al. 2010). According to Willitsch and Sturm (2002), the PSW used in Europe may reach a maximum of around 16,000 BTU/lb.

A known inferiority of PSW is the high chlorine content which most likely attributes to the high volatile matter percentage shown in Table 2.7. Chlorine can adversely affect the process by corroding the kiln lining, clogging ducts and fans, and may also reduce the quality of the clinker. Therefore, according to Kikuchi et al. (2008), it may be beneficial to control the chlorine content of PSW feed by grouping them according to their chlorine content during the conditioning process discussed earlier. One major advantage seen from utilizing PSW is a reduction in shipping costs (Siddique et al. 2008). Compared to coal, PSW has a lower density, which reduces fuel consumption during transportation. Additionally, obvious environmental benefits are involved in diverting PSW from incineration, as discussed earlier.

Due to the recent implementation of PSW as alternative fuels in the cement industry, little research is available through literature to discuss its effects on cement production and quality. An earlier phase of this study compared the effects of two fuel scenarios; each was utilized at a full-scale cement plant over a 3-day trial period. One utilized only coal, while the other used a blend of coal, waste tires, and plastics. According to Swart (2007), the trial involving the waste plastics resulted in a reduction in CO, but an increase in NO_x, SO_2, and VOC when compared to the coal-only trial. Also, the waste plastics trial yielded compressive strengths slightly higher than coal-only trial. However, these effects not known to be a direct result of a change in fuel as conditions at the cement plant were thought to be inconsistent throughout the study.

2.3.4.3 Biomass as Fuel

According to Abbas et al. (1996), biomass fuels (bio-fuels) may be defined as renewable, combustible materials that originate from living, or recently living organisms, such as from the growing of plants or the raising of animals. Examples of bio-fuels include wood or wood wastes, rice hulls, cotton gin trash, coffee grounds, manure, and sewage sludge. One distinguishing aspect of bio-fuels is they are typically produced over a large-spread area and must be gathered up and concentrated in a single location prior to use as a fuel. This differs from a conventional fuel, such as coal, that is produced in a single location (i.e. a coal mine). Several adversities may hinder the use of bio-fuels as a permanent replacement option to coal, or may limit its replacement potential in cement production. According to Abbas et al. (1996), the following are typical traits of a bio-fuel:

1. Has high compositional variability,
2. Has a lower calorific value as compared to coal – about one-fifth by volume, or one-half by mass,
3. Contains many of the same potential pollutants (sulfur, nitrogen, chlorine, etc.) found in coal, though contents are typically lower,
4. Production is typically seasonal, implying expensive storage costs to provide a constant supply, and
5. Occupies agricultural land for energy instead of food production, presenting a moral dilemma.

The bio-fuels utilized in this study include forest trimmings and railroad ties. Little research exists on the use of these specific fuels in cement production. Due to similarities in origin, the two will be collectively referred to as bio-fuel, or more specifically, wood waste.

As with PSW, wood waste must be shredded prior to combustion. The cost associated with shredding wood waste is one of the major drawbacks to its use as a sustainable fuel (Esteban and Carrasco 2006). To reduce this cost, it is necessary to evaluate and optimize the particle size reduction process. A maximum particle size of 6 mm is typically an optimum size for adequate feeding and proper combustion characteristics (Willitsch and Sturm 2002). Since biomass is organic material, storage must be suitable to avoid excess smell, bacterial growth, and heat development. In addition, wood products retain moisture, so they must be covered or adequately stored to evade climate effects. High moisture contents can reduce the net heating value and lead to inefficient combustion.

Forest trimmings are a byproduct of the timber industry. Timber is grown worldwide for numerous applications, including sawn lumber for construction and paper production. Once cut, the timber is transported to a saw mill where the raw lumber is stripped of bark, limbs, and other unwanted material. This waste material may be used fuel for power generation and cement production. Certain species of trees are predominant in different regions of the world. Thus, the assortment of forest trimmings will depend on the region from which the trees were gathered. As mentioned earlier, forest-trimming production may be seasonal and could increase costs associated with storing a constant supply. However, this renewable source of energy is replenished each year, implying a sustainable and affordable alternative fuel.

Railway crossties, also known as sleepers or beams, are typically made of creosote-soaked hardwood timber, which is laid beneath the rails to support the track. There are currently more than 2.5 billion wooden crossties installed throughout the world, and most are deteriorating and becoming less capable of resisting the loads for which they were designed (Manalo et al. 2010). The Australian railway industry spends nearly 35% of their annual budget on railway maintenance (Manalo et al. 2010). For this reason, the industry is currently researching the use of reinforced concrete, steel, and composite materials to replace these wooden crossties, and many countries have already begun this process. Once deconstructed, the crossties are shredded and may be used as fuel for power generation or cement production. Environmental concerns exist regarding the large amount of creosote, or other chemical preservatives impregnated into the wood. According the European environmentalists, many crossties exceed the creosote critical limit, and should be treated as hazardous waste upon disposal (Manalo et al. 2010).

Table 2.8 shows results from an ultimate and proximate analysis performed on railway crossties, electric transmission line (ETL) poles, and untreated pinewood. ETL poles and railway ties are thought to resemble one another since they are both chemically treated timber. Forest trimming composition depends on the type of trees from which they were produced. The pinewood shown in the table would be indicative of forest trimmings in regions where pine trees are commonly grown.

Table 2.8: Comparison analysis of railway crossties, ETL poles, and pinewood (adapted from Zhurinsh et al. 2005)

Analysis (% wt.)	Railway Crossties	ETL Poles	Pinewood
Volatile Matter	76.2	76.9	77.8
Fixed Carbon	23.1	21.3	22.0
Ash	0.65	1.79	0.20
Carbon	47.51	46.39	46.79
Hydrogen	6.07	5.88	5.99
Oxygen	46.42	47.73	47.22
Sulfur	0.059	0.024	0.015

During an earlier phase of this study, a fuel blend of coal, waste tires, and woodchips, was evaluated at a full-scale cement plant during a 3-day trial period. Results were compared to a control condition utilizing only coal and waste tires. According to Akkapeddi (2008), the trial containing woodchips showed an increase in NO_x and VOC emissions but a reduction in SO_2 and CO when compared to the control trial. In addition, cement produced from both trials were used to mix concrete. Compressive strengths were higher in the woodchips trial as compared to the control condition. Though plant conditions may have been inconsistent through the study, the change in fuel was thought to be of some contribution to these effects.

2.3.4.4 Liquid Glycerin as Fuel

Glycerin, also known as glycerol, is a by-product of biodiesel production. Pure glycerin is a colorless, odorless, viscous liquid with a sweet taste and may be found in several products such as foods, beverages, pharmaceuticals, cosmetics, and detergents

(Rahmat et al. 2010). Due to the lack of literature specifying glycerin as an alternative fuel in cement production, biodiesel fuels will be used to represent this group of fuels.

Biodiesel is made by reacting animal or vegetable oils with alcohol in a process known as transesterification, resulting in a combustion product closely related to petroleum diesel fuel, but with less particulates emitted (Astbury 2008; Gerpen 2005). In the United States, biodiesel is commonly made from soybean oil. Table 2.9 shows properties of two diesel fuels (No. 1 and No. 2) and a bio-fuel made from soybean oil (B100). The gross heat of combustion is determined from the as-received material condition which accounts for the moisture present. The net combustion value is equivalent to the Lower Heating Value (LHV) which refers to the energy in which water from the combustion products is in a gaseous phase.

Figure 2.7 shows a schematic for the process flow of a typical biodiesel production technique. Once the glycerol leaves the separator, it is of little value and must be treated as a hazardous waste due to the excess methanol (Gerpen 2005). For this reason, acid is added to remove the free fatty acids and methanol is removed, resulting in a crude glycerol that is approximately 85% refined. At this point, the glycerol is typically sold to a refiner who can bring the purity up to about 99.7% using a vacuum distillation or ion exchange process (Gerpen 2005).

Table 2.9: Physical and chemical properties of No. 1, No. 2 diesel fuels, and B100 (adapted from Canakci 2007)

Test Property	No. 1 Diesel Fuel	No. 2 Diesel Fuel	B100
Carbon (% mass)	86.83	86.7	77.1
Hydrogen (% mass)	12.72	12.71	11.81
Oxygen (% mass)	-	-	10.97
Sulfur (% mass)	0.045	0.041	<0.005
Gross heat of combustion (BTU/lb)	19,705	19,500	17,150
Net heat of combustion (BTU/lb)	18,550	18,350	16,050
Kinematic viscosity (mm^2/s, @ 40 °C)	1.76	2.83	4.27
Total glycerin (%)	-	-	0.028
Free glycerin (%)	-	-	0.00

In the past ten years, the production of biodiesel has drastically increased, primarily in automotive application, due to its many health and environmental benefits over petroleum diesel (Rahmat et al. 2010). Though biodiesel fuels cannot completely replace petroleum-based fuels, they offer the following benefits (Gerpen 2005):

1. Provide a market for excess production of vegetable oils and animal fats,
2. Decrease U.S. dependency on foreign petroleum fuels,
3. Provide a renewable source of fuel with 78% reduction in CO_2 emissions,
4. Decrease CO, unburned hydrocarbon, and particulate emissions (slight increase in NO_x emissions), and
5. When 1-2% is used as a fuel additive, it can convert fuels with poor properties into those with acceptable quality.

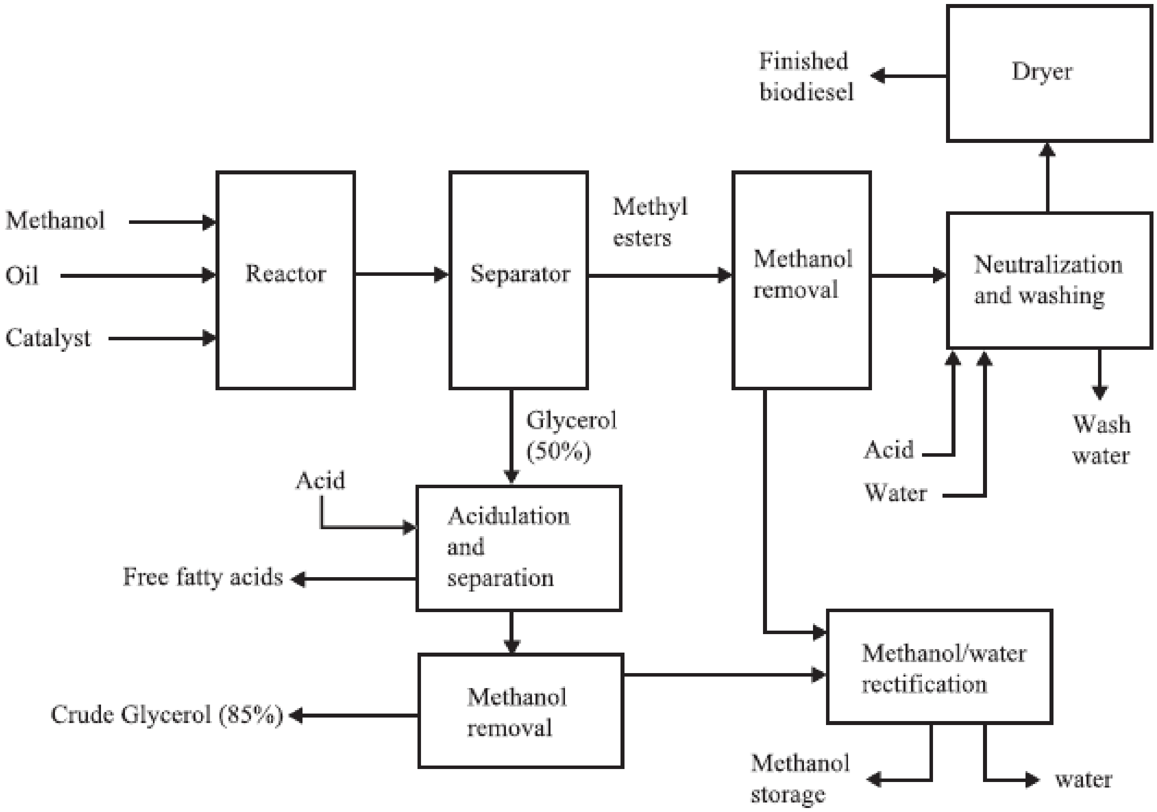


Figure 2.7: Process flow schematic for biodiesel production (Gerpen 2005)

As with all liquid fuels, delivery, storage, pumping, heating, flow control, and injection must be considered and will vary depending on their physical and chemical properties (Greco et al. 2004). Note the relatively high kinematic viscosity of B100 in Table 2.9. A liquid fuel such as this may require an external source of heat to reduce viscosity and facilitate pumping, so they are typically stored in cylindrical, steel tanks with thermal insulation on their external surface. During injection, liquid fuels must undergo nebulization, a process which converts a constant stream into a cloud of individual droplets (Greco et al. 2004). Mechanical nebulization, nebulization with auxiliary fluid, and nebulization by emulsion are the common methods, and the selection will depend on the specific characteristics of the fuel.

2.4 Emissions

During the pyro-processing stage of production, high temperatures and the combustion of raw materials and fuels within the kiln create and release toxic gases into the atmosphere. A production facility producing 1 million tons of cement will generate approximately 1.5 billion cubic meters of gases in the process (Jackson 1998). These atmospheric pollutants consists primarily of carbon dioxide (CO_2), nitrogen and sulfur oxides (NO_x and SO_x), and lesser amounts of carbon monoxide (CO), dioxins and furans (D/F), metals, particulate matter (PM), volatile organic compounds (VOCs), and other minor pollutants (Greer et al. 2004; Schuhmacher et al. 2004). There are three primary sources of emissions: fuels, raw materials, and reactions from the high temperatures of the pyro-process itself (Greer et al. 2004; Karstensen 2008). Therefore, the chemical composition of the raw materials, physical and chemical properties of the fuel, and kiln conditions and configuration will collectively determine the emission's makeup and quantity for each facility.

Toxic emissions pose serious environmental and human health risks as they can be directly transmitted to humans through air inhalation and indirectly through soils, vegetation, drinking water, etc. (Conesa et al. 2007; Schuhmacher et al. 2004). These risks have prompted several governmental agencies to instigate limits and regulations on each emission, requiring all facilities to undergo rigorous monitoring and controlling measures. These limits vary depending on location, kiln configuration, fuels utilized, and many other factors.

The physical and chemical properties of fuel will partially determine the quantity and state of each emission that a facility releases. Since oxygen is required during the combustion process, an imbalance of fuel and oxygen can result in incomplete combustion which leads to emissions (Karstensen 2008).

Air Pollution Control Devices (APCD) are used to clean or capture kiln exhaust prior to their release into the atmosphere. Electrostatic precipitators (ESP) are the most common APCD, and consist of vertical plates spaced evenly with a series of wires woven between them (Jackson 1998). Exhaust is directed through the ESP, and the wires ionize the dust particles with a negative charge, drawing them to the positively charged plates. These particles can then be gathered and disposed of.

It is apparent that alternative fuels can be justified from an economical standpoint, but environmental implications must be considered, in addition to their impact on cement quality before they can be deemed acceptable. Several studies have even reported reductions in emissions due to the implementation of alternative fuels. The following sections will discuss these as well as all primary emission components as they pertain to the scope of this project.

2.4.1 Carbon Emissions

Carbon monoxide (CO) and carbon dioxide (CO_2) are the two carbon-based emissions with which the cement industry is most concerned. Carbon dioxide is the result of both carbon-based fuel combustion and calcination, or decarbonization of limestone and other calcareous raw materials (Chen and Juenger 2009; Greer et al. 2004). Each source contributes approximately half to the overall CO_2 emitted. Carbon monoxide is a product of incomplete combustion of carbon molecules due to either insufficient amounts of oxygen during combustion, or from rapid cooling before the carbon has completed its oxidation process (Greer et al. 2004). Therefore, if conditions lead to incomplete combustion, CO emissions are formed rather than CO_2 (Hendrik and Padovani 2003). If ingested in high concentrations, CO can be deadly, and its lack of color and odor make it hard to detect.

For every ton of portland cement that is produced, approximately one ton of CO_2 is released (Greer et al. 2004). This accounts for approximately 5% of the global CO_2 emissions resulting from human activity, and therefore, cement manufacturing contributes considerably to the “greenhouse effect” (Chen and Juenger 2009; Karstensen 2008). Figure 2.8 shows the global cement industry’s contribution to carbon emissions separated by regions.

Carbon dioxide (CO_2) is one of the major greenhouse gases, and is thus closely monitored by environmental agencies around the world (Worrell 2001). There are limits set on how much CO_2 cement plants and other energy-intensive companies are allowed to emit. These companies are given a certain number of carbon credits, which quantify their emission limit. If emissions are reduced below their limit, remaining credits may be traded or sold to other companies that have problems staying within their limits (Lechtenberg 2009). Lechtenberg (2009) also reported that certain programs are in effect that will finance alternative fuel projects because of the reduction in CO_2 emissions. This provides yet another advantage for cement plants to replace traditional fuels.

One method of reducing CO_2 emissions is by incorporating fly ash from coal burning power plants and blast furnace slag from steel production into the cement making process (Chen and Juenger 2009). These calcium-bearing waste materials can partially replace natural limestone but can also be used as supplementary cementitious materials

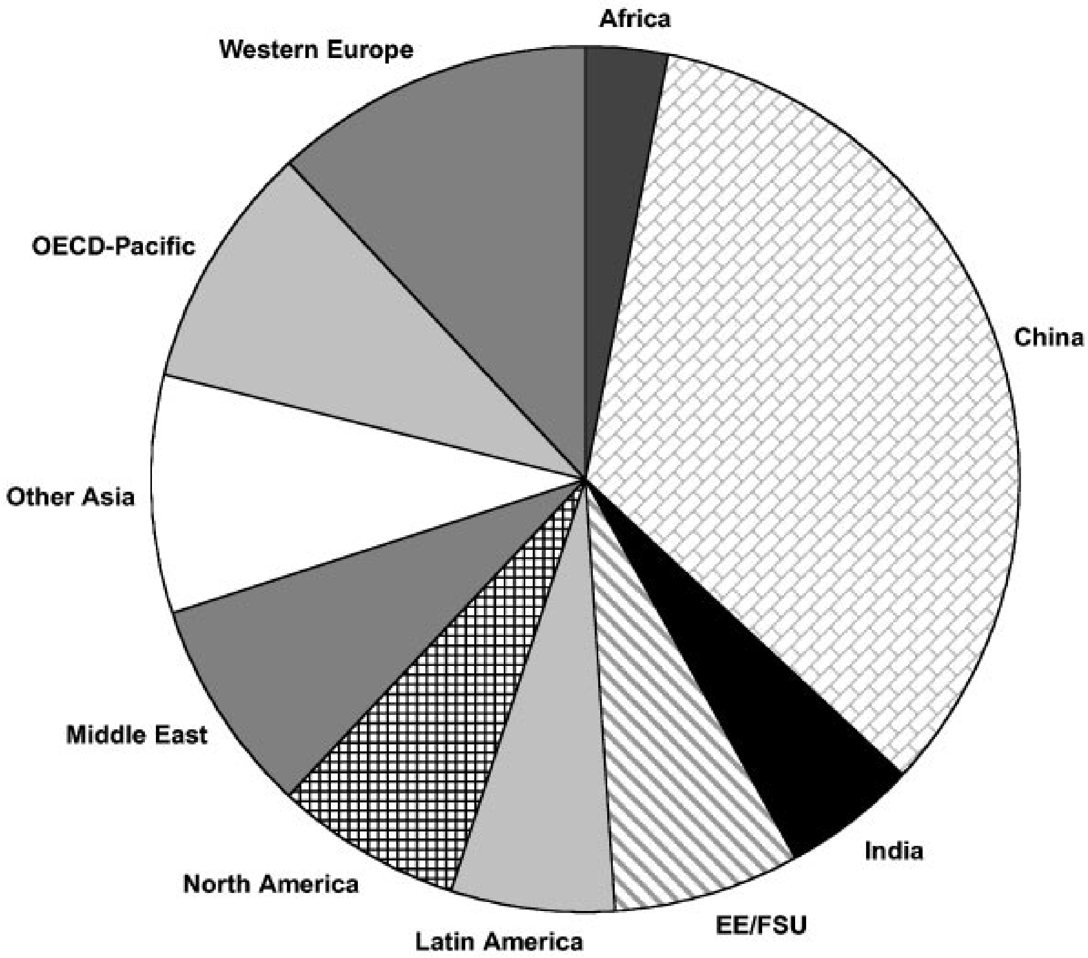


Figure 2.8: Share of carbon emissions from global cement production (Worrell et al. 2001)

(SCMs) to replace a portion of the cement in a concrete mixture. It was seen that limestone can be successfully replaced during production by as much as 27.5% fly ash and 35.0% slag without significantly altering the mechanical properties of commercial portland cement (Chen and Juenger 2009).

Another, indirect method of reducing CO_2 emissions is by utilizing alternative fuels for production. According to Worrell et al. (2001), by utilizing waste fuels as a substitute to fossil fuels, CO_2 emissions may be reduced by 0.1 to 0.5 kg per kg of cement being produced. Japan's Taiheiyo Cement Group used waste materials to constitute 20%

of the raw materials and 9% of the fossil fuels. This resulted in a 14% reduction in CO_2 emissions (Taniguchi 2001).

In 1987, Norcem's Brevik Plant in Norway used chipped car tires as an alternative fuel to partially replace coal (Syverud 1994). During the 56-hour study, CO, NO_x, and SO_x emissions were recorded. Reductions of up to 50% were seen in CO emissions.

The Environmental Protection Agency (EPA) reports U.S. greenhouse gas emissions are 14% higher than they were in 1990; however, a reduction of 3% was seen from 2007 to 2008 and 6% from 2008 to 2009 (Tankersley 2010). Although this reduction was primarily a result of the economic struggles and increased oil prices during these times, alternative fuel utilization is thought to be of some significance.

Burning waste materials as a fuel yields an overall net decrease in CO_2 as opposed to incineration without energy recovery (Cahn 1998). Assuming alternative or waste-derived fuels will undergo incineration, it only seems logical to utilize their energy towards cement production or other practical purposes. Otherwise, their contribution to CO_2 and other greenhouse gases will serve no benefit other than freeing landfill space for additional waste storage.

2.4.2 Nitrogen Oxide Emissions

Nitrogen oxides (NO_x) are a family of nitrogen-based compounds that are formed through combustion of fuels and raw materials in the presence of atmospheric air (Greco et al. 2004; Walters et al. 1999). For every ton of portland cement produced, 1.5 to 10 kg of NO_x is emitted into the atmosphere (Naik 2005). Nitric oxide (NO) is first formed, and quickly reacts with oxygen at low temperatures until it is oxidized into nitrogen dioxide

(NO_2) (Greco et al. 2004). Nitric oxide generally makes up 90% of NO_x emissions, and nitrogen dioxide comprises the remainder (Greer 2004; Greer et al. 2004). Both result from nitrogen oxidation within the fuels, air, and raw materials. Fuel type, feed rate, air flow, and kiln temperatures will all influence the amount of NO_x emissions (Greer 2004; Walters et al. 1999). Since these factors are all highly variable, several measurements at closely spaced time intervals are necessary to accurately detect NOx emissions.

Although NO is the main constituent of NO_x emissions, atmospheric conditions convert a large portion into NO_2, which is thought to be the main “environmental evil” (Greer 1989; Greco et al. 2004). When NO_2 comes in contact with water, nitrous acid (HNO_2) and nitric acid (HNO_3), two highly corrosive acids are formed. As rain falls in a highly NO_2 concentrated atmosphere, acid rain forms, which is highly destructive to buildings and vegetation. Also, NO_2 reacts with hydrocarbons in the presence of solar radiation to form “smog”. On November 7, 1997, the Environmental Protection Agency enacted a law requiring a 70% mass reduction in cement kiln NO_x emissions effective in 22 states (Walters et al. 1999). Credits were distributed to facilities, which were bought and sold in a similar fashion to the carbon credits earlier discussed.

There are four mechanisms of NO_x formation in a cement plant, namely, thermal, fuel, feed, and prompt NO_x; however, thermal NO_x and fuel NO_x are of the greatest concern (Greer et al. 2004). Atmosphere air contains 79% nitrogen, and in the presence of high heat, nitrogen is released as thermal NO_x (Greco et al. 2004). Thermal NO_x represents about 70% of NO_x emissions and is highly dependent on kiln temperatures (Greco et al. 2004; Hendrik and Padovani 2003). Concentrations increase as kiln temperatures increase. Thermal NO_x begins to form at temperatures around 1200 °C but rapid formation is thought to begin around 1600 °C (Hendrik and Padovani 2003).

Fuel NO_x is generated from the oxidation of nitrogen-rich bonds in the fuel (Greer et al. 2004). All fuels contain some amount of nitrogen, but of fossil fuels, coal contains the most (Greer et al. 2004; Hendrik and Padovani 2003). Fuel NO_x is formed through all combustion temperatures, but especially when temperatures exceed 800 °C (Hendrik and Padovani 2003).

Cement plants utilizing a preheater or precalciner will typically have lower NOx emissions (Greer et al. 2004; Nobis 2009; Worrell et al. 2001). This is because temperatures in this region remain below the threshold of thermal NO_x formation, and thus, fuel NO_x is the primary contributor (Hendrik and Padovani 2003). Therefore, utilizing fuels with lower nitrogen content can reduce overall NO_x emissions. The study conducted by Syverud (1994), mentioned in the previous section, utilized chipped tires as fuel to partially replace coal. Reductions of up to 45% were seen in NO_x emissions.

Other methods, such as Non-Selective Catalyst Reduction (NSCR or SNCR) are also used to control NO_x emissions by introducing a reducing agent such as ammonia into the stack. This is essentially the same technique as catalytic converters in automobile applications. Fuel and thermal NO_x emissions are both dependent on the amount of oxygen in the kiln (Greer 2004). Reducing excess air will reduce the strength of the oxidizing conditions in the kiln, thus reducing NO_x emissions. This reduction method will also slightly conserve energy which will lead to less fuel consumption and a decrease in CO_2 emission. However, this method may yield an increase in SO_2 and CO generation (Greer et al. 2004).

2.4.3 Sulfur Oxide Emissions

Sulfur oxides are referred to as SO_x and are primarily comprised of sulfur dioxide (SO_2) and sulfur trioxide (SO_3) (Greco et al. 2004). Both are formed during oxidation of sulfur compounds, typically in fuels, at temperatures ranging from 300 to 600 °C (Greer et al. 2004; Hendrik and Padovani 2008; PCA 2009). Concentrations of SO_2 are typically more abundant due to their formation during higher temperatures. This oxide is a colorless gas with a sharp odor that damages both vegetation and the respiratory system of humans (Greco et al. 2004). In the presence of rain water, SO_2 transforms into sulfuric acid (H_2SO_4) to create acid rain (Greco et al. 2004).

The amount of SO_x formed depends on conditions during kiln firing, such as the oxygen content. Some of the SO_x tend to build up or coat the inner lining of the kiln in regions of lower temperature. This can be beneficial by protecting the brick lining from damage, but excessive build-ups can prevent proper flow of material through the kiln, leading to shut-downs (Hendrik and Padovani 2008). Raw materials traveling through the kiln usually scrub most of the build-up, causing a large portion of original SO_x to become incorporated into the clinker, which inherently requires less calcium sulfate to be added during grinding (Hendrik and Padovani 2008). About 70% of SO_x formed is either incorporated into the clinker or remains in the kiln (Greer 1989; Hendrik and Padovani 2008).

During the Syverud (1994) study mentioned earlier, shredded car tires were used as an alternative fuel to partially replace coal. Sulfur emissions were monitored throughout the 56-hour operation. Although SO_3 levels rapidly increased, leading to operational problems such as build-up and a smell of sulfur in the preheater, SO_2 levels were seen to drop an average of 25%.

2.4.4 Other Problematic Emissions

The three major emissions previously discussed are the most prevalent in the cement manufacturing industry. Several studies have confirmed their formulation and levels are, in some way, affected by the type and quantity of fuels being utilized. There are several other minor emissions and compounds within the kiln, but little literature is available which describes a fuel's contribution to their formation. Therefore, these minor constituents will only be briefly discussed in the following sections.

2.4.4.1 Dioxins and Furans

Polychlorinated dibenzodioxins (dioxins) and polychlorinated dibenzofurans (furans) are byproducts of the manufacturing process and will be referred to collectively as D/F. Though little is known of D/F formation mechanisms, they seem to be most abundant in regions with lower temperatures, ranging from about 290 to 790 °C, above which furans appear to be more predominant (Bech and Mishulovich 2004; Karstensen 2008). Precalciner/preheater systems and Particulate Matter Control Devices (PMCDs) exhibit temperatures within this range, so their design configuration will largely control D/F emission quantities. By increasing the number of stages of a precalciner, temperatures can be lowered below the threshold of formation, thus reducing D/F levels (Bech and Mishulovich 2004). Precursors of D/F include chlorinated phenols, benzenes, and other chlorinated organic material contained in fuels (Worst 2003).

Primary concerns of D/F emissions include eye irritation, dermatitis, gastrointestinal disturbances, liver and kidney damage, and possibly cancer, all of which arise through ingestion (Kirk 2000). Human ingestion is typically instigated through consumption of infected animals. Several studies have shown that fuel type does not significantly affect the amount of D/F emitted into the atmosphere (Conesa et al. 2008; Karstensen 2008; Loo 2008).

2.4.4.2 Metals

Small concentrations of metals are present within the raw materials and fuels used during cement production, and some may be present in the stack gases (Bhatty 2004; Schuhmacher et al. 2004). According to Conesa (2008), several countries distinguish heavy metals (HMs) by their toxicity, and the following three classes exist:

Class I: Cadmium (Cd), Mercury (Hg), Titanium (Ti)

Class II: Arsenic (As), Cobalt (Co), Nickel (Ni), Selenium (Se), Tellurium (Te)

Class III: Lead (Pb), Cromium (Cr), Copper (Cu), Platinum (Pt), Vanadium (V), Tin (Sn), Palladium (Pd), Antimony (Sb), Manganese (Mn), Rhodium (Rh)

The HMs exhibiting the highest toxicity are found in Class I, and those in Class III contain the lowest. Mercury (Hg), cadmium (Cd), and lead (Pb) are thought to be of greatest concern as they are the most volatile, and cannot be efficiently controlled by dedusting of kiln exhaust gas (Conesa 2008).

As mentioned in Section 2.3, some alternative fuels are conditioned prior to combustion in the kiln to remove any excess metals or other contaminants that could disrupt the mechanical operation or render environmental concerns (Willitsch and Sturm 2002). This is necessary, as certain metals within the fuel contribute to emissions. Therefore, removing these metals from the fuels prior to combustion is a method for reducing metallic emissions (Bhatty 2004).

2.4.4.3 Particulate Matter and Cement Kiln Dust (CKD)

During the entire cement production process, from quarrying raw materials to grinding the cement, particulate matter is produced and released into the environment. This includes course and fine particulates, with 10 μm serving as the dividing line (Hendrik and Padovani 2003; Richards 2004). These particles may range from 1 to 100 μm in diameter. It may be helpful to note that the diameter of a typical human hair is about 50 μm. Fine particulates, especially those less than or equal to 2.5 μm ($PM_{2.5}$), are of greatest concern as they are more likely to penetrate the respiratory tract and potentially contain toxic metals and other harmful compounds (Hendrik and Padovani 2003; Richards 2004). The larger particles generally remain within the confines of the cement plant, and are more of a public nuisance than a health hazard.

The fine particulates generated during the pyro-process are typically referred to as cement kiln dust (CKD). CKD is comprised of partially burned or unburned kiln feed, clinker, and brick material from the kiln's inner lining (Hendrik and Padovani 2003). Chemical composition, mineralogy, and particle size of CKD is highly variable in and among facilities as they depend on the raw materials and fuels used, the types of PMCDs installed, and the kiln process employed (Hawkins et al. 2004; Hendrik and Padovani 2003). Hendrik and Padovani (2003) summarized a study performed by the EPA in 1995 which compared wet- to dry-process kilns. Wet-process kilns, on average, contained 7% $PM_{2.5}$ as compared to 18% from dry-process kilns.

The electro-static precipitators (ESP) mentioned earlier, and fabric filters have been used since the 1960's to capture much of the fugitive matter so they may be recycled back into the kiln system (Richards 2004). Modern PMCDs such as these are quite efficient as they typically capture about 99% of the CKD generated (Greer 2004; Hendrik and Padovani 2003). Returning a large portion of captured CKD back into the system is desired for several reasons, but concerns of equipment limitations and cement quality have limited the amount that can be recycled (Hawkins et al. 2004). Due to the stringent limitations set forth on clinker composition, these recycling limitations are primarily governed by the mineralogy of the CKD.

The major components of CKD are unreacted raw feed, partially calcined raw feed and clinker dust, free lime, and salts enriched with alkali sulfates, halides, and other volatile compounds (Hawkins et al. 2004). Table 2.10 shows typical chemical compositions of CKD and portland cement. It should be noted that these data are only typical as these values vary greatly among facilities.

Alkalies, such as sodium (Na) and potassium (K), can compromise cement quality by promoting adverse effects such as volume change and alkali-silica reactions between cement paste and certain aggregates. Alkalies can also be detrimental to the operation of the kiln system. It is necessary to control the rate of CKD returned to the kiln, thereby controlling the existence of alkalis in the system. Most specifications limit the alkali

Table 2.10: Typical chemical composition of CKD and portland cement (adapted from Greer 2004)

Constituent	CKD (%)	Ordinary portland Cement (%)
SiO_2	11 – 16	22
Al_2O_3	3 – 6	5
Fe_2O_3	1 – 4	3
CaO	38 – 50	64
MgO	0 – 2	1
SO_3	4 – 18	3
K_2O	3 – 13	<1
Na_2O	0 – 2	<1
Cl	0 – 5	<0.1
Loss on ignition	5 – 25	1
Free-lime	1 – 10	2

content of the cement to about 0.6% (Greer 2004). According to Hendrik and Padovani (2003), about two-thirds of the CKD captured is permitted to be recycled back into the kiln system, leaving one-third to be disposed through landfill or sale. In the UK alone, this unused CKD amounts to over 200,000 tons of landfill space and 80,000 tons of CO_2 per year that could have otherwise been avoided (Greer 2004). Some of this excess CKD can be used for agricultural, sewage and water treatment, soil stabilization, and other such applications and is sold accordingly.

The amount of CKD sent to landfills has significantly decreased in the past fifteen years. It is common for modern cement plants to recycle 100% of their generated CKD back into the kiln system (PCA 2009). In fact, over 163,000 metric tons of CKD were actually removed from landfills in 2008, and portions were returned to manufacture more clinker (PCA 2009). This is beneficial to cement producers as recycling CKD reduces the need for limestone and other raw materials, as well as reduced the energy required to produce clinker. However, recycling limitations still depend on CKD composition, and thus vary among facilities.

2.5 Effects of Major and Minor Elements on Portland Cement

There are several major and minor elements present during the manufacturing of portland cement. Some are emitted into the atmosphere while others are incorporated into the clinker and cement, collectively determining its overall performance. A few of these major elements are discussed in the following sections, but a summary of all minor elements and their possible effects on cement manufacturing and performance are listed in Table 2.11.

2.5.1 Alkalies (Sodium and Potassium Oxide)

Sodium oxide (Na_2O) and potassium oxide (K_2O) are the most common alkalies present in portland cement and are typically addressed collectively as they have similar effects on cement behavior. Both metals can be found in fuels as well as the raw materials, but mainly come from the raw materials (Bhatty 2004).

Depending on the amount of sulfur present in the clinker, alkalies in the kiln are incorporated into clinker in variable percentages of Na_2O or K_2O as either sulfates or minor components of cement minerals (Lawrence 1998a). These oxides are usually volatized in hotter portions of the kiln and condense in cooler portions. Potassium compounds are typically more volatile than sodium compounds (Bhatty 2004; Lawrence 1998b). During condensing, rings or blockages may form in the kiln lining, leading to

Table 2.11: Summary of possible effects of minor elements on cement manufacturing (adapted from Bhatty 2004)

Elements	Possible Effects
Antimony, Sb	Incorporates in clinker as calcium antimonates under oxidizing conditions and at high temperatures, reduced alite and belite size
Argon, Ar	No known effects
Arsenic, As	Volatile, goes to CKD, also incorporates in clinker as low-volatile calcium arsenates, reduces C_3S formation
Barium, Ba	Reduces melt temperature, replaces Ca I all clinker phase4es except ferrite, also improves clinker mineralogy
Beryllium, Be	In traces, decomposes alite, produces dentritic belite
Bismuth, Bi	No known effects
Boron, B	Decomposes C_3S, stabilizes βC_2S, promotes free-lime formation
Bromine, Br	Volatile, may form bromine alinites
Cadmium, Cd	Forms volatile halides/sulfates, enters CKD, reduces melt temperature, improves burnability
Carbon, C	CO_2 in emissions
Cesium, Cs	In traces, forms chlorides/sulfates
Cerium, Ce	Gets uniformly distributed in clinker, have very little volatilization
Chorine, Cl	Volatile, promotes chlorine cycle, causes ring formation, preheater build-up, can form chlorine alinites
Chromium, Cr	Reduces melt viscosity, primarily goes to belite and produces dentritic crystal, decomposes alite, improves grindability, imparts color
Cobalt, Co	Goes to ferrite, replace Fe in ferrite, imparts color, increase hardness
Copper, Cu	Goes to ferrite, can adversely effect alite and belite formation, lowers melt temperature, free-lime, imparts dark color
Fluorine, Fl	Lowers melt temperature, enhances C_3S formation and alkali fluorides, excess levels cause operational problems
Gadolinium, Gd	Forms triclinic and monoclinic phases with C_3S, replaces Ca in C_3S and C_2S
Gallium, Ga	In traces, volatile
Germanium, Ge	Replaces Si in C+S to form tricalcium germinate (C_3G) that reduces to dicalcium germinate (C_2G) and free-lime
Helium, He	No known effects
Hydrogen, H	No known effects
Indium, In	In traces, volatile
Iodine, I	In traces, volatile
Krypton, Kr	No known effects
Lanthanum, La	Replaces Ca in C_3S and C_2S, forms solid solution with C_3S, enhances clinkering
Lead, Pb	Volatile, goes to CKD but some stays in clinker, effects at higher levels uncertain
Lithium, Li	Forms oxide, lowers phase temperature
Magnesium, Mg	Improves burnability, goes into aluminate and ferrite phases, forms periclase
Manganese, Mn	Goes to ferrite, can replace Si and Ca in C_3S, gives dark brown to blue color

Table 2.11 (continued): Summary of possible effects of minor elements on cement manufacturing (adapted from Bhatty 2004)

Elements	Possible Effects
Mercury, Hg	Somewhat inert, volatile, goes in stack gases
Molybdenum, Mo	Reduces melt viscosity, forms large round alite crystals, modifies belite crystals
Neodymium, Nd	Forms solid solution with C_3S and C_2S, replaces Ca in C_3S and C_2S
Neon, Ne	No known effects
Nickel, Ni	Goes to ferrite, replaces Ca in alite and stabilizes monoclinic form, imparts dark brown color, volatile, reports in CKD
Niobium, Nb	Feeble effect
Nitrogen, N	NO_x emission
Oxygen, O	Enhances incorporation of metals with high oxidation states, modifies phases, formation, results in darker clinkers (reducing condition gives lighter clinker)
Phosphorus, P	Decomposes C3S to C2S and free-lime, reduces negative effects of alkalis
Potassium, K	Lowers melt temperature, promotes internal cycle, causes phase separation, forms complex chloride/sulfate compounds
Rubidium, Rb	In traces, forms chlorides/sulfates
Scandium, Sc	Replaces Ca in C_3S and C_2S, forms solid solution with C_3S of triclinic nature
Selenium, Se	In traces, volatile, goes to CKD or emissions, may also form unstable selenates
Silver, Ag	In traces, no known effects
Sodium, Na	Lower melt temperature, promotes internal cycle, causes phase separation, forms complex chloride/sulfate compounds
Strontium, Sr	Small amount favors alite formation, large amounts cause belite formation, also promotes free-lime formation
Sulfur, S	Volatile, promotes formation of complex alkali sulfates, sulfur cycle, causes plug formation, gives SO_2 emissions
Tellurium, Te	In traces, volatile, goes to CKD or emissions, may also form unstable selenates
Thallium, Tl	In traces, highly volatile, goes into CKD, also forms internal cycle
Tin, Sn	Stays in clinker, decomposes alite, produces dentritic belite, enlarges interstitial stages, no effect if in traces
Titanium, Ti	Goes in ferrite, decomposes alite to belite, reduces melt temperature, gives buff-color cement
Tungsten, W	Reduces melt viscosity, forms large round alite and Type III belite
Uranium, U	Gets uniformly distributed in clinker, shows little volatilization
Vanadium, V	Goes into alite, forms larger crystals, produces ragged belite, reduces melt viscosity, free-lime, effects grindability in lining, imparts tan color
Xenon, Xe	No known effects
Yttrium, Yb	Substitutes Ca in C_3S and C_2S
Zinc, Zn	Enters belite and alite, modifies alite crystals, reduces free-lime, improves clinkering
Zirconium, Zr	Modifies alite and belite crystals, imparts color

potential kiln shut-downs. To avoid this, many facilities install an alkali by-pass system to divert a portion of these gases into the cement kiln dust (CKD). This is why CKD typically has a high alkali content, as mentioned in Section 2.4.7, limiting the amount of CKD recycled.

Alkalies incorporated into the clinker minerals affect cement by increasing the concentration of hydroxide during hydration (Tennis and Kosmatka 2004). This increases the rate at which additional hydration products are formed, and thus, increases the rate of hydration. The hydration process is discussed more in Section 2.7. Consequently, this accelerated hydration will affect both setting time and strength development of a concrete mixture. According to Jackson (1998), cements with an alkali content above about 0.8% showed an increase in early-age strength of nearly 10% and a long-term strength reduction of about 10-15%. It was also reported that an increased alkali content will typically reduce setting times and increase drying shrinkage characteristics.

Setting time and compressive strength effects are shown in Tables 2.12 and 2.13 as reported by Lawrence (1998). In both tables, control cement was used to relate the effects of varying sodium and potassium contents. It can be seen in Table 2.12 that an increase in Na_2O delayed the setting times relative to the control, which contradicts Jackson's (1998) findings. However, an increase in K_2O shows accelerated setting times, indicating potassium has a greater tendency to accelerate hydration.

Table 2.13 shows the effect of alkalies on compressive strength. Compared to the control cement, an increased Na_2O content reduces strength at all ages. An increase in K_2O increases early-age strength and reduces long-term strength, which agrees with Jackson's (1998) findings mentioned earlier.

Table 2.12: Setting times of cement with varying alkali contents (Lawrence 1998b)

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

Table 2.13: Compressive strength of cement with varying alkali contents (Lawrence 1998b)

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	19.5	39.8	59.6	68.7
1.26 % Na_2O	18.4	39.2	57.5	68.2
0.88 % K_2O	21.9	44.8	60.7	72.1
1.48 % K_2O	20.0	43.1	61.0	73.2

Alkalies help maintain the high pH level necessary for chemical stability of cement paste (Hawkins et al. 2004). On the contrary, excessive pH levels may have deleterious effects on a concrete mixture via the phenomenon known as alkali-silica reaction (ASR). The silica found in certain aggregates reacts with the high pH pore solution to form an expanding gel that may crack and/or deteriorate a concrete structure. The quantity of gel is limited by either the alkali or reactive silica contents of a concrete mixture (Lawrence 1998a). This can be resolved by increasing the amount of sulfate in kiln feed or during the grinding operation (Bhatty 2004). There is an optimum sulfate content, which is dependent on the alkali content of the clinker (Aïtcin 2000).

2.5.2 Chlorine (Cl)

Chlorine (Cl), or chloride, is commonly found in both raw materials and fuels. According to Bhatty (2004), Cl concentrations typically constitute 10 to 2800 ppm of traditional fuels, 0.02% of kiln feed, and 90 ppm of clinker. Typical sources of Cl in raw materials are limestone and marine-originated clays. Fuels, such as coal and scrap tires, typically have high concentrations of Cl (Bhatty 2004).

Chlorine may be present as various forms of chloride, such as alkali chlorides (NaCl and KCl). As mentioned in the previous section, alkalies can encourage rings or blockages to form in the kiln, leading to operational malfunctions during the pyro-process. Therefore, Cl concentrations in the raw feed are typically limited to about 0.015% (Jackson 1998). In facilities processing preheaters, as much as 99% of all chlorides are recaptured by the incoming raw feed (Ritzmann 1971).

As mentioned in Section 2.3.4.2, plastic solid waste (PSW) tends to contain large amounts of chlorine. Kikuchi et al. (2008) reports on the severity of this problem in European cement plants, where PSW are commonly used as alternative fuels. There are current efforts to group plastics based their Cl content. The Cl-poor group (≤0.5%) is used for waste-to-energy applications, particularly cement production to adhere to the strict limitations of Cl content in cement. The Cl-rich group is disposed of in landfills or recycled. This grouping method was found to be time and cost intensive and slightly unsuccessful because of the variability in PSW composition.

Due to the high volatility of most chlorides, their concentrations in clinker are relatively low (<0.03%), in which case effects can be regarded as insignificant (Bhatty 2004). However, many waste-derived fuels contain various forms of chlorides at high concentrations which can be extremely detrimental to kiln operation and cement performance. One major adversity pertaining to concrete structures is chlorine's potential to corrode reinforcing steel (Jackson 1998). Over time, chloride deposits can penetrate the concrete's surface and deteriorate the concrete-to-steel interface. As rust accumulates on reinforcement, several adversities may develop, such as expansion, concrete spalling, and concrete-steel bond reduction. For this reason, most specifications for portland cement restrict Cl levels to about 0.01%.

2.5.3 Magnesium (Mg)

Magnesium (Mg) is a metal predominantly originating from magnesium carbonates found in raw materials. A typical raw material blend will contain about 0.63% Mg, and an average clinker sample will contain about 8900 ppm (Bhatty 2004). If present in small quantities, Mg is beneficial to the manufacturing process, but in excess, may significantly effect concrete behavior.

ASTM C 150 limits the magnesium oxide (MgO) content of portland cement to about 6 percent. At concentrations in excess of about 2%, a portion of MgO is thought to form large periclase crystals incorporated into the aluminate and ferrite clinker phases (Glasser 1998; Jackson 1998; Macphee and Lachowski 1998; Taylor 1997; Tennis and Kosmatka 2004). These crystals react slowly with water, and may expand to cause cracking and unsoundness of concrete over time. Conversely, within acceptable limits, Mg improves the burnability of clinker, which allows the pyro-process to proceed efficiently.

More so than the MgO content, the cooling rate of clinker is thought to dictate the behavior of Mg in clinker (Bhatty 2004; Lawrence 1998b; Long 1983). According to Lawrence (1998b), several studies have investigated the effects of MgO content on cement strength, but none were found to be significant. However, the rate at which the clinker was cooled did seem to have a profound effect. Table 2.14 shows cement strengths with varying levels of MgO from clinker that was cooled both rapidly and slowly. At an MgO content of 6%, a reduction in strength for all ages is seen from the clinker cooled slowly. Though this trend is not entirely consistent, the clinker that was cooled slowly does seem to lower the overall strength. According to Bhatty (2004), when clinker is rapidly cooled, most of the MgO is retained within the aluminate and ferrite phases, and some in the alite phase. When slowly cooled, only about 1.5% is retained in the solid solution, and the remainder is crystallized into large periclase crystals.

Table 2.14: Compression strength results from clinker cooled at different rates with various MgO content (adapted from Lawrence 1998)

Clinker cooling rate	**MgO (%)**	**Compressive Strength (MPa)**			
		2 days	**7 days**	**28 days**	**90 days**
Rapid	0	15.4	27.7	42.9	50.4
	2	12.9	31.2	46.3	55.7
	4	11.7	30.1	42.4	56.3
	6	12.0	30.1	37.8	43.3
Slow	0	13.2	24.3	31.4	54.4
	2	13.4	25.2	41.1	50.1
	4	13.8	27.5	44.1	48.4
	6	10.9	26.4	35.9	40.1

2.5.4 Phosphorus (P)

Phosphorus (P) is a nonmetal introduced into the kiln primarily through raw materials, particularly limestone. A typical concentration of P in raw materials is about 0.04% (Bhatty 2004). Phosphorus pentoxide, P_2O_5 is the most common form of phosphorus in the cement process and typically constitutes about 0.2% of clinker (Bhatty 2004). In proper proportions, P_2O_5 will enhance cement quality and soundness, but excessive quantities may adversely affect several hydration parameters and decrease concrete strength.

P_2O_5 is non-volatile, so is generally incorporated into the clinker, entering the C_2S phase and improving hydraulic properties, slightly extending setting times, and negating all negative alkali effects on strength (Bhatty 2004; Jackson 1998). However, in excess, P_2O_5 increases and retains free lime and inhibits the formation of C_3S. Sources disagree as to what is considered excessive, but all agree that the addition of fluorine prevents this effect and permits the formation of C_3S (Bhatty 2004; Jackson 1998; Macphee and Lachowski 1998; Miller 1976; Nurse 1952). Jackson (1998) states, "When the amount of P_2O_5 present exceeds 1 percent, it has been reported that 10 percent of C_3S is lost for each additional 1 percent of P_2O_5 added." According to Nurse (1952), this occurs at concentrations exceeding 2.5%, and Bhatty (2004) claims the threshold to be 3.0 percent. Miller (1976) reports that P_2O_5 levels above 0.5% may lead to a decrease in water requirements, reduction in heat of hydration, and increased shrinkage tendencies for cement pastes.

2.5.5 Sulfur (S)

Sulfur (S) is a nonmetal introduced into the kiln through both raw materials and fuels. Coal and oils are particularly prone to high levels of sulfur (Bhatty 2004). Typical concentrations include approximately 0.06% of kiln feed, 3200 ppm in clinker, and up to 6.0% of coal and petroleum coke (Bhatty 2004).

Sulfur is found in the form of sulfates and sulfides, and for raw materials, it is important to distinguish between the two. Sulfides oxidize within the kiln at temperature ranging from 400-600 °C, and sulfates, between 900-1000 °C (Jackson 1998). Sulfates tend to combine with alkalies within the kiln to form alkali sulfates (Bhatty 2004; Jackson 1998). This is necessary to remove the alkalies from the kiln, preventing blockages and rings that cause kiln shut-downs. An optimum sulfate content is therefore dependent on the alkali content of the clinker (Aïtcin 2000). However, an excess of sulfate will lower the melting point of calcium and alkali sulfates, which can also lead to ring formation and blockages within the preheater (Jackson 1998). Calcium sulfate, commonly gypsum rock, is added during the grinding stage of production in amounts between 3 and 8 percent. This will retard the hydration of C_3A, controlling the setting time of cement and optimizing the strength-giving properties of calcium sulfates (Jackson 1998; Tennis and Kosmatka 2004).

Sulfides and elemental sulfur found in raw materials and fuels typically oxidize in the kiln to form sulfur dioxide (SO_2) (Greer et al. 2004). Approximately 15-40% of sulfides are converted into SO_2 emissions (Bhatty 2004). In facilities that employ a preheater system, the raw feed entering the kiln will absorb most of this SO_2, but some may still escape through the stack emissions. As with coal and oils, tire-derived fuels

(TDF) and plastic solid waste (PSW) typically have a high concentration of sulfur (Bhatty 2004; Jackson 1998). This will generally contribute to SO_2 emissions, but levels may be reduced by increasing combustion air into the system (Bhatty 2004). Emissions of SO_2 were discussed in greater detail in Section 2.4.3.

2.5.6 Zinc (Zn)

Zinc (Zn) is a metal introduced into the kiln through both raw materials and fuels. Typical concentrations of Zn include approximately 22-115 ppm in raw materials, 16-220 ppm in coal, and as much as 10,000 ppm in TDF (Bhatty 2004). Zinc oxide (ZnO) is the most common form of Zn in the cement process. About 80-90% of the ZnO found in raw materials is incorporated into the clinker, and the remainder becomes included in the CKD (Bhatty 2004). A typical clinker sample will contain about 0.2% ZnO (Taylor 1997).

During hydration of cement paste (and concrete), Zn (as well as Cd) delay setting time and diminish strength (Trezza and Scian 2000). This is because an increased amount of Zn leads to an increase in C_3S, as well as a decrease in C_3A (Odler 1998). However, the extremity is dependent on the amount of other metallic oxides and sulfates present in the cement (Olmo et al 2001). According to Pipilikaki et al. (2005) and Jackson (1998), small amounts of Zn (0.01-0.2%) actually increase the reactivity of C_3A, which may lead to possible setting problems. A study conducted by Olmo et al. (2001) shows an increase in ZnO led to an increase in initial and final setting times of 21.7% and 10.7%, respectively. This study also reported the influence of ZnO on unconfined compressive strength. From an increase in ZnO, results show a significant decrease in compressive strength at early ages, but the effect was minimized as the specimen age increased.

TDF usually have high contents of zinc, about 1.0-1.6% on average, which comes from the beads and steel belts imbedded beneath the rubber (Bhatty 2004). This typically limits TDF replacement to about 30 percent (Pipilikaki et al. 2005). However, when used at a 10% substitution rate, tires only increase ZnO contents in clinker by an estimated 0.02% (Bhatty 2004). In a study conducted by Pipilikaki et al. (2005), cement was produced from two fueling scenarios: one which utilized only coal and petroleum coke, and the other used a 6% replacement of coal with TDF in the precalcining system. The cement produced from the TDF contained twice as much Zn as that produced from traditional fuels. Though no significant effects were seen on compressive strength, initial and final setting times were increased by 22.2 and 47.8%, respectively. No problems were derived from the increased zinc content but were expected if the replacement rate of TDF was increased.

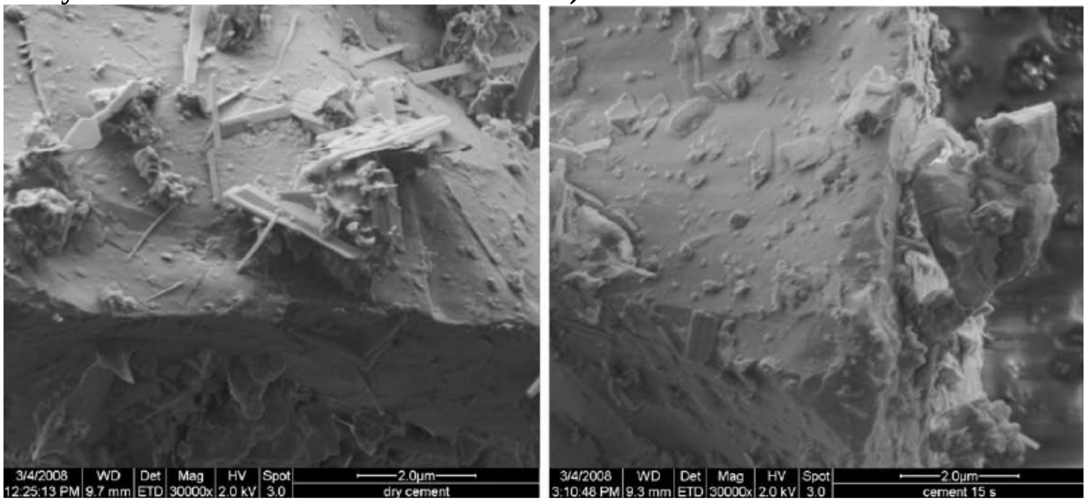
2.6 Hydration of Portland Cement

When portland cement is mixed with water, cement paste is formed through a series of chemical reactions in an exothermic process known as hydration. The hydration products formed in this process cause the paste to lose its plasticity until eventually becoming a solid material. The rate and degree of hydration is dependent on several factors, including the fineness and chemical composition of the cement, the amount of water relative to cement (referred to as the water-cement ratio), and the curing temperature (Odler 1998). Several standardized testing methods are in place to ensure the quality and predict the performance of the cement.

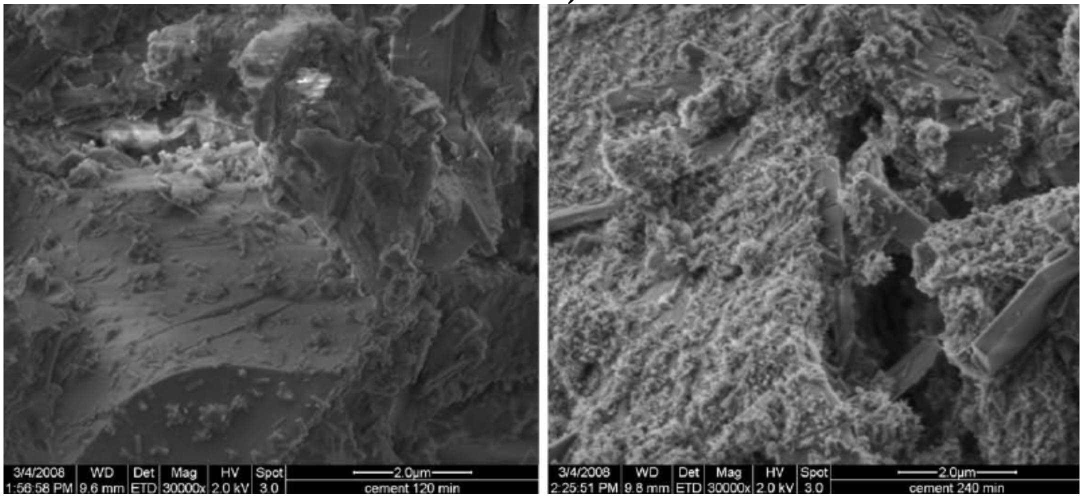
The chemical composition of the cement will greatly influence the rate and degree of hydration. As defined earlier, the four major clinker minerals that constitute the cement are C_3S (alite), C_2S (belite), C_3A (aluminate), and C_4AF (ferrite). Each of these Bogue compounds will provide a unique contribution to the process. Upon the introduction of water, the C_3S and C_2S react to form the hydration products, calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) (Odler 1998). Simultaneously, the C_3A and C_4AF react with the sulfate to form calcium trisulfoaluminate hydrate (ettringite). The ettringite retards the hydration of the aluminate, preventing the paste from setting too rapidly. This retardation is necessary to allow for the placement of concrete during construction. The ettringite remains active until the sulfate is completely consumed, at which point the remaining aluminates are able to resume hydration. As more hydration products form, the mixture begins to lose its plasticity until final set occurs. The time of final set is defined as the time at which the cement paste (or concrete mixture) initiates its compressive strength development. As long as water is available, hydration products will continue to form causing a continual increase in strength. The Scanning Electron Microscope (SEM) images shown in Figure 2.9 depict the cement particles throughout the hydration process.

Heat is released throughout the hydration process, but not at a constant rate (Tennis and Kosmatka 2004). A hydration curve is typically used to depict a graphical representation of the heat evolution through the process. An example of this curve is presented in Figure 2.10 with five stages defining the entire hydration process. Stage I is known as initial (pre-induction) hydrolysis, and begins when water is first introduced to the cement. The initial peak is primarily due to C_3A and is quickly subsides due the formation of ettringite. This peak takes place only within the first few minutes of hydration, and is therefore rarely captured through testing (Tennis and Kosmatka 2004). Stage II is known as the induction (dormant) period, during which, the rate of reaction slows significantly. During Stage III, the acceleration (post-induction) period, CH begins to precipitate due to the C_3S reacting, and a second peak is generated, generally referred to as the C_3S peak (Tennis and Kosmatka 2004). This peak often occurs between 6 and 12 hours from hydration. In Stage IV, the deceleration period, the ettringite is converted into monosulfate, and the remaining C_3A is free to react, yielding a third peak known as the C_3A peak. This peak usually occurs between 12 and 90 hours after hydration. The final stage, the diffusion period, can last several months (Odler 1998). The reaction slows and gradually ceases as the non-reacted C_3S is consumed.

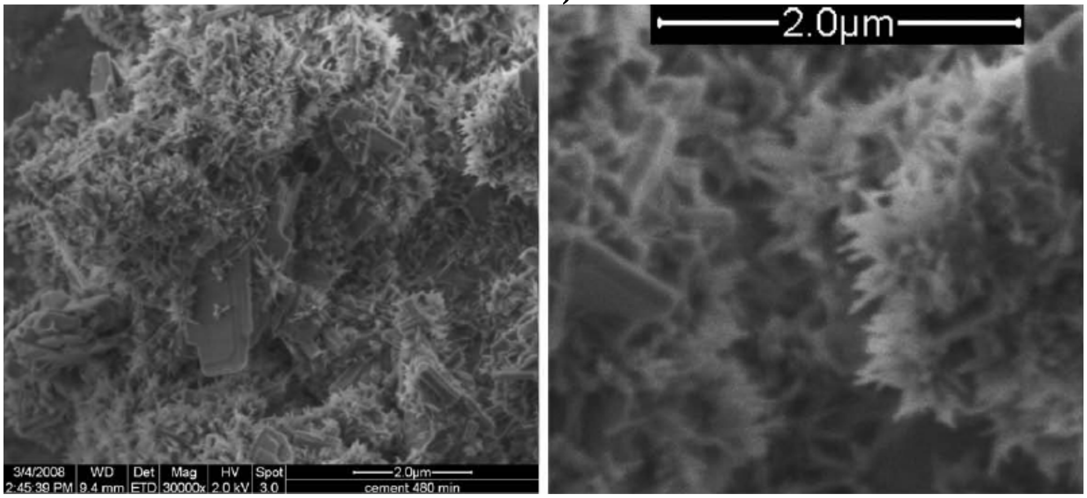
The shape and duration of the hydration curve is primarily dependent on the chemical composition of the cement, but is also affected by the water-cement ratio, the fineness of the cement, and ambient curing temperatures (Chen and Juenger 2009; Tennis and Kosmatka 2004). As cement content, fineness, and temperature increase, so does the heat of hydration. One peak in the C_3S portion of the hydration curve usually signifies ideal gypsum content. An additional hydration peak generally indicates the formation of calcium monosulfoaluminate from ettringite due to insufficient gypsum in the system (Chen and Juenger 2009).



a) Unhydrated **b) 15 seconds**



c) 120 minutes **d) 240 minutes**



e) 480 minutes **f) 480 minutes**

Figure 2.9: SEM images of cement throughout hydration (Ylmén et al. 2009)

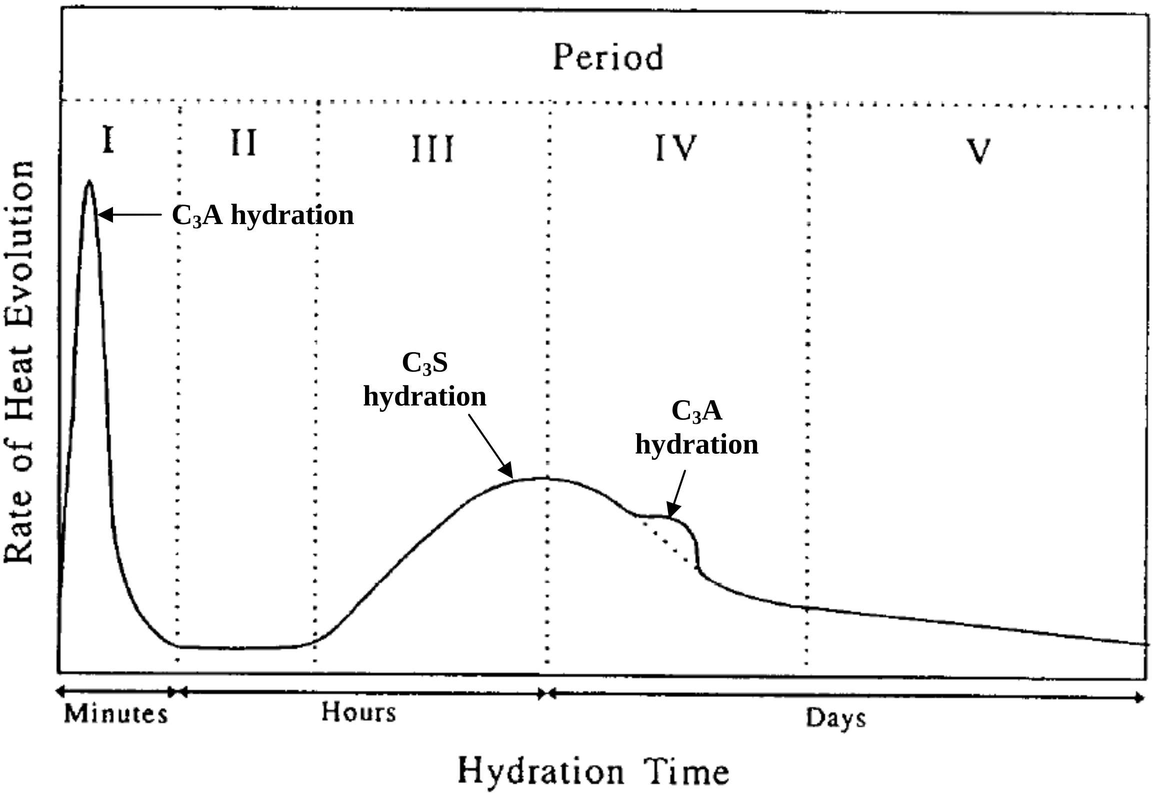


Figure 2.10: Stages of heat evolution (adapted from Shi and Day 1995)

Since alternative may alter the cement's chemical composition, this may affect the hydration process as well. According to Chen and Juenger (2009), several waste materials contain sulfur impurities, which may significantly affect the balance of oxides, and in turn, the formation of the four major clinker phases. Studies show that increasing the use of waste materials resulted in increasing C_3S contents and decreasing C_2S contents. Therefore, it is critical to assess the SO_3 content prior to their use in production (Chen and Juenger 2009).

During the early stages of hydration, several parameters exist which play a vital role in determining the quality and predicting the performance of a cement. Calorimetric tests, such as isothermal, semi-adiabatic, and fully adiabatic, are commonly used to determine these parameters and obtain the heat of evolution throughout the hydration process (Xu et al. 2010). Isothermal calorimetry is discussed in greater detail in the following section. Other parameters, such as setting time and workability, are thought to coincide with the hydration parameters and are discussed further in Section 3.4.2.1.

2.6.1 Isothermal Calorimetry

According to Cost (2008), calorimetry is defined as a quantified measure of heat evolved or absorbed through a chemical reaction. In a single chemical reaction, thermal power is proportional to the rate of a reaction, and heat produced is proportional to the extent of a reaction (Gerstig and Wadso 2010). Isothermal calorimetry is a method in which thermal power is used to maintain a constant temperature of a sample, such as hydrating cement paste. As heat is generated from the hydration process and flows to its surroundings, it is monitored by a heat flow sensor. The heat flow, caused by the temperature difference across the sensor, generates a voltage signal which is converted into the rate of heat evolution (Xu et al. 2010). The amount of power generated is recorded at numerous time intervals and is used to develop a hydration curve such as seen in Figure 2.10. Isothermal calorimetry is preferred when a quantitative measure is desired (Cost 2008).

As mentioned, the raw materials and fuels utilized during portland cement production will determine the composition of the clinker, and in turn, determines the hydration characteristics of cement. In the early ages of cement hydration, temperature evolution plays a vital role in concrete performance and development of material properties, such as strength. Strength development is thought to be in direct proportion to heat of hydration (Xu et al. 2010). Therefore, isothermal calorimetry is not only a valuable tool to distinguish hydration parameters of various cements, but it may help to predict material properties.

2.6.2 Chemical Admixture Effects on Portland Cement

Cement admixtures are chemicals added during or immediately prior to mixing to modify fresh or hardening concrete properties (Kosmatka et al. 2002). Inorganic and organic cement additives have been used for many years, and evidence indicates that their discovery was most likely accidental (Edmeades and Hewlett 1998). For instance, using blood as an air-entraining agent, animal milks and fats to improve workability, and urine to alter setting times were all implemented with no awareness of the chemistry involved. Around the early 1970's, much research and development was performed to become more knowledgeable on the implications of admixtures, and their use in the concrete industry has drastically increased since (Edmeades and Hewlett 1998). Some would argue that admixtures influence concrete behavior even more than the cement, and the costs of both are often comparable (Hanehara and Yamada 1999). High performance concretes with ultra-high strengths, superior workability, and self-consolidating abilities are primarily attributed to the advancement of admixtures. Though they seem to offer only improvements to concrete performance, these admixtures have been known to cause such adverse effects as stiffness and strength development problems, setting and flow variation, immense shrinkage, and corrosion issues (Edmeades and Hewlett 1998; Hanehara and Yamada 1999; Kosmatka et al. 2002).

The many benefits of chemical admixtures have led to their growth in popularity throughout the global concrete industry. According to Kosmatka et al. (2002), admixtures:

- Reduce costs associated with concrete construction,
- Are more effective than other means in achieve desired concrete properties, and
- Maintain the quality of concrete and resolve certain safety concerns throughout the stages of mixing, transporting, placing, and curing in all weather conditions.

Table 2.15 lists common admixtures types according to their ASTM C 494 classification with a brief description of their functions. Several other chemical admixtures used today include corrosion inhibitors, shrinkage reducers, alkali-silica reactivity inhibitors, and many others, but will not be discussed further as they fall beyond the realm of this study.

Chemical admixtures can be broken into three primary categories: active, interactive, and passive (Edmeades and Hewlett 1998). Active admixtures react with cement components that promote hydration products, thus altering the rate of hydration. These include accelerators, retarders, and waterproofing admixtures. Interactive admixtures are those that alter the natural surface charge of cement and water particles, causing dispersion or flocculation. These include water reducers such as plasticizers or superplasticizers, and air-entraining agents. Passive admixtures are not absorbed into the solution but remain in suspension. Their involvement is mainly physical, modifying

Table 2.15: Common admixtures and their functions

(adapted from Kosmatka et al. 2002)

ASTM C 494 Classification	Admixture Type	Desired Effect
Type A	Water-Reducer	Reduce water content (≥ 5%)
Type B	Retarder	Retard setting time
Type C	Accelerator	Accelerate setting and early-strength development
Type D	Water-reducer & Retarder	Reduce water content (≥ 5%) and retard set
Type E	Water-reducer & Accelerator	Reduce water content (≥ 5%) and accelerate set
Type F	High range water-reducer	Reduce water content (≥ 12%)
Type G	High-range water reducer & Retarder	Reduce water content (≥ 12%) and retard set

viscosity by way of molecular capture or solvent association, or altering color through light reflection (Edmeades and Hewlett 1998).

An admixture's effectiveness will depend on dosage, water-cement ratio, aggregate shape, gradation and proportions, mixing time and temperature, and others (Kosmatka et al. 2002). Admixtures are generally used in conjunction with concrete, but they are assumed to have a similar impact on cement paste. Due to the reduction in material costs and ease of mixing, cement paste is generally the preferred method for testing admixture effects. Since cement paste does not contain aggregates, obvious differences are expected, particularly in flow.

It should be noted that the aim of this study places emphasis on the following admixture effects on cement paste: hydration, setting time, and rheology (the study of a material's workability, or ability to flow). Consequently, the admixtures utilized in this study will be discussed in the following sections as they pertain to these effects. Air-entraining admixtures were not employed in cement pastes, but in concrete mixtures, and their effects will therefore be discussed as they relate to concrete.

2.6.2.1 Water-Reducing Admixtures

Water-reducers are used to reduce the amount of mixing water necessary to acquire a particular slump (Kosmatka et al. 2002). Effects include reduction in water-cement ratio or cement content and an increase in slump or workability. According to Edmeades and Hewlett (1998), "water-reducing admixtures are hydrophilic surfactants which, when dissolved in water, deflocculate and disperse particles of cement." This is essentially achieved by changing the surface charge and creating repulsion which reduces friction between the particles. Water-reducers are categorized by their potency, and are labeled as low-range, mid-range, and high-range water reducers (also known as superplasticizers). Water reduction can range from 5 to 30% depending on the type and dosage used (Edmeades and Hewlett 1998; Kosmatka et al. 2002).

The extent of a water-reducer's effects will be primarily dependent on the dosage of admixture used and the chemical composition of the cement. Generally speaking, water-reducers typically lead to an increase in early-strength gain, increase in overall strength (possibly exceeding 70 MPa), decrease in permeability, and other potential benefits (Kosmatka et al. 2002). For concretes with equal cement content, air content, and slump, Kosmatka et al. (2002) reports a 10 to 25% increase in 28-day compressive strength for those using water-reducers. However, water-reducers may cause increased drying shrinkage, segregation problems, large entrained air voids, rapid slump loss, and durability issues (Edmeades and Hewlett 1998; Kosmatka et al. 2002). Cement possessing a low C_3S content may result in retardation of the mixture, but this has only been seen with high dosage levels and may be offset by the addition of an accelerator (Edmeades and Hewlett 1998).

2.6.2.2 Retarding Admixtures

Retarders are used to delay the setting time of a concrete mixture by extending the induction period of hydration (Edmeades and Hewlett 1998; Kosmatka et al. 2002). This is necessary to allot more time for placement and extend workability. Since temperature is directly proportional to concrete setting, this may be crucial during high-temperature placement or when a substantial period of time is expected for placement completion. According to Edmeades and Hewlett (1998), retarders form a low-permeability coating around the cement particles, reducing the solubility of the hydration components of cement, thus slowing hydration.

Retarders generally yield a reduction in strength at early ages, as well as increase the bleeding rate and bleeding capacity (Kosmatka et al. 2002). Effects on other concrete properties tend to be variable. Therefore, acceptance tests are typically conducted with similar materials under anticipated conditions prior to construction.

2.6.2.3 Accelerating Admixtures

Accelerating admixtures are used to accelerate the rate of hydration and promote early-strength development. Calcium chloride ($CaCl_2$) is most commonly used in accelerators and acts as a catalyst during the hydration of C_3S and C_4AF, accelerating the formation of ettringite and other hydration products (Edmeades and Hewlett 1998; Kosmatka et al. 2002).

Accelerators allow for accelerated construction, which is highly desired. Unfortunately, high early-age strength gains typically sacrifice the long-term strength of concrete, and this effect is exaggerated with increasing dosages (Edmeades and Hewlett 1998). Table 2.16 shows the effect of increasing dosages of accelerators on setting times and compressive strength. An overdose can result in rapid stiffening, increase in drying shrinkage, corrosion of reinforcement, and an increase for scaling potential.

Table 2.16: Effect of accelerator on setting time and compressive strength (adapted from Edmeades and Hewlett 1998)

Accelerator Dosage (wt% of cement)	**Final Set** (min)	**Compressive Strength** (MPa)	
		17 days	**28 days**
0.00	200	29.3	37.5
1.50	120	21.0	23.4
2.75	40	17.1	19.5
5.50	10	12.1	14.7

2.6.2.4 Air-Entraining Admixtures

During the mixing process, air bubbles are generated through agitation of the concrete ingredients. Air-entraining admixtures are surfactants added during mixing to stabilize these microscopic air bubbles uniformly throughout the concrete. Water tension is reduced to facilitate bubble formation, and a charge is formed around the bubbles to repel one another, preventing agglomeration into large bubbles (Edmeades and Hewlett 1998).

Though most air-entraining admixtures do not affect the hydration process, excessive dosages have been known to retard the C_3S and accelerate the C_3A reactions (Edmeades and Hewlett 1998). Generally speaking, entrained air is known to greatly improve surface scaling resistance and freeze-thaw durability (Kosmatka et al. 2002). Other benefits include reduction or elimination of segregation and bleeding, and increasing workability. However, the air content is known to be inversely proportional to strength. According to ACI (1992), “Incorporation of entrained air may reduce strength at a ratio of 5 to 7 percent for each percent of air.”

Air-entraining admixtures may be affected by several chemical properties of the cement. According to Kosmatka et al. (2002), an increase in alkalies, or a decrease in the fineness, carbon content, organic material content, loss on ignition, or the presence of impurities, may increase the effectiveness of an air-entraining admixture.

2.7 Concluding Remarks

The production of portland cement is a complex and energy-intensive process, involving several materials and temperatures approaching 1500 °C. Fossil fuels have traditionally been used to generate this immense heat, but recent concerns of their depletion, increasing cost, and environmental hazards have forced the industry to consider alternative fuels as a viable replacement option.

Alternative fuels are typically waste by-products from other industries, and offer several potentials benefits to cement production facilities and the environment. Due to the rising cost of coal and other traditional fuels, waste fuels can significantly lower production costs. Certain alternative fuels can also replace portions of the raw materials required during production, thus lowering material costs. Alternative fuels offer several environmental advantages as well. These include reducing fossil fuels consumption, landfill waste disposal, and typically, harmful greenhouse gases. Though several studies confirm these advantages, other potential concerns must be addressed before alternative fuels are deemed acceptable.

Introducing alternative fuels into cement kilns introduces new materials into the clinker and cement. These can alter the chemistry of both clinker and cement, which could be detrimental to their performance. In addition, several alternative fuels have been seen to vary greatly in chemical composition. Cement manufacturers and consumers both depend on a reliable, consistent product, so it is crucial that cement quality and performance are not compromised.

During the pyro-process, several toxic gases are generated in the kiln and released into the environment. It has been shown that these emissions are heavily dependent on the fuels used during production. Therefore, prior to their use, waste materials must be tested, and certain limitations must be met to ensure their safety regarding the environment. Once employed, emissions must be continuously monitored to ensure acceptable levels are maintained.

Another concern for alternative fuels is their response to chemical admixtures. In today’s industry, engineers and designers rely on chemical admixtures to produce unique, yet consistent concrete mixtures. It is necessary that cement produced from alternative fuels will respond to the addition of chemical admixtures as expected.

Several alternative waste fuels are available, and each will have unique effects on portland cement and its production. Effects may also differ among facilities. Therefore, each fuel must be evaluated individually to determine the ideal fuel and optimum replacement rate at each facility. If the chemical composition of the cement is not compromised, and environmental adversities are not foreseen, an alternative fuel may be deemed acceptable, and the deciding factor will rely on cost. Facility modifications are costly, yet necessary, for most of the alterative fuels used today. Each manufacturer must weigh the potential benefits against the predicted drawbacks in order to approach an educated decision regarding their affiliation with alternative fuels.

Chapter 3

Experimental Plan

3.1 Introduction

The production of portland cement is a complex process involving many materials and systems working in tandem. Altering any stage of the process may affect various elements of production and/or the overall performance of the final product. The objectives of this study are to examine the effects on both the manufacturing and performance of portland cement by partially replacing traditional fuels with alternative fuels. The remainder of this chapter will detail the experimental work regarding each objective.

The scope of this study included three alternative fuels co-fired with traditional fuels. Cement was produced during 3- to 4-day trial periods at *Lafarge North American Roberta cement plant*, a full-scale, cement-manufacturing facility located in Calera, AL. Five distinct collection and testing periods were conducted, herein referred to as burns. Each burn was unique in the collection of fuels utilized. These burns are listed and briefly described below. From this point forward, each burn will be referred to by its respective identification.

Note that two of the burns listed below are considered baseline burns, and three are considered trial burns. Burns beginning with a ‘B’ indicate a baseline burn, with the remaining letters serving as an acronym for the fuels utilized. Baseline burns serve as a reference to one or more trial burns. Trial burns contain the same fueling scenario as their baseline with the addition of a single alternative fuel.

1. **FT** – Coal, petroleum coke (coke), tires, plastics, and forest trimmings (FT) were the fuels utilized during this burn period. This was a 72-hour, non-continuous trial burn that took place in January of 2009.
2. **B-CCTP** – Coal (C), coke (C), tires (T), and plastics (P) were the fuels utilized during this burn period. This was a baseline burn to serve as a reference for the FT burn shown above. This was a 72-hour, continuous burn that took place in March of 2009
3. **B-CCP** – Coal (C), coke (C), and plastics (P) were the fuels utilized during this burn period. This is a baseline burn to serve as a reference for the railway tie (RR) and glycerin (GL) burns shown below. This was a 72-hour, continuous burn that took place in July of 2009.
4. **RR** – Coal, coke, plastics, and railway ties (RR) were the fuels utilized during this burn period. This was a 96-hour, continuous burn that took place in July of 2009.
5. **GL** – Coal, coke, plastics, and liquid glycerin (GL) were the fuels utilized during this burn period. This was a 72-hour, continuous burn that took place in November of 2009.

The fuels utilized during this study are categorized in Figure 3.1. The combination of fuels used during the baseline burns represent the conventional fuels used by the cement plant at the time of production. Although tires and plastics, by definition, are considered alternative fuels by the industry, they are used during normal production, and thus will be considered conventional fuel for the purposes of this study. Forest trimmings, railway ties, and glycerin are the only materials individually evaluated as alternative fuels throughout the remainder this study.

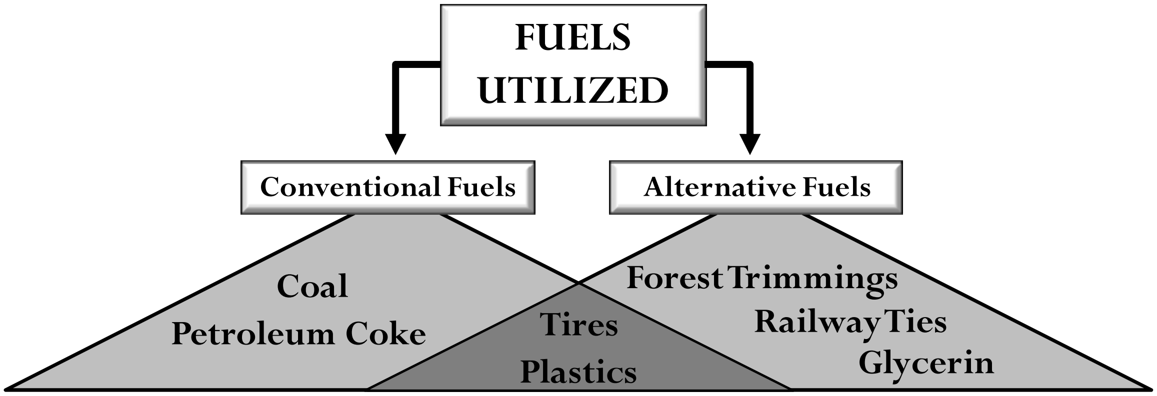


Figure 3.1: Classification of fuels utilized during the study

During the beginning stages of this study, tires were utilized during normal operation, and thus were incorporated into the FT and B-CCTP burns. However, complications arose in obtaining an economical supply of waste tires, which discontinued their use during normal operation. Therefore, a new baseline, B-CCP was conducted to serve as a reference for the two remaining trial burns, RR and GL. Also, during the FT burn, the kiln was temporarily shut down due to technical issues. Once resolved, the burn was continued through completion. This burn is therefore considered a non-continuous burn.

The combination of fuels utilized during each burn was intended to serve as the independent variable with all other conditions held constant. Though much effort was made in this regard, variations in conditions at a full-scale cement plant are inevitable, which results in some degree of variability in cement composition and performance.

Therefore, it is difficult to conclude that any changes are due, exclusively, to the addition of the alternative fuels.

It should be noted that this study is a continuation of previous work (Swart 2007; Akkapeddi 2008). Therefore, previous findings may be mentioned and/or briefly discussed throughout the remainder of this document, and their sources will be adequately cited for further reference.

3.1.1 Definitions

All materials involved in production may be referred to as process inputs and/or process outputs. Process inputs are those materials placed into the system, including raw materials, kiln feed, cement kiln dust (CKD), and fuels. Process outputs are the products resulting from the production process, including clinker, CKD, portland cement, and emissions. Note that CKD is considered both a process input and process output, as CKD is generated in the kiln and recycled back into the system.

The process of sampling refers to the methods by which a portion of material is gathered from a larger source. A specimen refers to the portion of a sample that will be tested. Conditioning refers to the methods used to prepare a specimen. Two types of specimens were prepared, discrete and composite specimens. A discrete specimen refers to a portion of a sample that was collected from a single source from one particular time period. A composite sample refers to a gathering of material from a single source collected over several time periods.

3.2 Sampling and Testing Overview

To better understand and carry out the objectives of this project, a detailed sampling and testing plan was developed and will be discussed throughout this chapter. A diagram of this plan is shown in Figure 3.2. The plan consists of sampling and testing all process inputs and outputs throughout production in order to evaluate the overall effects of implementing various alternative fuels. This section provides a general overview of the sampling and testing performed during this study. Details on sampling and testing are provided in Section 3.3 and 3.4, respectively.

There were three general parties involved during this study, each of which had specific contributions toward the fulfillment of the objectives. These parties include the cement plant, external laboratory, and Auburn University. Many tests were performed by two parties to ensure consistency in test results, with the exception of concrete testing. Auburn University was the only party to mix concrete and perform associated tests.

Each burn took place within the *Lafarge North American Roberta cement plant*, a full-scale, cement-manufacturing facility located in Calera, AL. Modifications were made to accommodate each of the alternative fuels burned. Cement was produced and distributed under normal production operation. All materials involved in the process, with the exception of fuels, were collected and underwent a chemical analysis by cement plant personnel. The cement plant prepared and tested mortar and paste samples to determine several physical properties of each cement. In addition, clinker and portland cement samples were sent to the cement plant's specialty laboratory to conduct additional testing. Emissions were also continuously monitored by the cement plant during each burn to evaluate the impact of alternative fuels, as well as to ensure environmental regulations were met.

An external laboratory was chosen to perform chemical analyses of all materials used during the operation. Samples collected by the cement plant staff were shipped to the external laboratories by Auburn University. Results were used to determine how the fueling scenario affected all other process inputs and process outputs of the operation. Various testing methods were used to determine several parameters of each material, and are explained in Section 3.4.

The primary test conducted on all materials was a chemical analysis, which was performed by the cement plant and/or external laboratory. All chemical compounds were determined by X-Ray Fluorescence (XRF), with the exception of raw material three (RM3) and the plant emissions. The chemical composition of RM3 was determined at the cement plant by a Prompt Gamma Neutron Activation Analyzer (PGNAA). A chemical analysis was not performed on plant emissions. Details on emission testing are discussed in Section 3.4.4. In addition to an XRF analysis, the external laboratory conducted a proximate, ultimate, and combustion analysis, and determined the ash content of all fuels utilized during each burn.

Auburn University was the final party involved in this study. All samples collected by the cement plant staff were received, conditioned, and shipped to external laboratories by Auburn University. All information and results were compiled and analyzed by Auburn University in order to present them in this document. Additionally, Auburn University collected cement from each burn to mix concrete and evaluate fresh properties, physical properties, and durability, and was the only party to do so. Many of

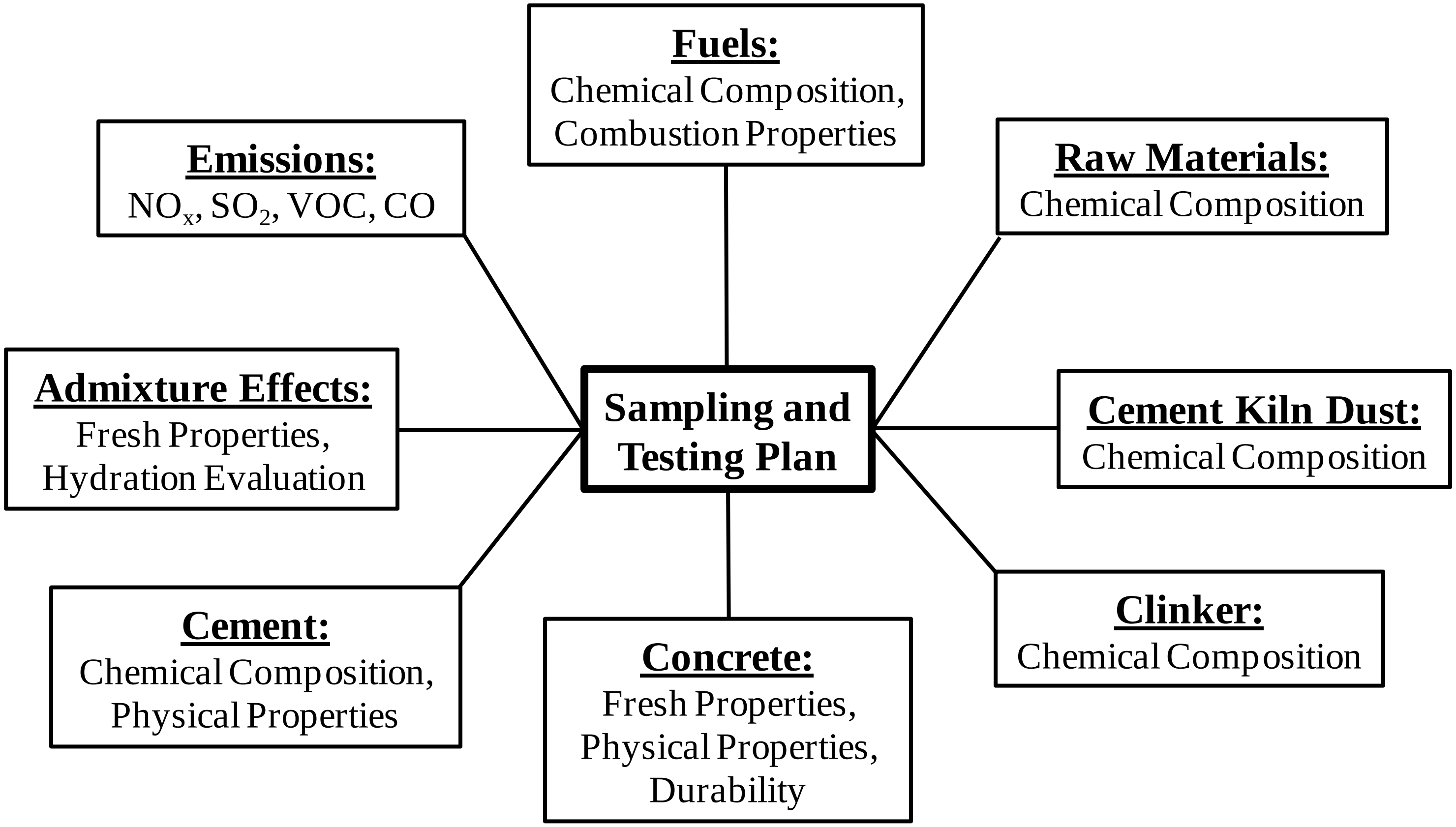


Figure 3.2: Sampling and testing plan (adapted from Swart 2007)

the cements' physical properties determined by the cement plant were also determined by Auburn University.

An admixture study was also incorporated into this phase of the study. All cement samples collected throughout this study were used to determine the effects of chemical admixtures on cement produced from alternative fuels. Accelerating and retarding admixtures were mixed with cement paste from each burn to study their effects on hydration, rheology (flow), and setting time. This admixture study is discussed in detail in Section 3.4.2.1.

3.3 Sampling

Samples of all materials used in production were collected by the cement plant staff throughout each burn. Portland cement was collected in 1-gallon plastic containers, and liquid glycerin was collected in 16-oz., high-density polyethylene bottles. All other materials were collected in 1-gallon tin containers, which will be referred to as the typical sampling container. For convenience, the sampling frequency followed that which the cement plant routinely used to perform their quality assurance measures. However, no fuels were tested by the cement plant, so Auburn University developed a modified sampling plan to include all fuels. Table 3.1 shows the modified sampling plan given to the cement plant prior to each burn.

Note that Table 3.1 lists the projected number of total samples to be collected during each burn period. Fewer samples may have actually been collected based on the plant's staffing during the burns. Raw materials (RM) one through five were collected once during each burn period. Remaining materials were collected at constant frequencies throughout the burn or grinding period. For instance, during the FT burn, which lasted 72 hours, one kiln feed sample was collected approximately every 12 hours, totaling 6 samples collected.

Table 3.1: Projected sampling plan

Material	**Samples per burn**				
	Trial Burns			**Baseline Burns**	
	FT (Jan. 2009)	**RR** (Jul. 2009)	**GL** (Nov. 2009)	**B-CCTP** (Mar. 2009)	**B-CCP** (Jul. 2009)
RM1 - RM5	1	1	1	1	1
Kiln Feed	6	8	6	6	6
Pulverised Coal	6	8	6	6	6
Petroleum Coke	6	8	6	6	6
Tires[1]	1	NA	NA	1	NA
Waste Plastics	3	4	24	6	24
Alternative Fuel	3	4	24	NA	NA
ASF Blend	24	32	NA	NA	NA
Cement Kiln Dust	6	6	6	6	6
Clinker	24	32	24	24	24
Material	**Samples per grinding period**				
RM6	6				
Cement	10				

Notes: **[1] Collected by Auburn University**
RM - Raw Material
ASF - Alternative Solid Fuel

Since the RR burn lasted 96 hours, more samples were collected during this burn period. During the FT and RR trial burns, the alternative fuels were mixed with waste plastics to form an alternative solid fuel (ASF) blend. Though the forest trimmings, railway ties, and plastics were all sampled individually, the ASF blend was the final product introduced into the kiln, and thus was sampled more frequently. During the GL trial burn, glycerin was not blended with the waste plastics, in which case glycerin and plastics were frequently sampled individually. During the B-CCTP burn, waste plastics were only sampled every 12 hours. Variability in the waste plastic's composition was noticed during this burn, so it was decided to increase the frequency of the sampling of the waste plastics stream during the B-CCP and GL burns.

There were specific sampling points for each of the materials being sampled, which can be seen within the schematic of the cement plant layout shown in Figure 3.3. The following section provides details on each material sampled.

3.3.1 Sample Collection

Six raw materials (RMs) were utilized and sampled during each burn. Upon request of *Lafarge North America*, the origin of these materials will not be disclosed, but will be referred to as RM1 through RM6. The primary raw material, RM3, is mined from the quarry and delivered to the primary crusher where it is reduced to a manageable size. It is then conveyed through the Prompt-Gamma Neutron Activation Analyzer (PGNAA) where several chemical parameters are determined. The remaining RMs, excluding RM6, are blended into a stream in proportions dependent on the composition of RM3. The proportions of each are such that the desired chemistry of the blend is as defined for cement production. Prior to entering the stream, each RM is sampled individually at their corresponding sampling points shown in Figure 3.3. Figure 3.4 shows an image of a typical RM sampling point. Each RM was sampled once per burn period.

The stream is then conveyed to the roller mill where RM1 through RM5 are crushed to desired proportions and sent towards the homogenizing silo. Recycled cement kiln dust (CKD) is then fed into the stream where the collection of materials enters the homogenizing silo. Prior to entering the stream, CKD is collected at sampling point 14

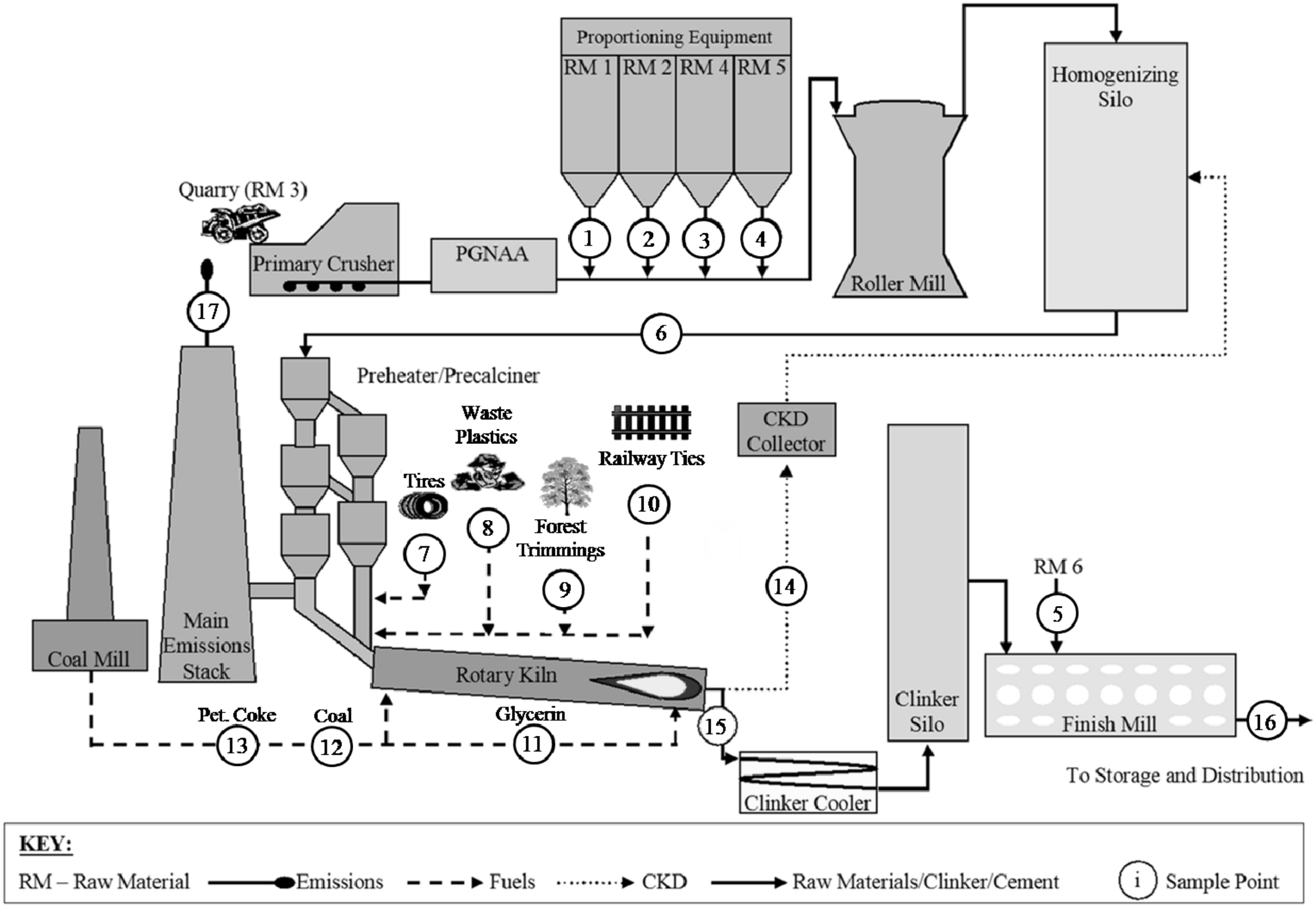


Figure 3.3: Schematic of cement plant operation (adapted from Swart 2007)

Figure 3.4: Raw material sampling point

from Figure 3.3. During each burn, CKD samples were collected approximately every twelve hours.

Within the homogenizing silo, the raw materials and CKD are blended to form a homogeneous mixture known as kiln feed. The kiln feed is then sent to the preheater/precalciner where it is sampled from sampling point 6 shown in Figure 3.3. An image of the kiln feed sampling point is provided in Figure 3.5. During each burn, kiln feed was sampled twice per 24-hour period.

All fuels were sampled throughout each burn period, though the alternative fuels more frequent than the traditional fuels. The rotary kiln system has two locations at which fuels are introduced. The upper or free end of the kiln consumes the majority of the coal, the waste tires, and the waste plastics or ASF blend (i.e. not glycerin). The fuel

Figure 3.5: Kiln feed sampling point

consumed at this location was used to preheat and partially calcinate the raw materials before they enter the kiln. The glycerin, petroleum coke, and remaining coal are introduced in the lower or exiting end of the kiln. The fuel consumed at this location was used to fire the main burner to induce the pyro-process.

The coal and coke were sampled at sampling points 12 and 13, respectively shown in Figure 3.3. Both were collected by an automated plunger system that removes the pulverized material from the stream, as shown in Figure 3.6. Coal and coke samples were each collected twice per 24-hour period.

Figure 3.6: Automated plunger system collecting coal/coke samples

Waste tires were fed to the kiln by a conveyor system installed at the cement plant. Whole tires were conveyed one at a time to a drop chamber that released them into the kiln. Images of the conveyer system and drop chamber are shown in Figures 3.7 and 3.8, respectively. For each burn utilizing waste tires, eight tires were collected by Auburn University to make one composite sample per burn. Details on preparing these samples are described in Section 3.2.2.

Figure 3.7: Tires conveyed to kiln

Figure 3.8: Tires entering kiln through drop chamber

During the FT and RR burns, forest trimmings and railway ties were combined with waste plastics to form an alternative solid fuel (ASF) blend. Predetermined proportions of each were shredded, blended, and conveyed toward the kiln into an injection system. This system consisted of a screw that fed the ASF into the kiln at a controlled rate. This conveyer and injection system can be viewed in Figure 3.9. Prior to being fed into the kiln, the ASF was sampled at sampling points 9 and 10 shown in Figure 3.3, depending on which burn was being conducted. For the baseline burns and the GL burn, plastics were not blended with any other materials prior to kiln entry. In these cases, waste plastics were sampled and sent to the kiln in the same fashion as the ASF. Note that sampling point 8 in Figure 3.3 is in the same location as sampling points 9 and 10. This sampling point can be viewed in Figure 3.10. During the FT and RR burns, ASF samples were collected approximately every 3 hours; plastic and alternative fuel samples were collected approximately every 24 hours. During the GL and baseline burns, waste plastic samples were collected approximately every 3 hours.

Liquid glycerin entered the fuel stream at the main burner, located at the lower or exiting end of the kiln. A pressurized injection system was installed at plant to pump the liquid from its storage tank to the kiln. The storage tank, shown in Figure 3.11, was heated to lower the viscosity of the glycerin, ensuring a consistent flow through the fuel line. An access valve was installed in the fuel line to allow sampling of the glycerin, which was done at sampling point 11 shown in Figure 3.3. Figure 3.12 shows an image of glycerin being sampled at this location. During the GL burn, glycerin was sampled at the same frequency as the other alternative fuels, approximately once per 3 hours.

Samples were collected in high-density polyethylene, nalgene bottles to prevent rust accumulation and to accommodate the higher temperatures of the glycerin.

Figure 3.9: ASF/waste plastics conveyer and injection system

Figure 3.10: ASF sampling point

Figure 3.11: Glycerin storage tank

Figure 3.12: Glycerin sampling point

Once the fuel provides adequate heat to the system, the kiln feed is sent from the homogenizing silo through preheater/precalciner as it approaches the kiln. By the time the kiln feed enters the kiln, it is approximately 95% calcinated (Ewing 2009). Section 2.2.2 provides more information on the calcination process. The molten mass then exits the kiln and is sent to the cooler to form clinker. The clinker was sampled at sampling point 15 shown in Figure 3.3 immediately after exiting the kiln. An access hole allows samples to be taken directly from the clinker stream. Figure 3.13 shows images of the clinker being sampled.

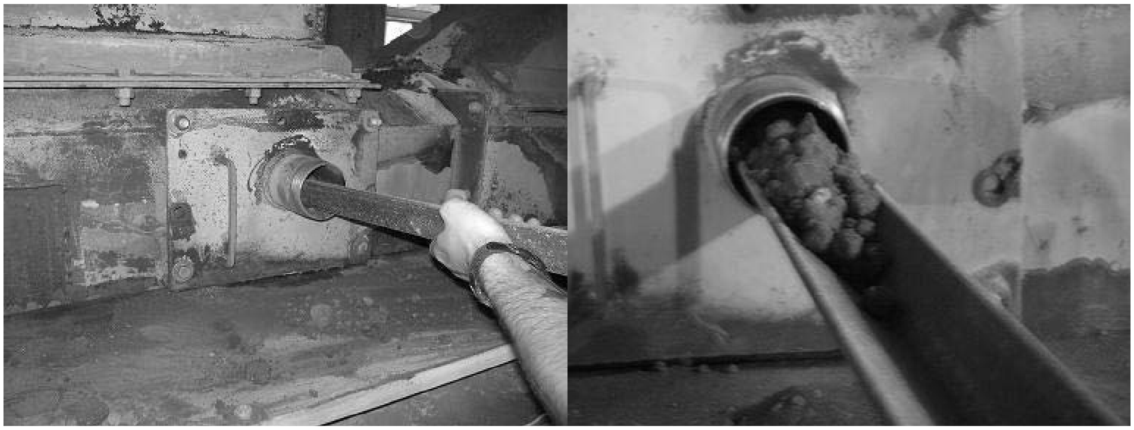


Figure 3.13: Clinker sampling point

Once the clinker has cooled, it is sent to the finishing mill where it meets RM6. The two materials are ground together to form the final product, portland cement. Prior to the grinding operation, RM6 is sampled in the same fashion as the other raw materials, shown in Figure 3.4, and approximately six samples were collected during each burn period. Once grinding is complete, portland cement samples were collected. Portland cement was sampled approximately ten times per burn period at sampling point 16 shown in Figure 3.3. An automated plunger removes the product upon exiting the mill and deposits it into a plastic sampling container, as shown in Figure 3.14.

Figure 3.14: Portland cement sampling point

3.3.2 Sample Conditioning, Shipping, and Storage

Once collected by the cement plant staff, all samples were transported to Auburn University. Samples were immediately placed into 2-gallon, re-sealable bags to prevent the sample’s moisture from corroding the inner lining of the aluminum containers, thus disturbing the *in situ* chemistry of the contents. All bags were labeled according to content, and date and time received. Samples were then conditioned to prepare specimens for shipping and testing.

Two types of specimens were prepared, discrete and composite specimens. A discrete specimen refers to a portion of a sample that was collected from a single source from one particular time period. A composite sample refers to a gathering of material from a single source collected over several time periods. Regardless of the type, specimens were placed into smaller re-sealable bags, labeled with an identification number for reference purposes, and shipped to a laboratory for testing.

In preparing discrete specimens, a random portion of material was chosen from an original sample, and sealed within its corresponding bag. Typically, discrete specimens were prepared from material whose composition was thought to vary greatly throughout the burn period.

In preparing a typical composite specimen, an equal amount of a single material was taken from each original sample and sealed within a 5-gallon bucket. The bucket was then shaken vigorously, horizontally and vertically, for several seconds until the material was sufficiently blended. A random portion was then chosen from the bucket and sealed within its corresponding bag. The remaining material was discarded, and the bucket was cleaned with pressurized air prior to introducing a new material. Two types of composite samples were prepared. A daily composite specimen was prepared using samples collected over a 24-hour time period. A 3-day composite specimen was prepared using samples collected over a 72-hour time period.

During the burns utilizing waste tires, eight different tires were collected by Auburn University. One radial section was removed from each tire, and these sections were cut into one-inch square pieces. A single composite specimen was then prepared from these pieces in the same manner as described above.

During the GL burn, twenty-four glycerin samples were collected in 16-oz., high-density polyethylene bottles. Discrete specimens were prepared from each sample by transferring the contents into 4-oz. bottles, which were also labeled with an identification number. Samples were shaken prior to transferring contents to ensure consistency in each specimen.

All specimens were boxed and shipped to appropriate laboratories to undergo a chemical analysis. All remaining, unused materials were placed into 55-gallon drums and transported to a temperature- and moisture-controlled storage facility to serve as backup in the case additional samples or future testing was desired.

3.4 Test Methods

All materials involved in the production process were tested to evaluate all possible effects from utilizing alternative fuels. Emphasis was placed on consistency in testing to isolate the fueling scenario as the independent variable, with all other conditions held constant. Though much effort was made in this regard, variations in conditions at a full-scale commercial plant are inevitable, and therefore, a certain degree of deviation is expected. Consequently, the addition of alternative fuels may only *partially* contribute to variability in test results.

A chemical analysis was conducted on all collected samples and specimens by the cement plant and/or external laboratory. Physical properties of the cement were determined by the cement plant and Auburn University. An admixture study was also incorporated into this phase of the study to determine if the various trial burns impacted the effectiveness of retarding and accelerating admixtures. Concrete was mixed by Auburn University to evaluate fresh properties, physical properties, and durability.

Emissions were also monitored by the cement plant to evaluate the impact of alternative fuels, as well as to ensure environmental regulations were met.

All test results were gathered and analyzed by Auburn University in order to present them in this document. Analysis and presentation of results can be found in Chapter 4. The remainder of this section details the testing methods utilized to satisfy the objectives of this study.

3.4.1 Chemical Compositions

As discussed in Chapter 2, the chemical composition of all process inputs will collectively determine the chemistry and performance of the process outputs. Therefore, the primary test conducted on all materials was a chemical analysis. Most chemical compounds were determined by X-Ray Fluorescence (XRF). Components were reported as either percent by weight (wt. %), or as parts per million (ppm). Percent by weight is the percentage of the total unit weight for the chemical of parameter in question. Parameters are typically reported in ppm if their presence in the material is relatively small, as these units provide a better representation.

Both the cement plant and external laboratory performed a chemical analysis on the materials, but there is a slight difference in the standard parameters obtained between the two. Table 3.2 lists the standard parameters collected by both entities. All parameters shown in Table 3.2 were determined by XRF, with the exception of Na_2O_{eq}. This parameter was calculated from the concentrations of Na_2O and K_2O using the formula presented in ASTM C 150 (2007). Table 3.3 lists the approximate detection limits for XRF used at the external laboratory.

Table 3.2: Standard chemical parameters

Standard cement plant parameters	Standard External laboratory parameters	
(wt. %)	**(wt. %)**	**(ppm)**
Al_2O_3	Al_2O_3	Arsenic (As)
CaO	CaO	Cadmium (Cd)
Fe_2O_3	Fe_2O_3	Chlorine (Cl)
K_2O	K_2O	Cobalt (Co)
MgO	MgO	Cromium (Cr)
Na_2O	Na_2O	Copper (Cu)
Na_2O_{eq}	P_2O_5	Mercury (Hg)
SiO_2	SiO_2	Molybdenum (Mo)
SO_3	SO_3	Nickel (Ni)
Moisture	TiO_2	Lead (Pb)
LOI	Moisture	Selenium (Se)
	LOI	Vanadium (V)
		Zinc (Zn)

Table 3.3: Approximate XRF detection limits used by external laboratory

Parameter (wt. %)	Limit	Parameter (ppm)	Limit
Al_2O_3	0.01	Arsenic (As)	2
CaO	0.01	Cadmium (Cd)	3
Fe_2O_3	0.01	Chlorine (Cl)	5
K_2O	0.01	Cobalt (Co)	10
MgO	0.01	Cromium (Cr)	16
Na_2O	0.01	Copper (Cu)	13
P_2O_5	0.01	Mercury (Hg)	0.01
SiO_2	0.01	Molybdenum (Mo)	9
SO_3	0.01	Nickel (Ni)	9
TiO_2	0.01	Lead (Pb)	4
Moisture	0.01	Selenium (Se)	1
LOI	0.01	Vanadium (V)	20
		Zinc (Zn)	9

3.4.1.1 Raw Materials and Kiln Feed

There were six raw materials (RMs) sampled during the operation. The names and sources of the RMs are proprietary information, and by request of the cement plant, are not disclosed. RM1 through RM5 were sampled once during each burn, prior to grinding and blending, and a discrete specimen was tested from each by the external laboratory. RM6 was ground with clinker to produce portland cement. Prior to grinding, it was sampled approximately six times throughout each grinding process, and a single composite specimen was tested by the external laboratory for each burn.

The kiln feed consisted of a blend of RM1 through RM5 and cement kiln dust. Kiln feed samples were collected approximately twice per day, which were tested at the cement plant. All kiln feed samples were used to prepared a 3-day composite specimen, which was tested at the external laboratory.

The test specimens for RM1-RM5 and the kiln feed were analyzed by the cement plant and external laboratory to obtain the standard parameters shown in Table 3.2. RM6 was not typically tested by the cement plant. All specimens were analyzed by XRF, except RM3 at the cement plant, which was analyzed by a Prompt-Gamma Neutron Activation Analyzer (PGNAA). This was necessary to obtain immediate compositional results, so the remaining RMs could be proportioned accordingly.

The cement did not test all raw materials during each burn. This was either because the RM's source of origin remained consistent, or because tests were not conducted. However, all data provided by the cement plant are the most recent available for each burn period.

3.4.1.2 Cement Kiln Dust (CKD)

Cement kiln dust (CKD) is unique in that it is a process input as well as a process output. As dust is generated in the kiln during clinkering, it is recycled back into the system via the kiln feed.

CKD was sampled at a frequency of two per day, all of which were tested as discrete specimens by both entities. All parameters in Table 3.2 were obtained by XRF, except moisture and LOI. These parameters were only obtained by the external laboratory.

3.4.1.3 Fuel Sources

All fuels utilized during each burn were sampled at various frequencies. Refer to Table 3.1 for total samples collected during each burn. Though the fuels were tested differently than the other materials, the same tests were conducted on all fuels. In addition to the XRF scan conducted on all materials, proximate and ultimate analyses were performed by the external laboratory. A detailed list of parameters collected during these analyses is shown in Table 3.4. Furthermore, a calorific value was obtained for each fuel specimen by measuring the energy released through combustion. This value, expressed in BTU/lb, was reported on a dry basis. Once combustion was complete, the ash was analyzed by XRF to determine the standard parameters shown in Table 3.2.

Coal and petroleum coke were each sampled twice per day. Samples were used to prepare a single, 3-day composite specimen for both materials, which were testing by the external laboratory. Results consisted of all parameters shown in Tables 3.2 and 3.4, in addition to the combustion and ash analyses previously discussed. Coal and coke were the only fuels tested by the cement plant.

Table 3.4: Proximate and ultimate analysis parameters

Proximate Analysis (wt. %)	Ultimate Analysis (wt. %)
Moisture	Carbon (C)
Ash	Hydrogen (H)
Volatile Matter (VM)	Nitrogen (N)
Fixed Carbon (FC)	Oxygen (O)
	Sulfur (S)
	Ash
	Moisture

Eight tires were collected by Auburn University during the FT and B-CCTP burns. A single composite specimen was prepared and tested by the external laboratory to obtain the parameters shown in Tables 3.2 and 3.4, in addition to the combustion and ash analyses results previously discussed. Preparation of this specimen was discussed in Section 3.3.2. Complications developed in obtaining an economical supply of tires, thus discontinuing their use in the remaining three burns.

Waste plastics were sampled in accordance with Table 3.1. Waste plastics were a blend of multiple wastes, so its composition was thought to vary greatly. Therefore, waste plastics were sampled more frequently than the other fuels. During the GL and both baseline burns, plastics were sampled eight times per day. Discrete specimens were tested by the external laboratory to obtain all the typical fuel parameters discussed.

During the FT and RR burns, each alternative fuel was mixed with waste plastics to produce an alternative solid fuel (ASF) blend. Though the forest trimmings, railway ties, and plastics were all sampled individually, the ASF blend was the final product introduced into the kiln, and thus was sampled more frequently. During the GL burn, waste plastics and glycerin were not blended prior to kiln entry. Therefore, glycerin and plastics were each sampled individually at a frequency of eight times per day. As with all other fuels, discrete specimens were prepared from these samples and were tested by the external laboratory to obtain all the typical fuel parameters discussed.

The liquid glycerin fuel was not pure glycerin, but a combination of glycerin and oil. It was noted by the external laboratory that the glycerin specimens were segregated upon arrival. This was resolved by shaking each specimen prior to testing. Also, it was not possible to determine the Volatile Matter (VM) and Fixed Carbon (FC) contents through the proximate analysis performed by the external laboratory. These results were not obtained, and thus are not presented in this document.

3.4.1.4 Clinker

Clinker was sampled by the cement plant staff approximately eight times per day and was tested by the cement plant to determine all of the standard parameters shown in Table 3.2. In addition, the cement plant calculated the equivalent alkali content and Bogue compounds in accordance with ASTM C 150 (2007). The cement plant also determined the free lime (FCaO) content of each clinker specimen.

All collected samples were used to prepare 24-hour composite specimens from each burn period. These composite specimens were tested by the external laboratory to determine the standard parameters shown in Table 3.2. Also, based on the data provided, Auburn University calculated the Bogue compounds for each specimen in accordance with ASTM C 150 (2007).

Similar composite specimens were also sent to the cement plant's specialty lab. The specialty lab conducted a Rietveld analysis on each clinker specimen to determine the four major clinker phases, similar to the Bogue compounds. This test typically provides more accurate results than the Bogue calculations given in ASTM C 150 (2007).

3.4.1.5 Portland Cement

Ten samples of portland cement were collected during the grinding period of each burn, which were tested by the cement plant to determine all of the standard parameters shown in Table 3.2. In addition, the cement plant calculated the equivalent alkali content and Bogue compounds in accordance with ASTM C 150 (2007). The cement plant also determined the free lime (FCaO) content and Blaine SSA (Specific Surface Area) of each cement specimen.

All collected samples were used to prepare 24-hour composite specimens from each burn period, which were tested by the external laboratory. In addition to the standard parameters shown in Table 3.2, the total organic carbon (TOC) was also determined using a TOC analyzer. Also, based on the data provided, Auburn University calculated the Bogue compounds for each specimen in accordance with ASTM C 150 (2007).

Similar composite specimens were also sent to the cement plant's specialty lab. The specialty lab conducted a Rietveld analysis on each cement specimen to determine the four major clinker phases, similar to the Bogue compounds. This test typically provides more accurate results than the Bogue calculations given in ASTM C 150 (2007).

Limestone is commonly added to portland cement to adjust the final composition. This increases the carbon dioxide (CO_2) content of the cement, which, according to

ASTM C 150 (2007), must be included in the Bogue calculations previously discussed. For this reason, the CO_2 content was an additional parameter calculated by the cement plant. Though limestone was not added to the cement during the FT burn, this parameter is still reported in the results.

3.4.2 Cement Physical Properties

Cement produced during each burn was used to determine several physical properties. Various properties were tested by three entities: the cement plant, Auburn University, and the cement plant's specialty lab. The cement plant and Auburn University conducted several similar tests for comparison purposes.

The cement plant used portland cement sampled from each burn period to conduct their tests. Table 3.5 lists all tests performed by the cement plant, as well as the units and ASTM specification associated with each test.

As described in the previous section, cement samples collected during each burn were used to prepare composite samples and were sent to the cement plant's specialty laboratory. In addition to the Rietveld analysis, the specialty laboratory also determined the particle size distribution for each cement by laser diffraction.

Auburn University received bags of portland cement from each burn for further testing. Table 3.6 lists the tests conducted by Auburn University to determine the physical properties of each cement.

Table 3.5: Cement physical properties determined by the cement plant

Property	ASTM Specification
Air in mortar, %	C 185 (2002)
Blaine specific surface area, m^2/kg	C 204 (2007)
Autoclave expansion, %	C 151 (2005)
Cube flow, %	C 230 (2003)
Compressive strength, MPa (1, 3, 7, and 28 days)	C 109 (2007)
Normal consistency, %	C 187 (2004)
Gillmore initial set, min.	C 266 (2008)
Gillmore final set, min.	
Vicat initial set, min.	C 191 (2008)
Vicat final set, min.	

Table 3.6: Cement physical properties determined by Auburn University

Property	ASTM Specification
Autoclave expansion, %	C 151 (2005)
Cube flow, %	C 230 (2003)
Compressive strength, MPa (1, 3, 7, and 28 days)	C 109 (2007)
Normal consistency, %	C 187 (2004)
Gillmore initial set, min.	C 266 (2008)
Gillmore final set, min.	
Vicat initial set, min.	C 191 (2008)
Vicat final set, min.	
Drying Shrinkage development, %	C 596 (2007)

3.4.2.1 Admixture Study

An admixture study was also incorporated into this phase of the alternative fuels study. Auburn University was the only party to conduct tests related to admixture effects. All cements collected throughout the study were used to determine the effects of chemical admixtures on cement produced with various alternative fuels. Accelerating and retarding admixtures were mixed with cement paste from each burn to study their effects on hydration, rheology (flow), and setting time. Figure 3.15 shows all cements that were used during the admixture study and the baseline cement that will be used for comparison of the results.

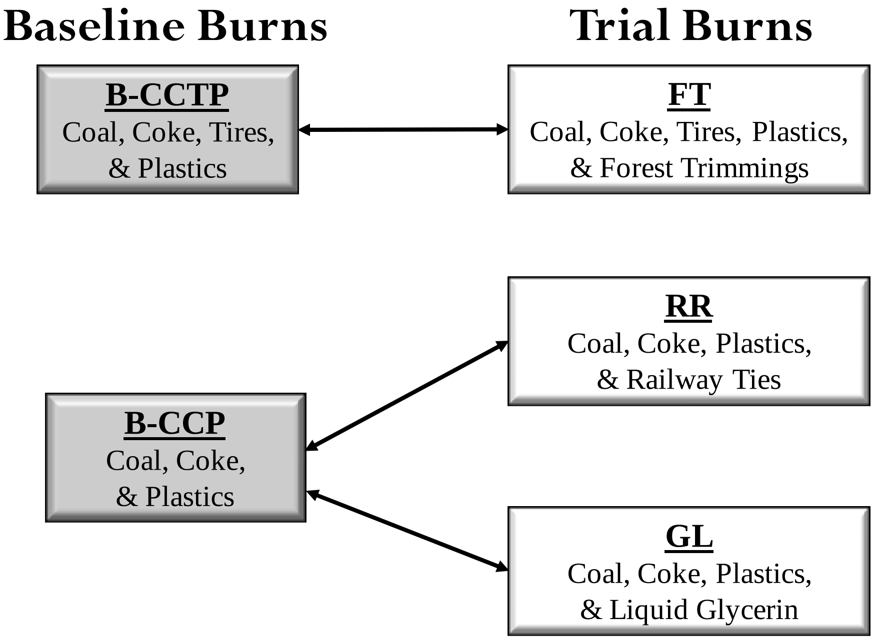


Figure 3.15: Cements used in admixture study

Three cement paste mixtures were prepared from each cement: one control mixture containing no admixture, one containing an accelerating admixture, and one containing a retarding admixture. Two comparisons were made. First, the admixture mixtures were compared to the control mixture to determine the effects of each admixture on that cement. These results were then compared to those from its corresponding baseline burn in an attempt to link admixture performance to the use of alternative fuels. Throughout the study, much effort was made to hold the following conditions constant: water/cement ratio (w/c), mixing procedure, temperature of materials during mixing, admixture dosage, and the time delay between mixing and testing.

Daraset 200 (accelerator) and *Daracem 19* (retarder) were the chemical admixtures used. A dosage of 35.0 oz/cwt was used for the accelerator, and 14.5 oz/cwt was used for the retarder. These dosages were found to accelerate and retard the setting times of an arbitrary cement sample by approximately two hours. This was determined by trial and error, beginning with the recommended dosage provided by the admixture supplier and adjusting accordingly. Several attempts were made with various dosages, and setting times were measured for each until an adequate dosage was determined for both admixtures. These dosages were then used for all cements involved in the study. The method for determining setting times is described later in this section.

A standardized mixing and testing procedure was developed to isolate the admixture as the only variable. The cement paste was mixed in a general, household blender. A standard w/c ratio of 0.44 was used, consisting of 176 g water and 400 g cement. All materials were stored, and mixing was performed within a temperature-controlled environment, held within 23 ± 2 °C. The following mixing procedure was used:

1. Place water into the blender, followed by the cement,
2. Mix for 10 seconds,
3. Scrape the sides of the blender with a spatula to remove clumps,
4. Resume mixing for 60 seconds,
5. Add admixture (Note: if no admixture is used, stop mixing and remove lid as if admixture were being used),
6. Resume mixing for 60 seconds,
7. Rest for 60 seconds, and
8. Mix for 60 seconds.

Once the cement paste was mixed, three tests were conducted to determine hydration, flow, and final time of setting. Due to the time-dependent nature of the hydrating cement, two people were used to conduct these tests. The hydration test was conducted by one person, and the tests for flow and setting time were conducted by another.

As discussed in Section 2.6, when portland cement is mixed with water, cement paste is formed, which hydrates through a series of chemical reactions as an exothermic process. This hydration process was measured with a *TAM Air* isothermal calorimeter. This device consists of eight isolated channels connected in series. Each channel contains two chambers, one for a reference sample and another for the test sample. Also in each channel are two heat flow sensors, one under each chamber. Figure 3.16 shows a typical channel from the *TAM Air* isothermal calorimeter. A glass ampoule filled with sand is used as the reference sample, which is calibrated to maintain a temperature of 23 °C. Another glass ampoule is filled with the test sample and introduced into its chamber to initiate the test. In the case of cement paste, the heat generated from the hydration process is monitored by the sample's heat flow sensor. This creates a voltage signal proportional to the heat flow. The sample voltage is compared to the reference sample's voltage, and the difference is used to calculate the rate of heat production in the sample. This is recorded at numerous time intervals throughout the hydration process and is used to determine the heat of hydration release. A typical hydration curve is shown in Figure 3.17, in addition to the five stages of heat evolution.

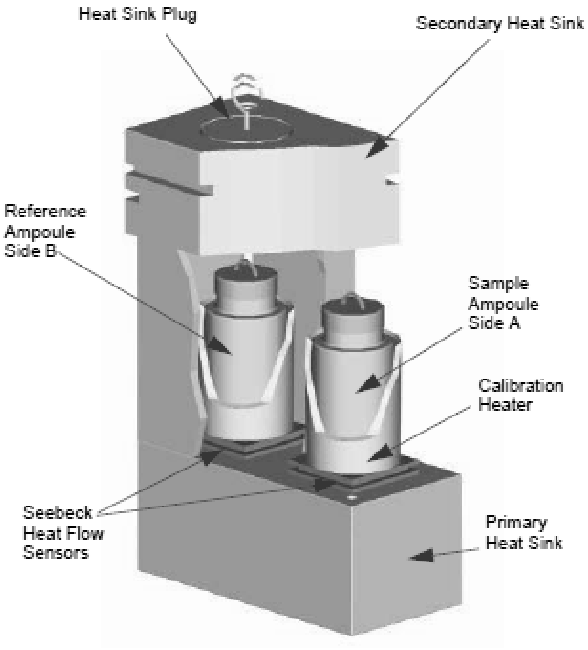


Figure 3.16: One of eight calorimetric channels
(TA Instruments Operator's Manual 2007)

Once a cement paste sample was mixed, a glass ampoule filled with 20 ± 2 g of paste was placed into the *TAM Air* calorimeter to begin monitoring hydration. It took approximately ten minutes from the time of mixing to begin the test. Therefore, it was not possible to monitor the initial peak in the hydration curve during Stage I shown in Figure 3.17. Only the decline of this peak was captured.

The remaining cement paste was used to test the rheology, or flow of the sample. Due to the fluid nature of the paste, a new test was developed by Auburn University staff. This test is similar to ASTM C 1437 (2007), *Flow of Hydraulic Cement Mortar*. A flow mold was placed onto a standard flow table. Paste was poured into the flow mold in one lift, tamped 12-15 times with a trowel, and cut off to a plane surface flush with the top of the mold. The dimensions of this flow mold, as shown in Figure 3.18, deviate from those

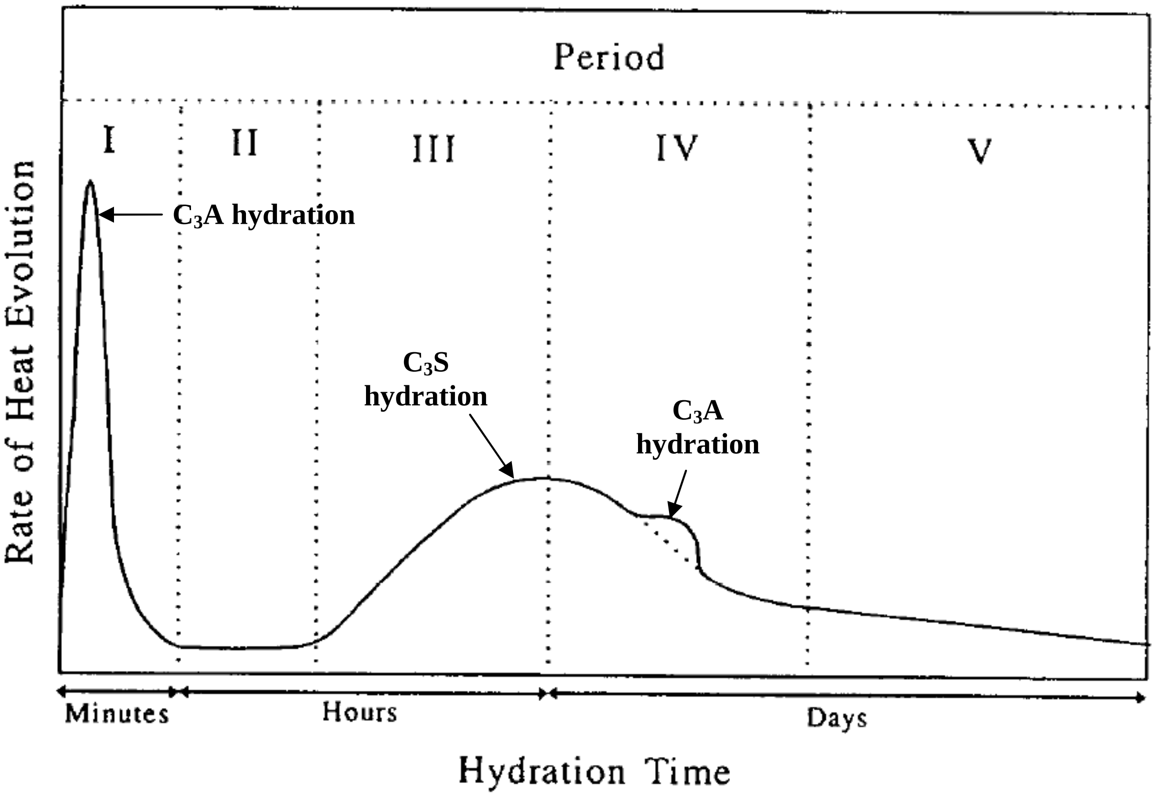


Figure 3.17: Hydration curve and stages of heat evolution
(adapted from Shi and Day 1995)

described in ASTM C 230 (2003). As the mold was lifted off the paste, the flow table was dropped 15 times in approximately 10 seconds. A ruler was used to measure diameters along the four lines scribed in the tabletop. Flow was then recorded in accordance with ASTM C 1437 (2007). The remaining cement paste was used to determine the time of final set by using a variation of the *Vicat* method described in ASTM C 191 (2008). This method deviated from the specification in that the paste was not proportioned or mixed to normal consistency. In addition, due to the fluid nature of the paste, the *Vicat* ring and plate were modified. The ring was essentially clamped to the plate to prevent the paste from seeping underneath the ring. The paste was poured into the ring in two lifts, tapping the apparatus on the counter several times after each lift to remove entrapped air. The ring and paste

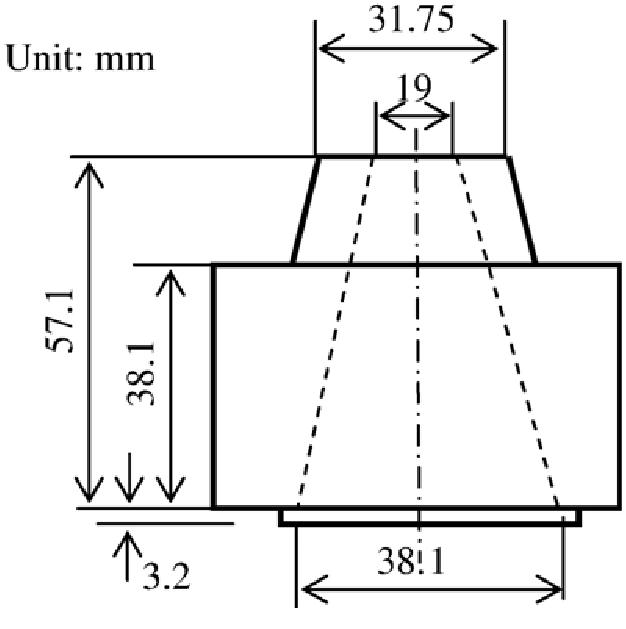


Figure 3.18: Dimensions of mini-flow mold (Sonebi 2006)

were then placed into a moist room, where they remained undisturbed for several hours. A standard *Vicat* apparatus and 1-mm diameter needle were used to determine the final time of setting for the paste in accordance with ASTM C 191 (2008). Initial time of setting was not recorded due to difficulties resulting from the consistency of the paste.

3.4.3 Concrete Properties

At the end of each burn, portland cement was bagged in accordance with the cement plant’s normal operation. Approximately ten bags were collected by Auburn University in order to mix concrete. This was done in an attempt to establish any links between the fuels and the properties of concrete.

There were two different mixture designs developed by Auburn University to produce concrete. The primary mixture design, Mix A, had a water-to-cement ratio (w/c) of 0.44 and used No. 57 crushed limestone and natural river sand as aggregate. The secondary mixture design, Mix B, had a w/c of 0.37 and used No. 78 crushed limestone and the same natural river sand as fine aggregate. A summary of the mixture proportions for Mix A and Mix B are shown in Tables 3.7 and 3.8, respectively.

All concrete was mixed within the mixing laboratory at Auburn University in accordance with ASTM C 192 (2007). Due to the limited size of the concrete mixer, Mix A and Mix B were each split into two batches of approximately equal proportions. However, this was not done for Mix A with the FT and B-CCTP cement. It was noticed during these mixes that a single batch would not sufficiently blend the materials. The remaining mixes were conducted in two batches to resolve this issue.

Once concrete was prepared for each mix, fresh concrete properties were tested. Additionally, various test specimens were prepared for testing. Table 3.9 summarizes the tests conducted for each mixture, in addition to the specification followed for each.

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

Material	Proportion	Volume
Water content	273 lb/yd^3	4.38 ft^3
Cement content	620 lb/yd^3	3.15 ft^3
Coarse aggregate content (# 57 crushed limestone)	1900 lb/yd^3	10.77 ft^3
Fine aggregate content (natural river sand)	1247 lb/yd^3	7.60 ft^3
Total air content	4.0 %	1.08 ft^3
Air-entraining admixture	1.2 oz/yd^3	0.001 ft^3
Water-reducing admixture	12.4 oz/yd^3	0.012 ft^3

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

Material	Proportion	Volume
Water content	260 lb/yd^3	4.17 ft^3
Cement content	705 lb/yd^3	3.59 ft^3
Coarse aggregate content (# 78 crushed limestone)	1942 lb/yd^3	11.40 ft^3
Fine aggregate content (natural river sand)	1104 lb/yd^3	6.73 ft^3
Total air content	4.0 %	1.08 ft^3
Air-entraining admixture	1.8 oz/yd^3	0.002 ft^3
Water-reducing admixture	35.3 oz/yd^3	0.035 ft^3

During the first batch, ten 6 x 12-in. cylinders were prepared for splitting tensile strength testing and four 4 x 8-in. cylinders were prepared for a rapid chloride penetration test (RCPT). During the second batch, eleven 6 x 12-in. cylinders were prepared. Ten were prepared for compressive strength testing and one was used for semi-adiabatic (heat of hydration) testing. Also during the second batch, a specimen was prepared to conduct a setting time test. Finally, three 3 x 3 x 11.25-in. prisms were prepared for testing the drying shrinkage development.

Table 3.9: Concrete tests

Test	ASTM Specification
Slump	C 143 (2008)
Total air content	C 231 (2008)
Setting Time	C 403 (2008)
Compressive Strength (1, 3, 7, 28, and 91 days)	C 39 (2005)
Splitting tensile strength (1, 3, 7, 28, and 91 days)	C 496 (2004)
Drying shrinkage development	C 157 (2006)
Permeability (RCPT)	C 1202 (2007)

In order to satisfy ASTM C 192 (2007), the slump and total air content tests were conducted for both batches. This was done to satisfy the tolerances set forth in Section 9.2 of ASTM C 192 (2007), ensuring consistency in the two batches. Also, two additional cylinders were prepared during the first batch to ensure the 28-day compressive strength was consistent with the second batch.

3.4.4 Plant Emissions

Plant emissions were collected by the cement plant during each burn using a Continuous Emissions Monitoring System (CEMS). This was necessary to ensure the Alabama Department of Environmental Management (ADEM) limits were satisfied. The emissions monitored from the main stack were carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOC).

Although emissions were continuously monitored, they were provided in average tons per hour. Production data gathered by the cement plant were used to normalize these data based on the amount of clinker produced. Emission quantities were reported in tons per ton of clinker produced. These data were used to evaluate the effects of utilizing alternative fuels.

3.5 Concluding Remarks

Five individual burns were conducted at a full-scale cement plant during this phase of the alternative fuels study, each yielding portland cement from a different fueling scenario. All sampling and testing methods used to satisfy the objectives of this study were described in this chapter. Procedures were developed to provide sufficient data regarding the effects of alternative fuels on the production and performance of portland cement.

All process input materials, including raw materials, kiln feed, CKD, and fuels were sampled and tested. All process output materials, including CKD, clinker, and portland cement were sampled and tested. Chemical analyses were performed on all materials mentioned above by the cement plant and/or external laboratory in order to determine any variations that may be attributed to the utilization of alternative fuels.

Various physical properties of portland cement were determined by the cement plant and Auburn University. An admixture study was also incorporated into this phase to evaluate the effects of accelerating and retarding admixtures on all cement produced through the entire alternative fuels study. Portland cement was collected by Auburn University during each burn to mix concrete and evaluate fresh properties, physical properties, and durability.

Emissions were continuously monitored by the cement plant to evaluate the impact of alternative fuels, as well as to ensure environmental regulations were met. Carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and volatile organic compounds (VOC) were the emissions monitored during each burn.

Chapter 4

Data Presentation and Analysis

4.1 Introduction

A summary of all data collected throughout this study in addition to an analysis and discussion of results are presented in this chapter. The data pertaining to each material follow the same order as described in Chapter 3. For each material tested, results obtained from all entities involved in the study are presented separately. Comparisons of results between different entities are made where deemed necessary. Comparisons are made primarily between the trial burns and their corresponding baseline burn.

The first task of this chapter is to present a summary of all available data collected throughout this study. This is presented in tabular form, but may also be in graphical form when thought to better represent the data. In cases where sufficient data are available for a material (typically ten data or more points), a complete set of summary statistics is provided.

The second task of this chapter is to analyze the available data. Since the overall objective of this study is to determine the effects of utilizing various alternative fuels, it is necessary to compare all materials from the trial burns with those from normal, or baseline conditions.

It should be noted that the term *significant* is used frequently throughout this chapter. This may indicate that a particular result merely appears extreme. *Statistical* *significance* is usually determined by a two-sample t-test. Typically, when a claim is supported by the evidence of a t-test, it will be declared as statistically significant. For further clarification, the use of the term, *practical significance* should also be defined. Practical significance is based on the performance of the cement or concrete. Data may be considered statistically significant but not practically significant, or visa versa.

The final task of this chapter is a thorough discussion of results. Emphasis is placed on the parameters that show the greatest change in mean. Any logical explanation of the cause for these changes will be presented. Also, this section will correlate results to those discussed in the literature review presented in Chapter Two. Any results found in this chapter that oppose those from previous findings will be discussed.

To carry out the objectives set forth in this study, an analysis plan was developed to estimate the effects of alternative fuels on the process inputs and outputs during each burn. This analysis plan can be seen in Figure 4.1. In this figure, the baseline burn used for each group of fuels is denoted by a box shaded in gray. The remaining burns in each group were compared to this baseline burn.

4.2 Statistical Background

All data and test results gathered during this study are presented in this chapter. Where sufficient data are available (typically ten or more data points), a set of summary statistics are provided. If sufficient data are not available, the data is represented by either the average alone, or the average and coefficient of variation (C.V.). The C.V. is calculated by dividing the standard deviation by the arithmetic mean and is expressed as a percent. The C.V. is a measure of the dispersion relative to the mean of the data.

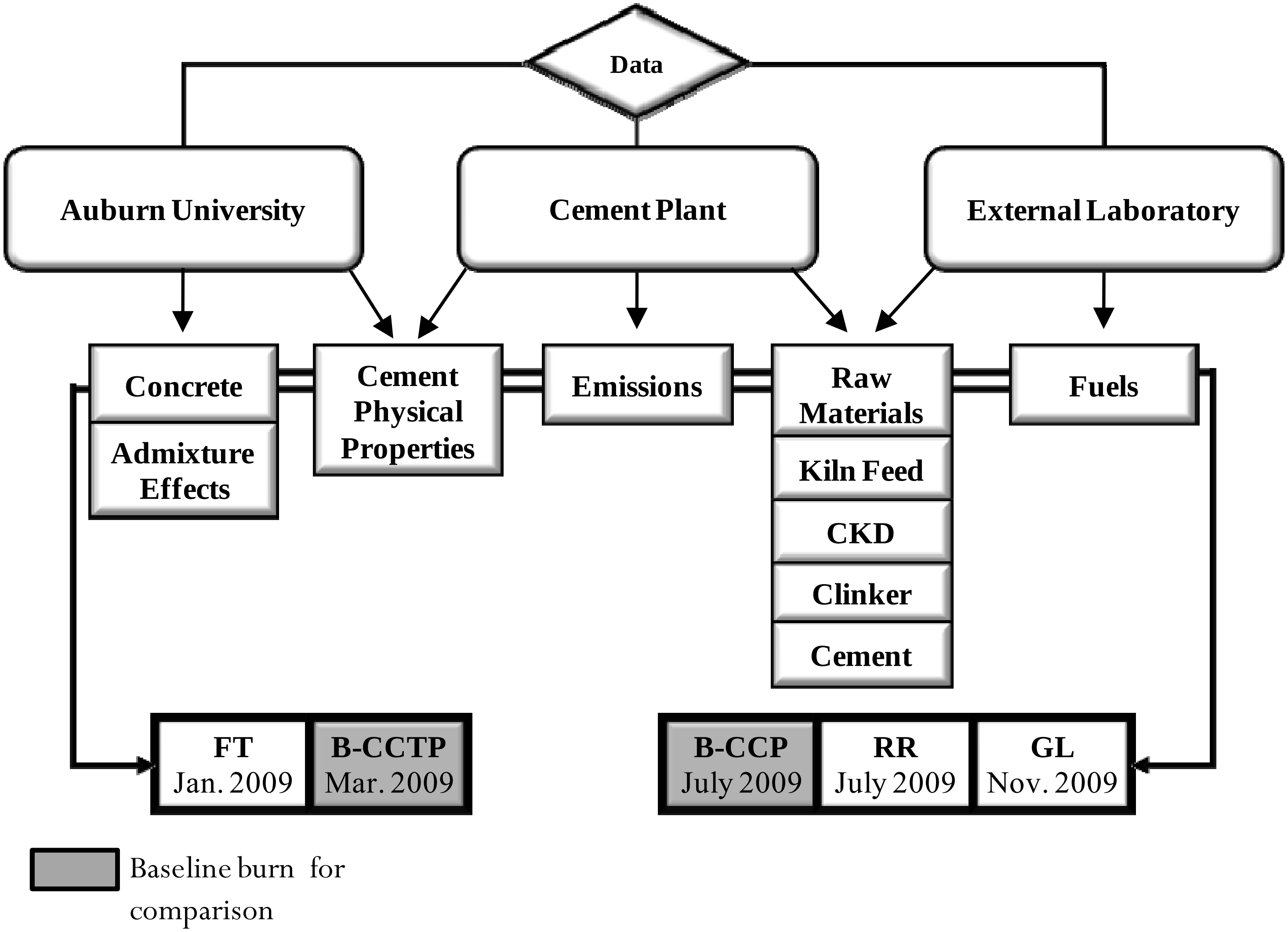


Figure 4.1: Analysis plan for burn data

In addition to the average and C.V., the summary statistics include an indication of how well the data follow a normal distribution. This was determined based on Anderson-Darling statistics (Gingerich 1995). In several cases, the percent difference is shown to indicate how closely trial burns' data match the data from their baseline burn. The percent difference may be deceiving when the average value is small. When sufficient data are available, a Wilcoxin rank-sum test was conducted to determine whether the percent difference is considered statistically significant. This non-parametric, two-sample t-test was chosen because conditions are not heavily dependent on normality or sample size (Bridge and Sawilowsky 1999).

Both the Anderson-Darling and Wilcoxin rank-sum tests are based on a method in which there are two competing hypotheses under consideration: the null hypothesis (H_o) and the alternative hypothesis (H_a) (Gingerich 1995). Initially, H_o is assumed correct. Results from the sample data are used to determine whether there is sufficient evidence to reject the null hypothesis, and accept the alternative hypothesis. Only if convincing evidence is available, is the null hypothesis rejected. This evidence is obtained in the form of a p-value, which represents the probability of failing to reject the null hypothesis (Gingerich 1995). In other words, a small p-value suggests that the null hypothesis is false, and is therefore rejected in favor of the alternative hypothesis.

The Anderson-Darling normality test is used to determine whether a data set follows a normal distribution. A p-value is obtained, which represents the probability that the sample data being tested was drawn from a population with a normal distribution. This test was conducted using SAS 9.1 (Statistical Analysis Software) with the following hypotheses:

H_o: The data follow a normal distribution

H_a: The data do not follow a normal distribution

The test is conducted, and the resulting p-value is obtained. A limiting alpha value of 0.10 was used, which represents a 90% confidence interval, and is typical for relatively small data sets. A p-value of less than 0.10 indicates that the null hypothesis is likely to be false, and thus the data follows a normal distribution. Throughout this chapter, all p-values resulting from the Anderson-Darling normality test will be indicated with a superscript when the data do not follow a normal distribution.

The Wilcoxin rank-sum test was used to determine whether there is a significant difference between the means of two data sets. A p-value is obtained, which represents the probability of the means of the two data sets being equal. This test was also conducted using SAS 9.1 with the following hypotheses:

H_o: The means of the two data sets are equal

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

The test is conducted, and the resulting p-value is obtained. A limiting alpha value of 0.10 was used, which represents a 90% confidence interval, and is typical for relatively small data sets. A p-value of less than 0.10 indicates that the null hypothesis is likely to be false, and thus the difference between two means is considered statistically significant. Throughout this chapter, all p-values resulting from the Wilcoxin rank-sum test will be indicated with a superscript when the data are considered statistically significant.

4.3 Research Conditions

This study is a continuation of previous research, succeeding two phases of investigation. Efforts were initiated by Swart (2007) who examined scrap tires and waste plastics as alternative fuels. Akkapeddi (2008) then observed the effects of broiler litter, woodchips, switchgrass, and a combination of plastics and woodchips as viable fueling options. Results from these previous phases will not be presented in this chapter.

Throughout the initial phase conducted by Swart (2007), it was difficult to conclude that any effects were a direct result to the fueling scenario. This was due to the variation in production inputs during the extensive time delay between trial burns and their baseline. To remedy this issue, Akkapeddi (2008) conducted baseline burns closer to the trial burns to limit the time gap between comparable burns, and thus reducing variation in production inputs. This practice was also followed in the current phase.

Recall from Chapter 3 that the alternative fuels evaluated in this phase were co-fired with traditional fuels over a 3- to 4-day burn period to produce portland cement within a full-scale cement plant. As a reminder, the five burns periods are listed below, in addition to the fuels utilized during each.

1. **FT** – Trial burn utilizing coal, petroleum coke (coke), tires, plastic, and forest trimmings (FT)
2. **B-CCTP** – Baseline burn utilizing coal (C), coke (C), tires (T), and plastics (P)
3. **B-CCP** – Baseline burn utilizing coal (C), coke (C), and plastics (P)
4. **RR** – Trial burn utilizing coal, coke, plastics, and railway ties (RR)
5. **GL** – Trial burn utilizing coal, coke, plastics, and liquid glycerin (GL)

Each burn period lasted approximately 72 hours, with the exception of the RR burn, which lasted 96 hours. Despite the efforts previously discussed, some time elapsed between each burn to allow the cement plant to carry out its typical production process without the influence of additional testing and fuel usage required by this study. During this time, many aspects of the production process may have changed relative to each burn in order to maximize production efficiency. These include kiln feed rates, fueling rates, and production rates, as well as sources of various process input materials (i.e. raw materials, coal, petroleum coke, etc.). However, production rates were continuously monitored during each burn, and can be viewed in Table 4.1.

Although waste tires and plastics were previously considered as alternative fuels, they are used during normal conditions at the cement plant and are therefore considered conventional fuels for the purpose of this study. However, forest trimmings and railway ties were mixed with waste plastics to form an alternative solid fuel (ASF) blend prior to kiln entry. Approximate proportions of this blend were used to calculate the average plastics and alternative fuel feed rates shown in Table 4.1. Although the ASF feed rate is not shown in Table 4.1, it is simply the sum of the plastics and alternative fuel feed rates.

The feed rate of the waste tires shown in Table 4.1 can be seen to fluctuate greatly throughout the FT and B-CCTP burns. This was necessary to control the sulfur content within the kiln to ensure proper operation. Plant personnel were required to load waste tires onto the conveyor system, which may have also contributed to its inconsistent feed rate.

Table 4.1: Summary of plant conditions during each burn

Burn	FT	B-CCTP	B-CCP	RR	GL
Period	Jan. 2009	Mar. 2009	Jul. 2009	Jul. 2009	Nov. 2009
Kiln Feed Rate (mtph)	170-315	205-281	203-306	230-307	252-297
Clinker Production Rate (mtph)	113-191	173-266	258-39	262-331	160-196
Coal Feed Rate (mtph)	8.8-21.5	5.4-18.4	3.7-12.4	6.1-14.9	4.9-13.4
Pet Coke Feed Rate (mtph)	0-6.1	0-6.3	4.0-7.5	3.2-7.8	5.4-7.4
Tire Feed Rate (mtph)	0-57.2	0-36.5	-	-	-
Plastic Feed Rate (mtph)	2.3-4.8	3.2-6.2	5.0-8.2	4.0-5.3	6.6-7.6
Alternative Fuel Feed Rate (mtph)	1.7-3.6	-	-	2.8-3.7	0-20.4
Alternative Fuel Replacement Rate (%)[a]	0.8-5.8	-	-	6.7-9.3	0-38.4

Note: [a] **Reported on an as-received, energy replacement basis**

The alternative fuel replacement rate was calculated using actual production data shown in Table 4.1. The fuels' as-received energy contents obtained from the external laboratory were used to calculate the total energy per hour of each burn. The percentage of energy provided by the alternative was calculated per hour, and the average value is shown in Table 4.1.

Note that the alternative fuel feed rate was relatively low. This was especially the case for the FT and RR burns. Since forest trimmings and railway ties are fibrous materials, they possess high moisture contents. This increased the density of the ASF, partially limiting its potential feed rate into the kiln. As with the plastics, forest trimmings and RR ties were also highly variable in their chemical compositions. This further limited their feed rates to maintain optimal kiln conditions.

It should be noted that several differences are seen in chemical compositions as reported by the cement plant and external laboratory. Although specimens were obtained from the same source, samples may have been collected at different times.

4.4 Data Presentation and Analysis

All tables and figures presented in this chapter have been labeled with a specific notation that designates the entity, or testing facility from which the data originated. This notation is shown below with the entities in the order they will be presented.

- Cement plant results (CPR) refers to those obtained from the cement plant laboratory.
- External laboratory results (ELR) refers to those compiled at the external laboratory.
- Specialty laboratory results (SLR) refers to those determined from the cement plant’s specialty laboratory.
- Auburn University results (AUR) refers to those collected at Auburn University.

The tables and figures represent summarized results gathered from the corresponding entity. The abbreviation *Avg.* refers to the average quantity of all values available for that material. In cases where a material is represented by only a single sample, the term *Value* is used. The abbreviation *C.V.* stands for the coefficient of variation. The abbreviation *% Diff.* refers to the percent difference in trial burn results relative to the results from the corresponding baseline burn gathered by that same entity. For instance, burn B-CCTP is the baseline for the FT burn. For any given parameter from the FT burn, the percent difference is relative to that same parameter from the B-CCTP burn collected by the same entity.

It should be noted that raw data from each material were used to produce the summary and analysis of results in this chapter. All raw data are provided for each burn individually in the appendices (Appendix A through E). Only the raw data not already provided in this chapter will be shown the appendices.

4.4.1 Chemical Composition of Raw Materials

Results for RM1 through RM6 are summarized in Tables 4.2 through 4.13. Percent difference is also shown for the trial burns relative to their baseline. Note that only one test specimen was used to represent each raw material. Therefore, these raw data shown in the tables are not replicated in Appendix A.

The cement plant and external laboratory results for RM1 are shown in Tables 4.2 and 4.3, respectively. Notice that cement plant did not perform tests on RM1 during the FT burn. The source of origin for RM1 did not change between the B-CCP and RR burns, and tests were only conducted once, hence the identical results between the two. Also shown is the percent difference for the trial burn results relative to their corresponding baseline results.

No notable trends were noticed for RM1 in Tables 4.2 and 4.3. However, there is a large difference between the two entities in the SO_3 content of the GL burn. The cement plant reports a value of 0.030% and the external laboratory reports 0.181%. The loss on ignition (LOI) is also seen to vary greatly between the two testing agencies.

Table 4.2: CPR – Chemical composition of RM1 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Al_2O_3	NR	NA	24.7	25.0	25.0	0.00	26.4	5.44
CaO	NR	NA	4.07	2.88	2.88	0.00	2.88	0.00
Fe_2O_3	NR	NA	11.5	11.9	11.9	0.00	11.4	-4.13
K_2O	NR	NA	2.32	2.39	2.39	0.00	2.37	-0.837
MgO	NR	NA	1.73	1.87	1.87	0.00	1.81	-3.21
Na_2O	NR	NA	0.520	0.570	0.570	0.00	0.500	-12.3
SiO_2	NR	NA	45.2	45.6	45.6	0.00	46.5	2.11
SO_3	NR	NA	0.080	0.130	0.130	0.00	0.030	-123
LOI	NR	NA	8.06	7.87	7.87	0.00	6.25	-20.6

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP** **NR - Not Reported**

Table 4.3: ELR – Chemical composition of RM1 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt.%)	**% Diff.[1]**	**Value (wt.%)**	**Value (wt.%)**	**Value (wt.%)**	**% Diff.[2]**	**Value (wt.%)**	**% Diff.[2]**
Al_2O_3	25.2	10.4	22.8	25.6	25.6	0.00	24.1	-5.71
CaO	2.41	-11.3	2.72	2.51	2.51	0.00	2.75	9.77
Fe_2O_3	10.5	21.4	8.64	11.7	11.7	0.00	11.0	-6.19
K_2O	2.35	8.21	2.17	2.49	2.49	0.00	2.30	-7.72
MgO	1.24	7.79	1.15	1.22	1.22	0.00	1.14	-6.32
Na_2O	0.545	7.79	0.506	0.615	0.615	0.00	0.507	-17.5
P_2O_5	0.617	16.2	0.531	0.568	0.568	0.00	0.568	-0.161
SiO_2	45.7	8.99	42.0	47.0	47.0	0.00	45.1	-3.90
SO_3	0.179	-25.7	0.240	0.224	0.224	0.00	0.181	-19.3
TiO_2	1.22	8.59	1.12	1.25	1.25	0.00	1.17	-6.35
Moisture	24.1	1.95	23.6	24.3	24.3	0.00	5.87	-75.85
LOI	9.60	-46.0	17.8	6.43	6.43	0.00	10.7	66.9
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	187	13.3	165	182	182	0.00	124	-32.0
Cd	4.00	NA	< 5	< 5	< 5	NA	< 5	NA
Cl	19.0	0.00	19.0	30.0	30.0	0.00	12.0	-60.0
Co	69.0	1.5	68.0	67.0	67.0	0.00	56.8	-15.3
Cr	138	51.6	91.0	349	349	0.00	86.0	-75.4
Cu	330	-9.6	365	796	796	0.00	314	-60.6
Hg	0.154	-18.5	0.19	0.030	0.030	0.00	0.048	60.0
Mo	16.0	-30.4	23.0	23.0	23.0	0.00	17.2	-25.2
Ni	122	-13.5	141	114	114	0.00	98.9	-13.3
Pb	70.0	2.9	68.0	92.0	92.0	0.00	156	69.2
Se	< 2	NA	< 2	< 2	< 2	NA	4.00	NA
V	373	-12.0	424	341	341	0.00	302	-11.5
Zn	176	23.9	142	202	202	0.00	155	-23.4

Notes:

[1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP**

The cement plant and external laboratory results for RM2 are shown in Tables 4.4 and 4.5, respectively. The source of origin for RM2 did not change between the B-CCP and RR burns, and tests were only conducted once, hence the identical results between the two. Also shown is the percent difference for the trial burn results relative to their corresponding baseline results.

Both testing agencies show an increase in SO_3 content of RM2 from the FT to B-CCTP burns. Also, several differences are noticed between the two agencies. Perhaps the most significant is the SiO_2 content of B-CCTP. The cement plant reports a value of 3.69% and the external laboratory reports 0.963%. This may be an indication of the variability of SiO_2 in RM2. As mentioned, the specimens tested by the cement plant and external laboratory were from the same source, but samples may have been collected at different times.

Table 4.4: CPR – Chemical composition of RM2 for all burns

Parameter	FT		B-CCTP	B-CCP	RR		GL	
	Value (wt. %)	% Diff.[1]	Value (wt. %)	Value (wt. %)	Value (wt. %)	% Diff.[2]	Value (wt. %)	% Diff.[2]
Al_2O_3	0.570	91.3	0.298	0.386	0.386	0.00	0.197	-49.0
CaO	53.2	-2.53	54.6	54.0	54.0	0.00	53.9	-0.276
Fe_2O_3	0.00	-100	0.228	0.283	0.283	0.00	0.281	-0.707
K_2O	0.080	-16.7	0.096	0.136	0.136	0.00	0.103	-24.3
MgO	1.22	34.7	0.906	0.981	0.981	0.00	0.847	-13.7
Na_2O	0.020	-39.4	0.033	0.051	0.051	0.00	0.040	-21.6
SiO_2	1.82	-50.7	3.69	4.14	4.14	0.00	3.73	-10.1
SO_3	0.160	240.43	0.047	0.054	0.054	0.00	0.016	-70.4
Moisture	NR	NA	NR	NR	NR	NA	NR	NA
LOI	43.5	1.40	42.9	42.4	42.4	0.00	42.4	-0.047

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP** **NR - Not Reported**

Table 4.5: ELR – Chemical composition of RM2 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt.%)	**% Diff.[1]**	**Value (wt.%)**	**Value (wt.%)**	**Value (wt.%)**	**% Diff.[2]**	**Value (wt.%)**	**% Diff.[2]**
Al_2O_3	0.318	45.1	0.220	0.815	0.815	0.00	0.476	-41.6
CaO	53.3	-2.0	54.5	52.9	52.9	0.00	51.9	-1.96
Fe_2O_3	0.19	27.2	0.152	0.408	0.408	0.00	0.206	-49.4
K_2O	0.06	122	0.028	0.105	0.105	0.00	0.143	36.0
MgO	1.22	46.1	0.833	1.46	1.46	0.00	1.21	-17.6
Na_2O	0.028	NA	ND	0.025	0.025	0.00	0.032	28.5
P_2O_5	0.00	NA	ND	0.012	0.012	0.00	0.00	-100
SiO_2	1.32	37.1	0.963	2.28	2.28	0.00	2.15	-5.91
SO_3	0.085	51.6	0.056	0.080	0.080	0.00	0.071	-11.1
TiO_2	0.00	NA	ND	ND	ND	NA	ND	NA
Moisture	2.57	87.9	1.37	2.53	2.53	0.00	20.4	706
LOI	43.4	0.313	43.2	41.8	41.8	0.00	43.8	4.64
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	3.00	-76.9	13.0	20.0	20.0	0.00	11.9	-40.5
Cd	< 3	NA	5.00	< 5	< 5	NA	< 5	NA
Cl	32.0	0.00	32.0	22.0	22.0	0.00	23.0	4.5
Co	12.0	0.00	12.0	22.0	22.0	0.00	10.3	-53.1
Cr	87.0	107	42.0	224	224	0.00	16.7	-92.6
Cu	22.0	-58.5	53.0	297	297	0.00	32.5	-89.0
Hg	0.103	80.7	0.057	0.170	0.170	0.00	0.197	15.9
Mo	10.0	NA	< 1	1.0	1.0	0.0	< 1	NA
Ni	6.00	-95.3	128.0	< 5	< 5	NA	1.59	NA
Pb	17.0	41.7	12.0	< 4	< 4	NA	< 4	NA
Se	< 2	NA	< 2	< 2	< 2	NA	< 2	NA
V	< 4	NA	< 4	< 4	< 4	NA	< 4	NA
Zn	9.00	-35.7	14.0	25.0	25.0	0.00	7.93	-68.3

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP **ND - Not Detected**

The cement plant and external laboratory results for RM3 are shown in Tables 4.6 and 4.7, respectively. Also shown is the percent difference for the trial burn results relative to their corresponding baseline results.

From Table 4.7, the lead (Pb) content is seen to change significantly between the FT and B-CCTP burns. Also, the zinc (Zn) content of RR is seen to increase greatly relative to its baseline. Several differences are also noticed between the two agencies. Perhaps the most significant is the SiO_2 content of B-CCTP. The cement plant reports a value of 3.69% and the external laboratory reports 0.963%.

Table 4.6: CPR – Chemical composition of RM3 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Al_2O_3	2.96	3.14	2.87	2.80	2.60	-7.32	2.83	0.893
CaO	41.3	1.62	40.6	41.5	41.9	1.09	41.2	-0.663
Fe_2O_3	1.07	-11.6	1.21	0.910	1.01	10.4	1.22	33.5
K_2O	0.300	15.4	0.260	0.280	0.275	-1.79	0.220	-21.4
MgO	3.82	-12.2	4.35	3.90	3.56	-8.85	4.00	2.56
Na_2O	0.150	7.14	0.140	0.150	0.140	-6.67	0.110	-26.7
SiO_2	13.4	-0.484	13.4	13.3	13.4	0.525	13.3	-0.150
SO_3	0.160	6.67	0.150	0.120	0.110	-8.33	0.115	-4.17
Moisture	NR	NA	NR	NR	NR	NA	NR	NA
LOI	NR	NA	NR	NR	NR	NA	NR	NA

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

Table 4.7: ELR – Chemical composition of RM3 for all burns

Parameter	FT		B-CCTP	B-CCP	RR		GL	
	Value (wt.%)	% Diff.[1]	Value (wt.%)	Value (wt.%)	Value (wt.%)	% Diff.[2]	Value (wt.%)	% Diff.[2]
Al_2O_3	3.29	11.3	2.96	1.14	0.800	-30.1	4.28	274
CaO	38.5	-2.37	39.4	57.5	52.5	-8.71	33.3	-42.1
Fe_2O_3	1.80	38.6	1.30	0.332	0.409	23.2	2.23	571
K_2O	0.387	4.96	0.369	0.066	0.120	80.1	0.315	374
MgO	2.02	-39.2	3.33	0.894	1.59	77.6	3.37	277
Na_2O	0.067	106	0.032	0.022	0.025	13.7	0.043	92.2
P_2O_5	0.020	3.15	0.019	0.052	0.006	-87.8	0.034	-34.1
SiO_2	20.5	22.2	16.8	2.70	4.33	60.3	24.8	819
SO_3	0.053	-78.8	0.252	0.04	0.076	70.6	0.068	53.7
TiO_2	0.167	84.2	0.091	NR	0.006	NA	0.307	NA
Moisture	7.19	-31.6	10.5	NR	4.19	NA	6.72	NA
LOI	33.1	-6.36	35.4	37.2	40.1	7.96	31.1	-16.3
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	15.0	-28.6	21.0	<4	17.0	NA	33.2	NA
Cd	< 3	NA	5.00	< 6	< 5	NA	< 5	NA
Cl	45.0	0.00	45.0	25.0	28.0	12.0	44.0	76.0
Co	15.0	-16.7	18.0	NR	11.0	NA	21.3	NA
Cr	129	119	59.0	113	420	272	< 5	NA
Cu	47.0	42.4	33.0	129	253	95.7	64.7	-50.0
Hg	0.145	209	0.047	0.034	0.040	17.6	0.040	17.6
Mo	4.00	-71.4	14.0	<1	3.00	NA	< 1	NA
Ni	13.0	-94.5	238	<5	< 5	NA	17.0	NA
Pb	22.0	175	8.00	41.1	< 4	NA	< 4	NA
Se	< 2	NA	< 2	6.00	< 2	NA	< 2	NA
V	49.0	4.26	47.0	4.70	9.00	91.4	45.1	860
Zn	39.0	18.2	33.0	4.70	31.0	559	33.2	606

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

The cement plant and external laboratory results for RM4 are shown in Tables 4.8 and 4.9, respectively. Notice that cement plant did not perform tests on RM4 during the FT burn. The source of origin for RM4 did not change between the B-CCP and RR burns, and tests were only conducted once, hence the identical results between the two. Also shown is the percent difference for the trial burn results relative to their corresponding baseline results.

From Table 4.8, the LOI value is seen to increase significantly from the GL to the B-CCP burn. This is also confirmed by the external laboratory in Table 4.9. The lead (Pb) content is also seen to increase significantly during the GL burn. Perhaps the most notable difference between the two entities is the Fe_2O_3 content from the RR and B-CCP burns. The cement plant reports a value of 20.9% where the external laboratory reports 38.9%. The loss on ignition (LOI) is also seen to vary greatly between the two testing agencies.

Table 4.8: CPR – Chemical composition of RM4 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.**[1]	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.**[2]	**Value (wt. %)**	**% Diff.**[2]
Al_2O_3	NR	NA	2.83	6.24	6.24	0.00	2.28	-63.5
CaO	NR	NA	31.1	30.5	30.5	0.00	15.4	-49.6
Fe_2O_3	NR	NA	31.3	20.9	20.9	0.00	48.6	133
K_2O	NR	NA	0.060	0.170	0.170	0.00	0.140	-17.6
MgO	NR	NA	9.27	12.4	12.4	0.00	3.10	-75.0
Na_2O	NR	NA	0.120	NR	NR	NA	0.190	NA
SiO_2	NR	NA	NR	23.4	23.4	0.00	10.2	-56.5
SO_3	NR	NA	0.250	0.850	0.850	0.00	0.370	-56.5
Moisture	NR	NA	NR	NR	NR	NA	NR	NA
LOI	NR	NA	6.78	3.21	3.21	0.00	18.2	465

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**
[2] **Relative to B-CCP** **NR - Not Reported**

Table 4.9: ELR – Chemical composition of RM4 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt.%)	**% Diff.[1]**	**Value (wt.%)**	**Value (wt.%)**	**Value (wt.%)**	**% Diff.[2]**	**Value (wt.%)**	**% Diff.[2]**
Al_2O_3	3.12	3.94	3.00	4.65	4.65	0.00	4.77	2.55
CaO	32.0	-5.28	33.8	26.6	26.6	0.00	16.5	-38.0
Fe_2O_3	37.6	14.9	32.7	38.9	38.9	0.00	50.3	29.2
K_2O	0.00	-100	0.020	0.020	0.020	0.00	0.297	1359
MgO	12.1	2.14	11.9	9.16	9.16	0.00	4.26	-53.5
Na_2O	0.030	47.4	0.020	0.031	0.031	0.00	0.135	342
P_2O_5	0.514	0.203	0.512	0.204	0.204	0.00	0.414	103
SiO_2	10.9	-16.4	13.0	13.6	13.6	0.00	12.7	-6.07
SO_3	0.282	-50.9	0.574	0.896	0.896	0.00	0.396	-55.8
TiO_2	0.252	11.6	0.225	0.244	0.244	0.00	0.396	62.1
Moisture	5.29	-0.116	5.30	6.04	6.04	0.00	10.4	72.2
LOI	0.265	-88.6	2.32	0.468	0.468	0.00	8.36	1688
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	6.00	-45.5	11.0	16.0	16.0	0.0	27.0	68.9
Cd	8.00	14.3	7.00	13.0	13.0	0.00	10.0	-23.1
Cl	170	0.00	170	280	280	0.00	178	-36.4
Co	43.0	4.88	41.0	44.0	44.0	0.00	50.4	14.6
Cr	9843	474	1715	7139	7139	0.00	1056	-85.2
Cu	43.0	-69.3	140	1034	1034	0.00	146	-85.9
Hg	0.316	67.2	0.189	0.080	0.080	0.00	0.040	-50.0
Mo	49.0	63.3	30.0	100	100	0.00	19.8	-80.2
Ni	38.0	-43.3	67.0	158	158	0.00	42.3	-73.2
Pb	< 4	NA	23.0	92.0	92.0	0.00	238	158
Se	3.00	NA	< 2	6.0	6.00	0.00	3.00	-50.0
V	692	7.96	641	605	605	0.00	324	-46.4
Zn	66.0	-9.59	73.0	2433	2433	0.00	867	-64.4

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP

The cement plant and external laboratory results for RM5 are shown in Tables 4.10 and 4.11, respectively. Notice that cement plant did not perform tests on RM5 during the FT burn. The source of origin for RM5 did not change between the B-CCP and RR burns, and tests were only conducted once, hence the identical results between the two. Also shown is the percent difference for the trial burn results relative to their corresponding baseline results.

No notable trends are noticed from the two tables. Perhaps the most notable differences between the two entities are in the K_2O content and LOI value from the RR and B-CCP burns. The cement plant reports values much higher than those reported by the external laboratory for both parameters. Also, from the B-CCTP burn, the cement plant reports a Na_2O content much higher than external laboratory. This indicates variability in these parameters, as specimens tested by both entities were not identical.

Table 4.10: CPR – Chemical composition of RM5 for all burns

Parameter	FT		B-CCTP	B-CCP	RR		GL	
	Value (wt. %)	% Diff.[1]	Value (wt. %)	Value (wt. %)	Value (wt. %)	% Diff.[2]	Value (wt. %)	% Diff.[2]
Al_2O_3	NR	NA	0.640	1.10	1.10	0.00	1.03	-6.32
CaO	NR	NA	0.470	0.425	0.425	0.00	0.430	1.18
Fe_2O_3	NR	NA	0.910	0.976	0.976	0.00	1.13	15.8
K_2O	NR	NA	NR	0.00	0.00	0.00	0.110	NA
MgO	NR	NA	440	0.102	0.102	0.00	0.150	47.1
Na_2O	NR	NA	NR	NR	NR	NA	0.00	NA
SiO_2	NR	NA	97.0	96.2	96.2	0.00	99.1	3.06
SO_3	NR	NA	0.170	0.677	0.677	0.00	0.080	-88.2
LOI	NR	NA	NR	0.520	0.520	0.00	2.29	340

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP** **NR - Not Reported**

Table 4.11: ELR – Chemical composition of RM5 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt.%)	**% Diff.[1]**	**Value (wt.%)**	**Value (wt.%)**	**Value (wt.%)**	**% Diff.[2]**	**Value (wt.%)**	**% Diff.[2]**
Al_2O_3	0.643	6.06	0.606	0.612	0.612	0.00	0.414	-32.4
CaO	3.15	755	0.368	0.114	0.114	0.00	0.343	201
Fe_2O_3	2.33	330	0.541	0.498	0.498	0.00	0.252	-49.3
K_2O	0.029	35.0	0.022	0.031	0.031	0.00	0.030	-2.75
MgO	0.818	440	0.151	0.083	0.083	0.00	0.040	-51.4
Na_2O	0.029	170	0.011	0.021	0.021	0.00	0.010	-51.4
P_2O_5	0.029	NA	NR	NR	NR	NA	ND	NA
SiO_2	91.7	-6.17	97.8	98.1	98.1	0.00	98.4	0.298
SO_3	0.049	NA	NR	NR	NR	NA	NR	NA
TiO_2	0.039	-48.6	0.076	0.124	0.124	0.00	0.071	-43.3
Moisture	5.76	14.1	5.05	2.56	2.56	0.00	0.035	-98.6
LOI	0.822	113	0.385	0.357	0.357	0.00	0.409	14.6
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	15.0	400	3.00	10.0	10.0	0.00	< 4	NA
Cd	< 3	NA	< 5	< 5	< 5	NA	< 5	NA
Cl	25.0	0.00	25.0	4.00	4.00	0.00	4.00	0.00
Co	3.00	-93.2	44.0	87.0	87.0	0.00	73.6	-15.4
Cr	205	659	27.0	262	262	0.00	15.1	-94.2
Cu	17.0	-80.5	87.0	113	113	0.00	70.6	-37.5
Hg	0.009	-95.2	0.192	0.010	0.010	0.00	0.021	110
Mo	15.0	50.0	10.0	4.00	4.00	0.00	< 1	NA
Ni	< 5	NA	312	< 5	< 5	NA	< 5	NA
Pb	6.00	-33.3	9.00	< 4	< 4	NA	36	NA
Se	< 2	NA	8.00	17.0	17.0	0.00	24.0	41.2
V	59.0	NA	< 4	4.0	4.00	0.00	< 4	NA
Zn	7.00	NA	< 5	< 5	< 5	NA	7.06	NA

Notes:

[1] Relative to B-CCTP **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

The cement plant and external laboratory results for RM6 are shown in Tables 4.12 and 4.13, respectively. Note that cement plant does not typically perform tests on RM6, and only did so during the B-CCTP burn. Also, the external laboratory did not determine TiO_2 contents for RM6. The percent differences for the trial burn results relative to their corresponding baseline results are shown in Table 4.13.

From Table 4.13, several differences are noticed in the parameters between the trial burns and their baseline. During the FT burn, As and Cr values are seen to increase greatly, while Co and Zn contents are decreased. During the RR burn, Cr, Zn, and several other parameters are seen to increase, while As and Cl are decreased. Cl, Cu, and Se contents appear to be significantly different than B-CCP. Moisture and LOI values are also seen to vary greatly throughout.

Table 4.12: CPR – Chemical composition of RM6 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Al_2O_3	NR	NA	0.00	NR	NR	NA	NR	NA
CaO	NR	NA	36.0	NR	NR	NA	NR	NA
Fe_2O_3	NR	NA	0.380	NR	NR	NA	NR	NA
K_2O	NR	NA	0.030	NR	NR	NA	NR	NA
MgO	NR	NA	0.98	NR	NR	NA	NR	NA
Na_2O	NR	NA	0.130	NR	NR	NA	NR	NA
SiO_2	NR	NA	3.99	NR	NR	NA	NR	NA
SO_3	NR	NA	73.3	NR	NR	NA	NR	NA
Moisture	NR	NA	NR	NR	NR	NA	NR	NA
LOI	NR	NA	NR	NR	NR	NA	NR	NA

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

Table 4.13: ELR – Chemical composition of RM6 for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt.%)	**% Diff.[1]**	**Value (wt.%)**	**Value (wt.%)**	**Value (wt.%)**	**% Diff.[2]**	**Value (wt.%)**	**% Diff.[2]**
Al_2O_3	0.00	-100	0.028	0.077	0.037	-51.9	0.00	-100
CaO	32.9	-14.2	38.4	36.0	40.4	12.4	34.5	-4.19
Fe_2O_3	0.139	-56.7	0.321	0.119	0.148	23.7	0.040	-66.5
K_2O	NR	NA	NR	NR	0.00	NA	0.008	NA
MgO	0.161	-2.42	0.165	0.119	0.231	93.3	0.104	-12.9
Na_2O	0.015	-20.2	0.018	0.009	0.009	8.26	0.016	87.7
P_2O_5	NR	NA	NR	0.009	0.009	8.26	0.00	-100
SiO_2	0.337	-26.6	0.459	0.435	0.498	14.6	0.296	-31.9
SO_3	44.8	-11.9	50.8	45.7	47.8	4.45	45.8	0.123
TiO_2	NR	NA	NR	NR	NR	NA	NR	NA
Moisture	10.6	-41.4	18.1	11.6	20.3	74.8	9.00	-22.4
LOI	21.6	121	9.78	17.5	10.8	-38.2	19.2	10.1
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	11.0	83.3	6.00	12.4	7.00	-43.5	< 4	NA
Cd	< 3	NA	< 2	< 6	< 5	NA	< 5	NA
Cl	94.0	0.00	94.0	397	156	-60.7	185	-53.4
Co	3.00	-66.7	9.00	5.16	11.0	113	8.00	54.9
Cr	43.0	153	17.0	47.5	274	477	< 5	NA
Cu	< 5	NA	22.0	37.2	173	365	68.0	82.8
Hg	0.401	-6.74	0.43	< 0.01	0.090	NA	0.039	NA
Mo	9.00	NA	< 1	<1	< 1	NA	< 1	NA
Ni	< 5	NA	< 5	<5	< 5	NA	3.20	NA
Pb	< 4	NA	31.0	<4	< 4	NA	< 4	NA
Se	34.0	36.0	25.0	5.00	25.0	400	20.0	300
V	< 4	NA	< 4	<4	NR	NA	< 4	NA
Zn	12.0	-42.9	21.0	14.5	21.0	45.3	17.6	21.7

Notes: **[1] Relative to B-CCTP** **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

4.4.2 Chemical Composition of Kiln Feed

Kiln feed is the primary input of the production process, representing a blend of several inputs into the kiln system. For this reason, a change in kiln feed composition can usually be attributed to a change in composition for one of the raw materials. Kiln feed was sampled twice per day during each burn to obtain an average chemical composition. The average percent by weight (Avg. wt.) and the coefficient of variation (C.V.) for all samples collected by the cement plant staff are tabulated in Table 4.14. The small sampling frequency did not provide enough data to conduct a proper normality test.

Table 4.15 shows the percent difference of all trial burns relative to their baseline burn. Again, insufficient data does not permit a t-test to determine the significance of this difference. Figure 4.2 also shows a graphical representation of the percent difference for some of the parameters listed in Table 4.15. Most parameters are seen to be relatively consistent with their respective baseline condition. The greatest difference is seen in the MgO content for the GL burn. This may be attributed to the large MgO content of RM3 shown in Table 4.7. Moisture content can also be seen to fluctuate greatly. The FT trial burn shows the greatest difference in moisture relative to its baseline.

The results for kiln feed specimens tested by the external laboratory can be seen in Table 4.16. From this table, FT can be seen to exhibit the greatest difference in moisture, which is consistent with the cement plant results. As mentioned, variation in moisture is expected. Cr and Cu contents can be seen to vary greatly for all burns. Also from Table 4.16, Mo and Pb contents are seen to differ greatly for the FT and GL burns, respectively. All other parameters seem to be relatively consistent.

Table 4.14: CPR – Kiln feed compositions for all burns

Parameter	FT		B-CCTP		B-CCP		RR		GL	
	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)
Al_2O_3	3.09	2.67	3.02	3.05	3.12	2.27	3.21	0.910	3.21	2.67
CaO	43.2	0.514	43.0	0.394	43.2	0.417	43.0	0.628	42.6	0.589
Fe_2O_3	2.02	0.684	2.07	1.32	2.14	0.964	2.19	1.87	2.19	0.965
K_2O	0.378	4.55	0.341	3.13	0.360	1.76	0.370	3.12	0.299	5.70
MgO	2.09	1.46	2.20	2.68	1.86	1.22	2.00	2.27	2.60	5.86
Na_2O	0.040	0.00	0.044	12	0.062	6.6	0.061	9.3	0.055	18.0
Na_2O_{eq}	0.292	4.56	0.269	4.52	0.299	2.16	0.306	4.26	0.246	5.18
SiO_2	13.3	1.32	13.1	1.89	13.5	0.986	13.6	0.957	12.9	1.64
SO_3	0.118	12.4	0.143	20.1	0.155	15.1	0.174	13.9	0.160	16.2
Moisture	3.25	13.9	2.50	16.3	2.36	4.90	2.22	10.1	1.91	10.3
LOI	36.1	1.45	36.1	0.744	NR	NA	NR	NA	36.4	0.603

Notes: **NA - Not Applicable**
NR - Not Reported

Table 4.15: CPR – Percent difference in kiln feed composition relative to baseline

Parameter	FT	RR	GL
	% Diff.[1]	% Diff.[2]	% Diff.[2]
Al_2O_3	2.43	2.89	3.06
CaO	0.375	-0.43	-1.37
Fe_2O_3	-2.72	2.32	1.96
K_2O	10.8	2.78	-16.9
MgO	-4.80	7.98	40.2
Na_2O	-9.68	-1.08	-10.2
Na_2O_{eq}	8.60	2.50	-17.6
SiO_2	1.28	0.92	-4.22
SO_3	-17.2	12.26	3.14
Moisture	29.9	-5.83	-19.0
LOI	-0.079	NA	NA

Notes:

[1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

NA - Not Applicable

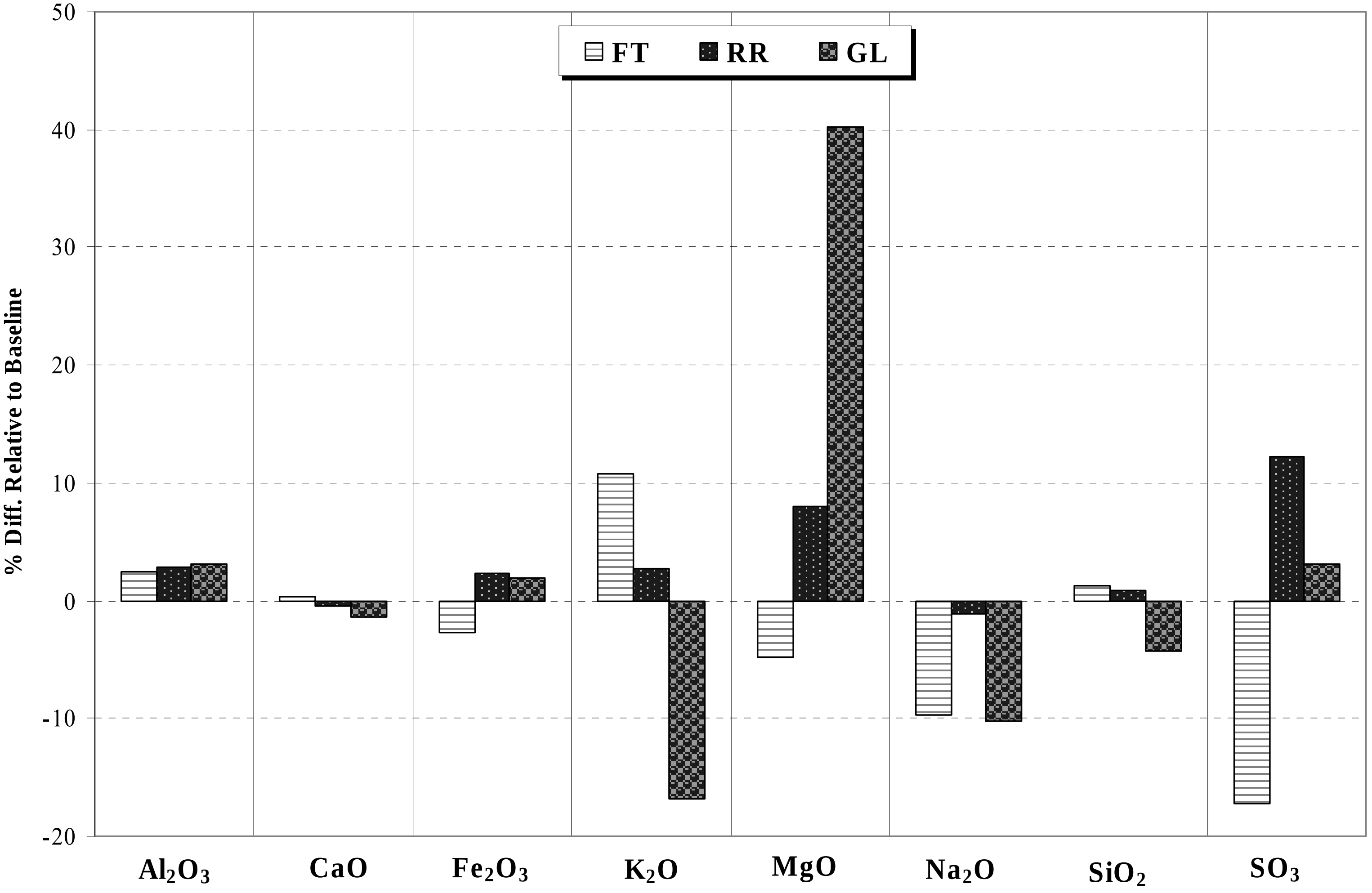


Figure 4.2: CPR – Percent difference in kiln feed composition relative to baseline

Table 4.16: ELR – Kiln feed compositions and percentage difference relative to baseline for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Al_2O_3	3.07	2.33	3.00	3.33	3.12	-6.13	3.02	-9.15
CaO	43.2	1.03	42.8	44.8	43.1	-3.84	42.6	-4.91
Fe_2O_3	2.07	-1.90	2.11	2.30	2.24	-2.43	2.57	11.8
K_2O	0.360	12.5	0.320	0.349	0.340	-2.62	0.285	-18.2
MgO	2.30	-1.29	2.33	2.06	2.14	3.75	2.65	28.5
Na_2O	0.040	-88.6	0.350	0.053	0.048	-10.4	0.062	17.7
P_2O_5	0.040	0.00	0.040	0.045	0.034	-25.3	0.036	-21.6
SiO_2	13.5	3.20	13.1	13.8	13.7	-0.82	12.32	-10.8
SO_3	0.510	-22.7	0.660	0.106	0.136	28.0	0.116	9.25
TiO_2	0.120	71.4	0.070	0.114	0.12	7.50	0.178	56.9
Moisture	0.150	650	0.020	0.135	0.125	-7.59	0.114	-15.7
LOI	34.5	-2.35	35.4	32.8	34.8	6.18	36.0	9.77
Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
As	13.0	-43.5	23.0	22.6	26.0	15.2	< 4	NA
Cd	< 3	NA	< 2	< 6	< 5	NA	< 5	NA
Cl	78.0	0.0	78.0	61.0	48.0	-21.3	72.0	18.0
Co	13.0	-13.3	15.0	21.4	19.0	-11.4	17.8	-16.8
Cr	162	175	59.0	292	544	86.2	< 5	NA
Cu	27.0	-62.5	72.0	127	339	166	37.5	-70.6
Hg	0.15	14.8	0.13	< 0.01	3.00	NA	0.03	NA
Mo	22.0	340	5.00	<1	4.00	NA	< 1	NA
Ni	15.0	7.14	14.0	20.3	29.0	42.8	13.4	-34.1
Pb	20.0	5.26	19.0	21.4	17.0	-20.7	120	458
Se	< 2	NA	< 2	<2	< 2	NA	< 2	NA
V	70.0	22.8	57.0	68.8	58.0	-15.7	39.3	-43.0
Zn	48.0	-9.43	53.0	126	131	3.67	41.9	-66.8

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP**

4.4.3 Chemical Composition of Cement Kiln Dust

Two cement kiln dust (CKD) samples were collected every day during each of the burns. Samples were tested as discrete specimens by the cement plant and external laboratory. Since sufficient data was not available, the normality and t-tests were not performed on these results.

The average percent by weight and coefficient of variation determined by the cement plant is shown in Table 4.17. All standard parameters are shown except the moisture content and LOI. These results were then used to calculate the percent difference of each trial burn relative to their baseline burns, as shown in Table 4.18. From Table 4.18, all values appear to be consistent with their baseline burns. The SO_3 content is seen to differ greatly, but again, this is deceiving as the average is small. The primary parameters from Table 4.18 are presented in graphical form in Figure 4.3.

CKD samples were tested by the external laboratory, and results are shown in Table 4.19. The Cr and Cu contents can be seen to vary greatly for each burn. The Cl and Pb contents are seen to be considerably higher for the GL burn when compared to its baseline. Also, Hg and Cl levels are significantly decreased for the RR and GL trial burns. These same factors were also noticed for the kiln feed. Since CKD is essentially recycled kiln feed, is makes sense that the two yield consistent results.

Table 4.17: CPR – CKD composition for all burns

Paramater	FT		B-CCTP		B-CCP		RR		GL	
	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)	Average (wt. %)	C. V. (%)
Al_2O_3	4.02	8.68	3.95	3.08	3.84	5.72	3.64	10.6	3.74	2.89
CaO	44.5	4.26	45.1	1.26	45.6	4.20	46.8	6.46	46.1	2.99
Fe_2O_3	1.85	4.52	1.85	2.87	1.80	8.82	1.79	11.3	1.97	6.14
K_2O	0.616	43.5	0.472	4.91	0.445	2.36	0.439	9.39	0.386	9.45
MgO	1.49	7.78	1.50	5.37	1.39	11.5	1.74	18.3	1.89	20.6
Na_2O	0.053	23.7	0.057	9.11	0.072	10.5	0.070	15.1	0.096	13.3
SiO_2	12.0	2.56	11.4	1.92	11.8	3.545	11.5	9.186	10.9	3.81
SO_3	0.604	69.8	0.643	45.1	0.372	87.3	0.686	86.2	0.600	68.4

Table 4.18: CPR – CKD composition relative to baseline burn

Parameter	FT	RR	GL
	% Diff.[1]	% Diff.[2]	% Diff.[2]
Al_2O_3	1.81	-5.18	-2.45
CaO	-1.31	2.65	1.13
Fe_2O_3	0.167	-0.814	9.34
K_2O	30.5	-1.35	-13.3
MgO	-0.98	25.5	36.1
Na_2O	-6.72	-2.33	33.6
SiO_2	4.55	-2.52	-7.60
SO_3	-6.07	84.6	61.4

Notes: [1] **Relative to B-CCTP**
[2] **Relative to B-CCP**

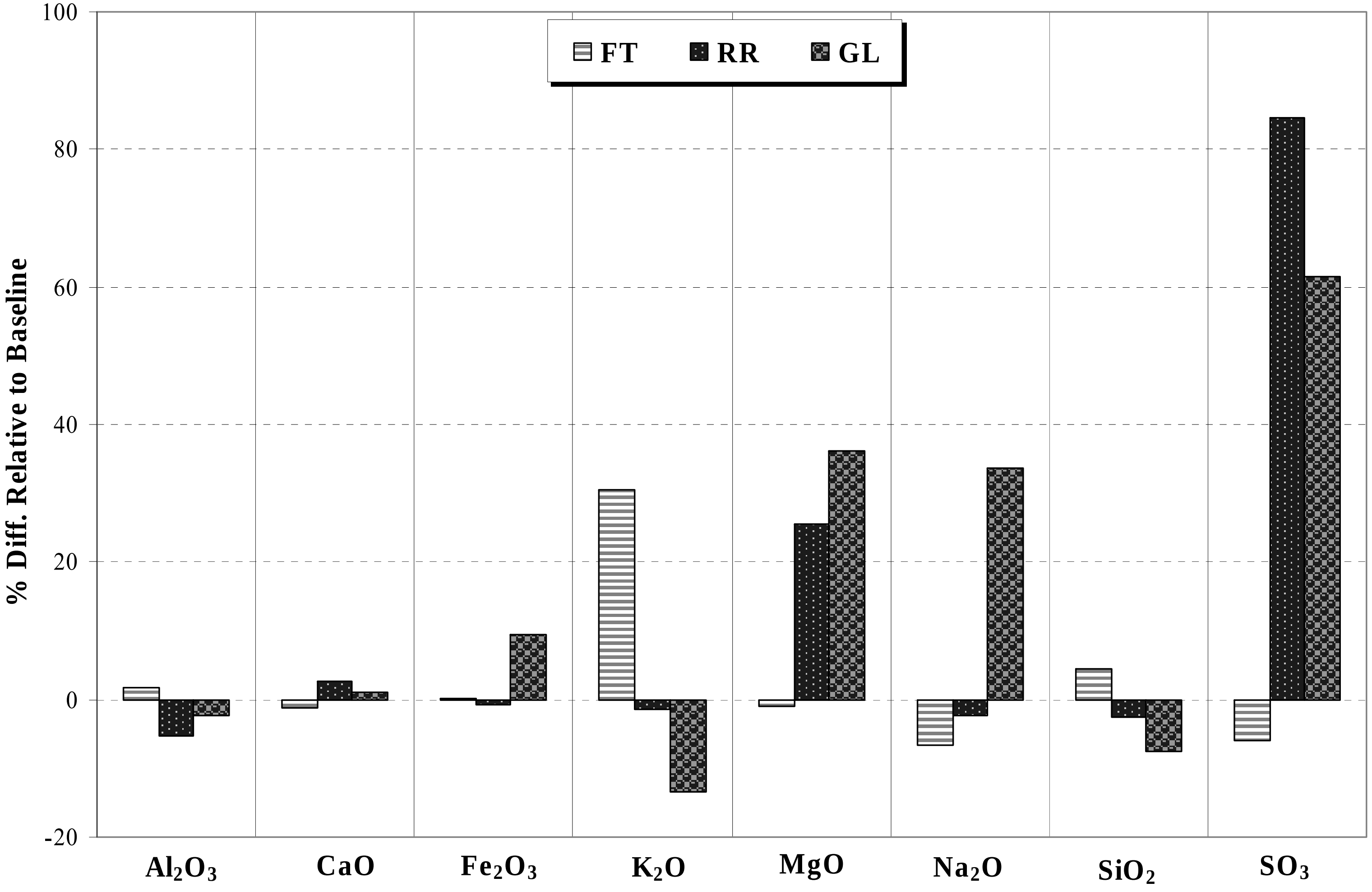


Figure 4.3: CPR – Percent difference in CKD composition relative to baseline

Table 4.19: ELR – CKD compositions for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg. (wt. %)	**% Diff.[1]**	**Avg. (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**	**% Diff.[2]**	**Avg. (wt. %)**	**% Diff.[2]**
Al_2O_3	3.85	1.24	3.80	3.63	3.64	0.394	3.69	1.74
CaO	45.5	-0.167	45.6	51.2	48.1	-6.02	46.6	-8.99
Fe_2O_3	1.79	-1.80	1.83	1.80	1.80	0.049	2.05	13.9
K_2O	0.482	17.9	0.409	0.352	0.408	15.9	0.402	14.1
MgO	1.54	-0.222	1.54	1.76	1.70	-3.23	1.93	9.44
Na_2O	0.081	12.8	0.071	0.068	0.078	15.1	0.107	57.4
P_2O_5	0.040	-10.8	0.045	0.041	0.045	8.96	0.072	76.0
SiO_2	11.6	6.18	11.0	10.5	10.6	1.33	9.88	-5.64
SO_3	0.543	-20.2	0.680	0.694	0.621	-10.5	0.593	-14.5
TiO_2	0.152	65.5	0.092	0.144	0.144	0.256	0.216	49.7
Moisture	0.053	-187	-0.061	0.139	0.175	26.0	0.090	-35.5
LOI	34.2	-1.82	34.9	29.7	32.7	10.1	34.3	15.6
Parameter	**Avg. (ppm)**	**% Diff.**	**Avg. (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**	**% Diff.**	**Avg. (ppm)**	**% Diff.**
As	28.0	2.44	27.3	33.3	36.0	8.18	28.8	-13.3
Cd	< 3.5	NA	< 2	NR	< 5	NA	< 5	NA
Cl	456	0.00	456	158	177	11.9	238	50.8
Co	17.0	0.990	16.8	19.0	16.5	-13.0	14.2	-25.3
Cr	105	103	51.7	153	421	174	31.8	-79.3
Cu	39.7	-36.2	62.2	97.8	422	332	117	19.9
Hg	0.515	6.67	0.482	0.263	0.102	-61.3	0.147	-44.0
Mo	< 4	NA	6.50	5.45	3.17	-41.9	3.73	-31.5
Ni	19.8	-6.30	21.2	20.7	22.2	7.14	14.4	-30.2
Pb	22.7	-15.3	26.8	21.2	20.8	-1.71	38.7	82.7
Se	< 2.8	NA	< 2	5.00	4.00	-20.0	< 2	NA
V	69.5	7.20	64.8	56.6	58.3	3.02	44.6	-21.2
Zn	61.5	13.5	54.2	98.7	127	28.9	67.9	-31.2

Notes:

[1] Relative to B-CCTP **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

4.4.4 Chemical Composition of Fuels

Fuel samples were collected at various frequencies and tested at the external laboratory. In this section, the chemical compositions and properties of each fuel will be presented and evaluated. First, a summary of all fuels used in each burn will be presented. Second, each of the traditional fuels (coal, pet. coke, tires, and plastics) will be discussed individually as they were utilized in each burn. Finally, each of the trial burns will be evaluated individually regarding the traditional and alterative fuels used during their burn periods.

At the particular cement plant used during this study, the following specifications were targeted for the as-received alternative fuels (Akkapeddi et al. 2008):

1. energy value ≥ 5,000 BTU/lb (11.6 MJ/kg)
2. chlorine content ≤ 0.2 %
3. sulfur content ≤ 2.0 %
4. nitrogen content ≤ 1.4 %
5. moisture content ≤ 14%
6. ash content ≤ 18 %

Table 4.20 summarizes the average heating values of each fuel utilized during each burn. Values are shown based on the as-received condition, calculated from the moisture content and dry heating value obtained from the external laboratory. Note that the forest trimmings heating value does not meet the targeted specification, as described above. This is due to the high moisture content of the forest trimmings fuel, which averaged 47%, as seen in Table 4.31. It may be necessary to store the forest trimmings in a moisture-free environment during future use. A lower moisture content would increase the as-received heating value and remedy this issue.

The heating values are also plotted in Figure 4.4. The bar labeled *Alt. Fuel* corresponds to the alternative fuel utilized during each burn. Note the absence of this bar in the two baseline burns as only traditional fuels were utilized (waste tires and plastics are considered traditional fuels for this study). The alternative fuel containing the highest energy per unit weight is the glycerin, followed by the railway ties, then forest trimmings. The conventional fuel with the highest energy content is the waste tires. Waste plastics contained the lowest energy content of all conventional fuels.

The percentages of all fuels utilized during each burn period (from an energy standpoint) are also quantified in Table 4.20. These values were obtained using the feed rates provided by the cement plant and energy values provided by the external laboratory. It should be noted that all values are based upon average feed rates throughout the entire burn period. These values are also plotted in Figure 4.5. Coal constituted the primary fuel in all burns except for the B-CCP burn, in which petroleum coke provided the most energy. The use of waste plastics was higher for both baselines as compared to their respective trial burns. In all cases, the alternative fuel was the fuel least utilized. Relative to the baseline burns, fossil fuel utilization (i.e. coal and pet. coke) were reduced in all trial burns except the RR burn.

Table 4.20: As-received heating value and utilization of all fuels

Fuel	FT	B-CCTP	B-CCP	RR	GL
	Avg. (BTU/lb)	**Avg. (BTU/lb)**	**Avg. (BTU/lb)**	**Avg. (BTU/lb)**	**Avg. (BTU/lb)**
Coal	10727	11245	11500	11011	11354
Pet. Coke	11683	13721	13756	13191	13270
Tires	13713	14540	NA	NA	NA
Plastics	9024	9158	9010	9529	6854
Alt. Fuel	4141	NA	NA	6136	7726
Fuel	**Utilization (%)[1]**	**Utilization (%)[1]**	**Utilization (%)[1]**	**Utilization (%)[1]**	**Utilization (%)[1]**
Coal	59.6	53.8	36.3	42.4	39.5
Pet. Coke	19.4	27.9	37.2	32.7	30.6
Tires	5.4	2.3	NA	NA	NA
Plastics	11.2	15.6	26.5	18.2	25.0
Alt. Fuel	3.9	NA	NA	8.2	5.0

Notes: [1] As-Received Energy Basis

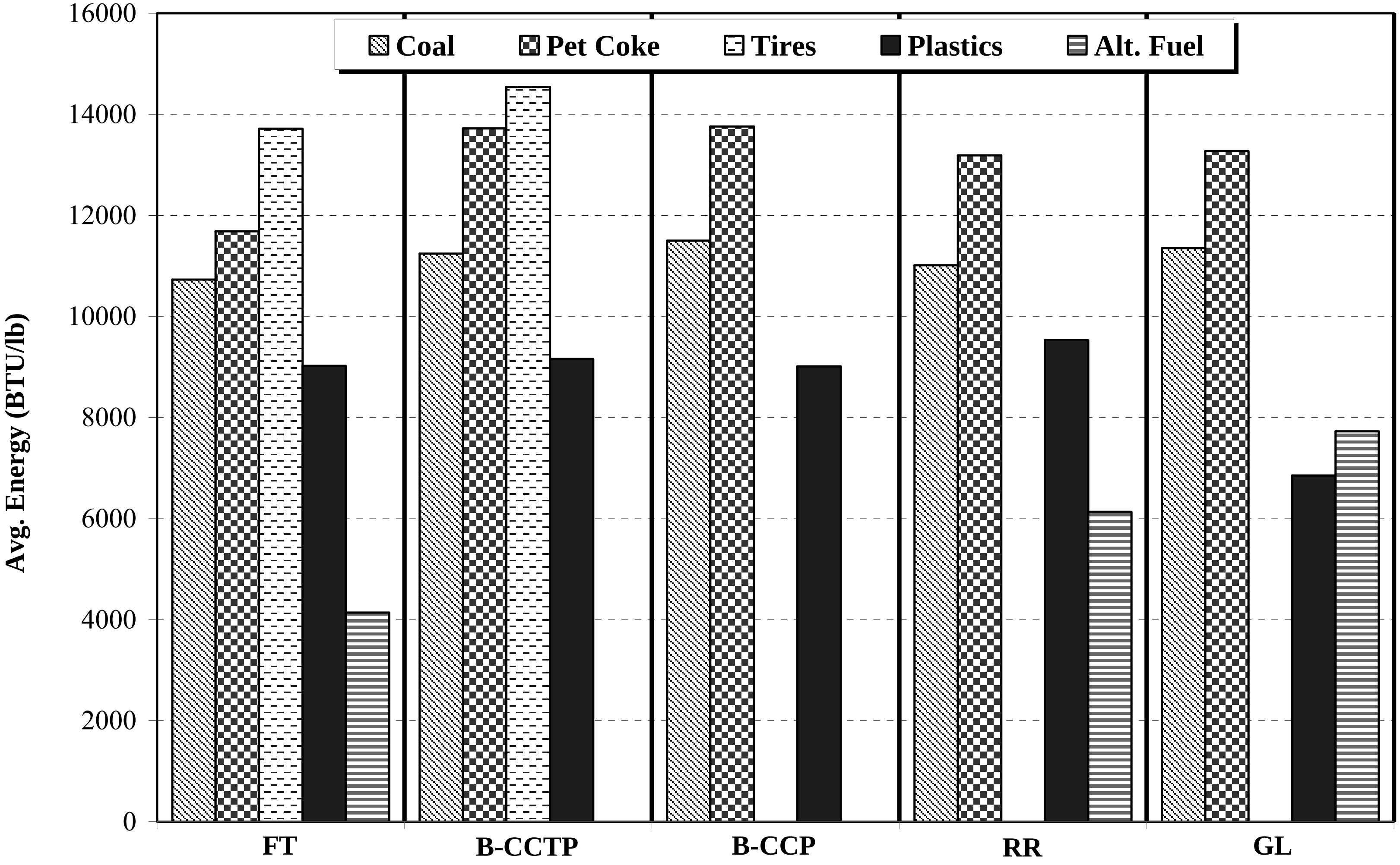


Figure 4.4: ELR – As-received heating values of all fuels

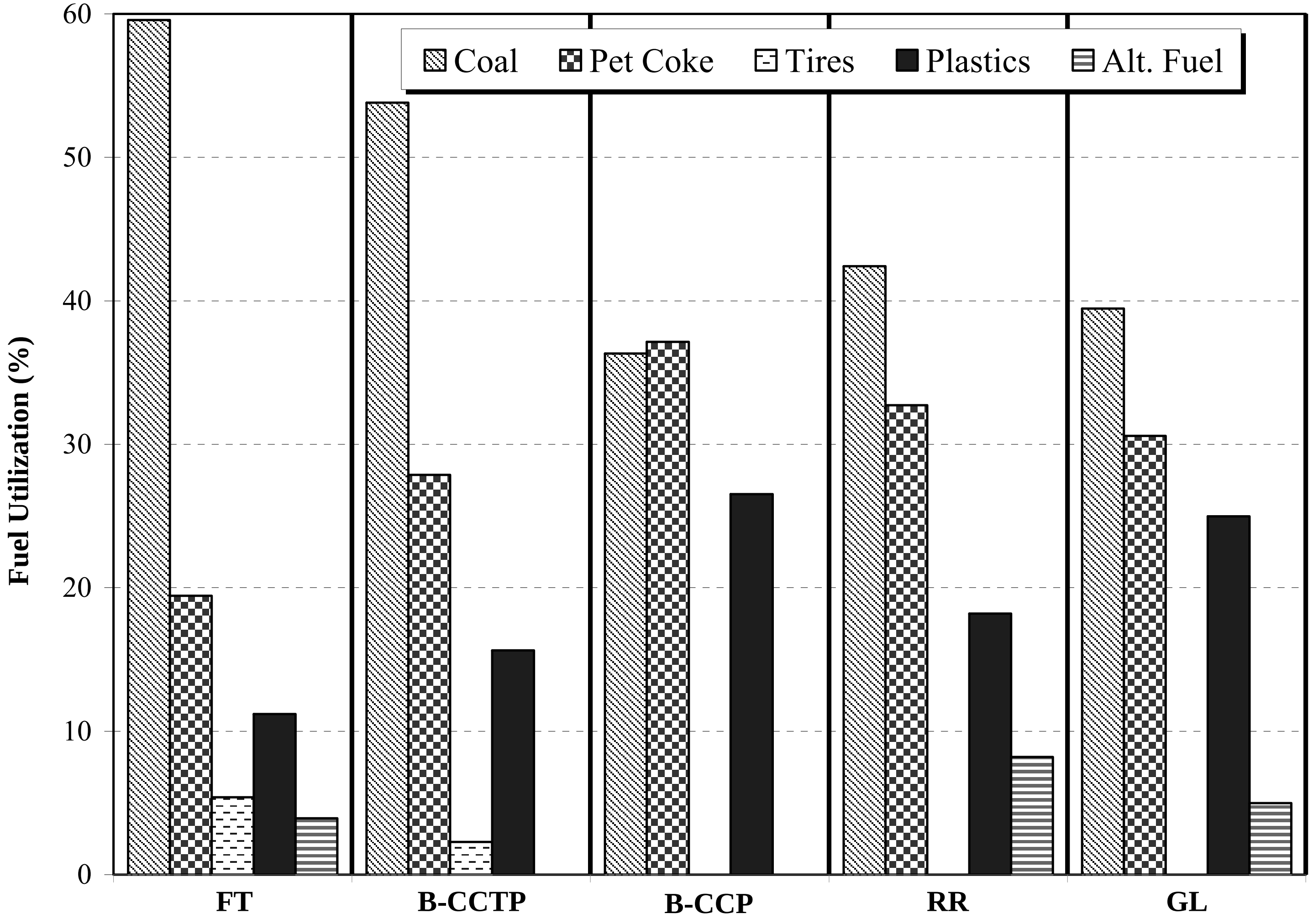


Figure 4.5: ELR – Fuel utilization for all burns

4.4.4.1 Coal

Pulverized coal was the primary fuel used in each burn except the B-CCP burn. Two coal samples were collected every day during each burn, which were tested as 24-hour composite samples by the external laboratory. A proximate, ultimate, and combustion analyses were conducted. In addition, an ash analysis was conducted to determine the standard parameters. This was done to account for the ash incorporated into the clinker after combustion.

The external laboratory results from the proximate, ultimate, and combustion analyses are shown in Table 4.21, and the standard parameters are shown in Table 4.22. Based on Table 4.21, the coal from the FT and RR burns appear to be fairly consistent with their baseline burns. The sulfur content of GL appears to be significantly less than B-CCP. From Table 4.22, the SO_3 content is seen to increase tremendously for each of the trial burns relative their baseline. Hg levels for RR and GL also show a significant increase.

Table 4.21: ELR – Proximate, ultimate, and combustion analysis of coal for all burns

Test	Parameter	FT		B-CCTP	B-CCP	RR		GL	
		Value (wt. %)	% Diff.[1]	Value (wt. %)	Value (wt. %)	Value (wt. %)	% Diff.[2]	Value (wt. %)	% Diff.[2]
Proximate Analysis	Ash	28.3	13.4	24.9	22.2	24.7	11.3	23.8	7.03
	Fixed Carbon	46.5	-6.46	49.7	55.0	50.6	-7.99	50.4	-8.24
	Moisture[3]	1.33	20.9	1.10	1.79	1.67	-6.56	1.12	-37.4
	Volatile Matter	25.3	-0.512	25.4	22.8	24.7	8.26	25.8	13.0
Ultimate Analysis	Carbon	61.6	-4.51	64.5	66.5	64.7	-2.59	63.8	-4.09
	Hydrogen	3.13	-3.40	3.24	3.01	2.99	-0.664	3.23	7.31
	Nitrogen	0.950	-6.86	1.02	0.990	0.983	-0.758	1.07	8.08
	Oxygen	2.94	3.52	2.84	5.07	4.44	-12.4	6.76	33.3
	Sulfur	3.11	-10.4	3.47	2.27	2.14	-5.62	1.44	-36.6
Heat Value[4] (BTU/lb)		10872	-7.34	11370	11710	11199	-4.37	11483	-1.94

Notes:

[1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

[3] **As-received**

[4] **Dry Basis**

Table 4.22: ELR – Standard parameters of coal for all burns

Test	**Parameter**	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
		Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Standard Parameters	**Al_2O_3**	20.7	-8.51	22.6	23.6	21.7	-8.02	21.8	-7.60
	CaO	8.91	-19.7	11.1	8.18	10.1	24.0	10.7	30.4
	Fe_2O_3	11.2	11.8	10.0	9.86	8.76	-11.1	7.57	-23.2
	K_2O	2.23	669	0.290	2.86	2.53	-11.4	2.36	-17.4
	MgO	1.12	-9.31	1.23	1.27	1.24	-2.30	1.25	-1.40
	Na_2O	0.207	-28.8	0.290	0.251	0.273	8.69	0.250	-0.612
	P_2O_5	0.186	9.36	0.170	0.161	0.157	-2.22	0.180	11.8
	SiO_2	45.0	-11.0	50.6	52.2	49.5	-5.20	43.7	-16.2
	SO_3	9.17	3428	0.260	0.37	4.51	1113	10.7	2785
	TiO_2	1.00	-5.48	1.06	1.09	1.02	-6.20	1.05	-3.37
	Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
	As	167	35.8	123	195	130	-33.2	162	-17.0
	Cd	< 5	NA	6.00	< 6	< 6	NA	< 6	NA
	Cl	129	-78.2	592	NC	114	NA	123	NA
	Co	44.0	-4.35	46.0	44.3	37.6	-14.9	37.0	-16.4
	Cr	104	46.5	71.0	164	306	86.7	70.0	-57.3
	Cu	148	-14.0	172	373	577	54.7	868	133
	Hg	0.334	1.21	0.330	0.052	1.01	1842	0.52	906
	Mo	49.0	-5.77	52.0	40.2	38.2	-5.03	29.0	-27.9
	Ni	81.0	-60.3	204	183	175	-4.45	85.0	-53.6
	Pb	31.0	NA	ND	82.5	32.0	-61.2	25.0	-69.7
	Se	3.00	0.00	3.00	<2	< 2	NA	3.00	NA
	V	246	-69.4	804	630	659	4.7	323	-48.7
	Zn	77.0	83.3	42.0	102	91.4	-10.0	121	19.1

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**
[2] **Relative to B-CCP** **ND - Not Detected**

4.4.4.2 Petroleum Coke

Petroleum coke was sampled at the same frequency and tested in the same manner as the coal, described in the previous section. The external laboratory results from the proximate, ultimate, and combustion analyses are shown in Table 4.23, and the standard parameters are shown in Table 4.24.

From Table 4.23, several parameters of the petroleum coke used in the FT burn were different from that of the B-CCTP burn. The most significant is seen in the sulfur content, which was 153% higher during the FT burn. During the RR burn, the ash content increased and oxygen decreased as compared to its baseline. The oxygen in GL increased by over 160% as compared to B-CCP.

According to Table 4.24, SO_3, As, and Zn contents were all seen to increase significantly during the FT burn. During the RR burn, SO_3, Hg, and Pb were all increased. The most notable difference during the GL burn is the increased contents of Na_2O, SO_3, Hg and Pb.

Table 4.23: ELR – Proximate, ultimate, and combustion analysis of petroleum coke for all burns

Test	Parameter	FT		B-CCTP	B-CCP	RR		GL	
		Value (wt. %)	**% Diff.^{1}**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.^{2}**	**Value (wt. %)**	**% Diff.^{2}**
Proximate Analysis	**Ash**	10.2	-59.2	24.9	8.81	12.3	40.0	13.0	47.9
	Fixed Carbon	74.0	49.0	49.7	78.3	71.1	-9.2	71.9	-8.2
	Moisture^3	0.340	-69.1	1.10	0.800	0.680	-15.0	0.580	-27.5
	Volatile Matter	15.8	-37.7	25.4	12.9	16.6	28.6	15.08	16.9
Ultimate Analysis	**Carbon**	78.5	21.6	64.5	78.7	76.3	-3.0	72.5	-7.9
	Hydrogen	3.15	-2.78	3.24	2.7	2.76	2.3	2.77	2.6
	Nitrogen	1.02	0.00	1.02	1.23	1.07	-13.0	1.14	-7.3
	Oxygen	1.56	-45.1	2.84	1.81	0.223	-87.7	4.74	161.9
	Sulfur	8.78	153	3.47	6.74	7.26	7.8	5.81	-13.8
Heat Value^4 (BTU/lb)		11723	-7.34	11370	13867	13281	-4.2	13347	-3.7

Notes: **^{1} Relative to B-CCTP** **^{3} As-received**

^{2} Relative to B-CCP **^{4} Dry Basis**

Table 4.24: ELR – Standard parameters of petroleum coke for all burns

Test	**Property**	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
		Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
Standard Parameters	**Al_2O_3**	12.7	-22.3	16.4	11.3	11.9	5.15	6.89	-39.2
	CaO	19.1	-22.6	24.7	26.6	22.3	-16.2	29.2	9.94
	Fe_2O_3	7.14	-9.7	7.9	6.89	5.27	-23.6	3.25	-52.8
	K_2O	1.47	-10	1.63	1.72	1.37	-20.6	0.742	-56.9
	MgO	1.17	-16.8	1.41	1.30	1.15	-11.6	1.35	3.81
	Na_2O	0.194	-64.1	0.540	0.333	0.179	-46.3	0.793	138
	P_2O_5	0.120	-40.0	0.200	0.130	0.120	-7.61	0.173	32.7
	SiO_2	28.8	-23.5	37.7	27.4	27.8	1.56	16.1	-41.1
	SO_3	26.4	369	5.64	20.9	27.3	30.8	39.4	88.7
	TiO_2	0.563	-22.9	0.730	0.536	0.547	2.07	0.366	-31.7
	Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**% Diff.[2]**	**Value (ppm)**	**% Diff.[2]**
	As	192	134	82	127	116	-8.86	46.8	-63.3
	Cd	< 5	NA	7.0	< 6	< 6	NA	< 6	NA
	Cl	107	-67.3	327	125	124	-0.800	103	-17.6
	Co	40.0	-11.1	45.0	57.9	36.1	-37.6	33.6	-42.0
	Cr	< 10	NA	ND	<10	107	NA	< 10	NA
	Cu	165	-51.3	339	165	544	229	79.3	-51.9
	Hg	0.167	11.3	0.150	0.020	0.900	4400	0.496	2380
	Mo	199	-36	311	429	210	-51.1	149	-65.1
	Ni	3690	-20	4630	4972	1435	-71.1	1669	-66.4
	Pb	436	NA	11.0	18.8	68.4	263	73.2	289
	Se	< 2	NA	< 2	<2	< 2	NA	< 2	NA
	V	9340	-24.7	12400	11269	5919	-47.5	6988	-38.0
	Zn	300	103	148	177	175	-1.19	167	-5.57

Notes:
[1] Relative to B-CCTP **NA - Not Applicable**
[2] Relative to B-CCP **ND - Not Detected**

4.4.4.3 Waste Tires

Waste tires are typically considered alternative fuels. Since they are used during normal operation at the cement plant, they will be considered conventional fuels for the purpose of this study.

Table 4.25 shows the external laboratory results from the proximate, ultimate, and combustion analyses, and Table 4.26 shows the standard parameters. Much variability can be seen in both tables. This is most likely due to the variability in type and source of the tires used at the cement plant. Note the high Fe_2O_3 for both burns shown in Table 4.26. This is because the steel belts of the tires provide a source of iron. Also note the Fe_2O_3 content of the kiln feed in Tables 4.14 and 4.16. For the FT and B-CCTP burns, less iron is required from the raw materials due to the tires being used.

Notice the high zinc content of the tires shown in Table 4.26. Though the zinc content for B-CCTP is higher than FT, both are significantly higher than most fuels, which will be seen in Section 4.4.4.5. As explained in Section 2.3.4.1, these high zinc contents may lead to setting problems, which will be examined later in this chapter.

Table 4.25: ELR – Proximate, ultimate, and combustion analysis of tires for FT and B-CCTP burns

Test	Parameter	FT		B-CCTP
		Value (wt. %)	% Diff.[1]	Value (wt. %)
Proximate Analysis	**Ash**	18.2	-29.3	25.7
	Fixed Carbon	27.6	75.0	15.7
	Moisture[3]	0.320	191	0.110
	Volatile Matter	54.3	-7.31	58.6
Ultimate Analysis	**Carbon**	72.7	0.014	72.6
	Hydrogen	4.85	-6.01	5.16
	Nitrogen	0.480	-25.0	0.640
	Oxygen	1.63	-71.9	5.81
	Sulfur	2.21	33.1	1.66
Heat Value[4] **(BTU/lb)**		13757	-5.49	14556

Notes: [1] **Relative to B-CCTP** [3] **As-received**

[4] **Dry Basis**

Table 4.26: ELR – Standard parameters of tires for FT and B-CCTP burns

Test	**Parameter**	**FT**		**B-CCTP**
		Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**
Standard Parameters	**Al_2O_3**	0.78	-86.1	5.60
	CaO	3.03	103.7	1.49
	Fe_2O_3	76.2	20.5	63.2
	K_2O	0.26	53.7	0.17
	MgO	0.39	11.5	0.35
	Na_2O	0.55	-75.2	2.22
	P_2O_5	0.12	-30.3	0.17
	SiO_2	3.80	-68.1	11.9
	SO_3	4.58	42.2	3.22
	TiO_2	0.29	-94.7	5.34
	Parameter	**Value (ppm)**	**% Diff.[1]**	**Value (ppm)**
	As	7.61	-55.2	17
	Cd	< 5	NA	7.0
	Cl	1415	148	571
	Co	490	-22.7	634
	Cr	286	484	49.0
	Cu	1300	138	546
	Hg	0.03	NA	ND
	Mo	9.31	-51.0	19.0
	Ni	< 10	NA	90.0
	Pb	12.6	-80.8	66.0
	Se	< 2	NA	< 2
	V	37.7	-96.0	946
	Zn	77200	-20.2	96774

Notes: **[1] Relative to B-CCTP**

NA - Not Applicable

ND - Not Detected

4.4.4.4 Waste Plastics

As with tires, waste plastics are typically considered alternative fuels. Since they are used during normal operation at the cement plant, they are considered conventional fuels for the purpose of this study. As discussed in Chapter 3, waste plastics were sampled at various frequencies throughout each burn. Composite specimens were tested by the external laboratory.

The external laboratory results from the proximate, ultimate, and combustion analyses are shown in Table 4.27. Overall, there is much variability in the composition of the plastics. This is expected considering this fuel is a collection of various post-industrial plastics from several sources. The percent difference in plastic composition for the trial burns relative to their baseline burn is shown in Table 4.28. Note the large decrease in sulfur for plastics used during the RR and GL burns.

The standard parameters determined by the external laboratory are shown in Table 4.29. The same variability can also be seen in this table. The percent difference in standard parameters from the trial burns relative to their baseline burns is listed in Table 4.30. The largest differences can be seen in the Cr, Mo, and Ni contents during the RR burn. These values appear to be significantly increased during this burn.

Unfortunately, not enough samples were collected during each burn to conduct the normality or t-tests. Therefore, plastics cannot be properly evaluated to determine the significance of their variability.

Table 4.27: ELR – Proximate, ultimate, and combustion analysis of plastics for all burns

Test	Parameter	FT		B-CCTP		B-CCP		RR		GL	
		Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)
Proximate Analysis	**Ash**	11.2	15.4	10.6	31.2	14.6	46.1	8.57	34.2	9.59	69.2
	Fixed Carbon	7.57	18.2	6.04	52.2	9.83	26.9	7.63	37.9	11.2	15.0
	Moisture [3]	6.35	38.4	7.64	32.9	3.44	69.4	1.74	41.1	18.9	72.0
	Volatile Matter	81.2	0.435	83.4	1.55	75.6	7.26	83.8	4.31	79.2	8.91
Ultimate Analysis	**Carbon**	53.8	11.0	54.7	5.99	50.7	14.1	52.6	9.51	49.6	11.0
	Hydrogen	5.40	3.28	5.73	11.7	5.74	19.0	5.71	23.6	5.58	17.7
	Nitrogen	0.815	13.0	1.50	34.9	0.98	25.5	1.21	20.0	0.954	56.9
	Oxygen	28.3	28.1	27.4	25.4	27.6	34.9	31.7	15.7	34.1	15.0
	Sulfur	0.405	57.6	0.127	28.3	0.375	51.6	0.213	28.2	0.228	57.6
Heat Value [4] **(BTU/lb)**		9636	2.03	9915	10.9	9331	17.0	9725	10.6	8448	16.0

Notes: [1] **Relative to B-CCTP** [3] **As-received**

[2] **Relative to B-CCP** [4] **Dry Basis**

Table 4.28: ELR – Percent difference in proximate, ultimate, and combustion analysis of plastics relative to baseline

Test	**Parameter**	**FT**	**RR**	**GL**
		% Diff.[1]	**% Diff.**[2]	**% Diff.**[2]
Proximate Analysis	**Ash**	6.34	-41.2	-34.2
	Fixed Carbon	25.2	-22.4	14.4
	Moisture [3]	-17.0	-49.3	448
	Volatile Matter	-2.63	10.9	4.72
Ultimate Analysis	**Carbon**	-1.51	3.81	-2.26
	Hydrogen	-5.80	-0.472	-2.82
	Nitrogen	-45.6	23.3	-2.54
	Oxygen	3.26	14.6	23.4
	Sulfur	219	-43.1	-39.2
Heat Value [4] **(BTU/lb)**		-2.82	4.22	-9.47

Notes: [1] **Relative to B-CCTP** [3] **As-received**

[2] **Relative to B-CCP** [4] **Dry Basis**

Table 4.29: ELR – Standard parameters of plastics for all burns

Test	Parameter	FT		B-CCTP		B-CCP		RR		GL	
		Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)	Avg. (wt. %)	C.V. (%)
Standard Parameters	**Al_2O_3**	26.9	69.2	18.4	58.2	26.8	49.5	23.9	55.3	17.7	59.1
	CaO	29.4	59.2	25.7	47.3	26.2	31.2	39.0	47.8	23.9	40.3
	Fe_2O_3	0.614	12.7	8.72	138	6.07	84.7	4.38	76.6	4.60	99.8
	K_2O	0.213	17.7	0.479	90.5	0.589	51.1	0.325	50.2	1.36	85
	MgO	1.44	2.8	4.56	71.7	2.79	54.1	2.21	48.6	4.46	57.5
	Na_2O	13.4	40	4.05	114	4.48	79.7	2.21	66.3	5.63	157
	P_2O_5	0.181	54.0	0.415	43.2	0.471	65.6	0.258	53.6	0.593	96.5
	SiO_2	22.3	27.9	21.8	31.5	24.1	20.0	21.0	45.5	34.0	34.9
	SO_3	3.17	68.2	7.28	99.8	3.23	59.2	2.01	64.9	3.53	285
	TiO_2	2.27	1.6	3.53	65.7	1.90	33.6	2.35	54.9	3.01	161
	Parameter	**Avg. (ppm)**	**C.V. (%)**	**Avg. (ppm)**	**C.V. (%)**	**Avg. (ppm)**	**C.V. (%)**	**Avg. (ppm)**	**C.V. (%)**	**Avg. (ppm)**	**C.V. (%)**
	As	11.0	NA	92.5	146	63.7	235	38.2	99.7	43.5	185
	Cd	6.50	10.9	8.00	0.00	< 6	NA	< 6	NA	< 6	NA
	Cl	91.0	45.1	380	126	670	76	334	73.0	549	195
	Co	32.0	53.0	317	191	102	143	107	56.5	122	115
	Cr	69.0	4.1	159	139	771	79	2970	101	1200	121
	Cu	2332	13.1	2925	163	12725	169	1135	213	1053	100
	Hg	0.044	4.9	0.039	67.7	0.174	127	0.272	22.3	0.184	171
	Mo	44.0	NA	308	87	115	75	429	123	45.2	109
	Ni	66.5	84.0	1048	155	246	127	1576	111	292	167
	Pb	69.5	109	627	125	406	177	198	113	188	97.2
	Se	ND	NA	< 2	NA	<2	NA	<2	NA	< 2	NA
	V	151	35.2	794	167	171	24	160	37.0	216	91.3
	Zn	340	44.8	10509	174	8179	141	1228	132	3171	89.6

Notes:

[1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP** **ND - Not Detected**

Table 4.30: ELR – Percent difference in standard parameters of plastics relative to baseline for trial burns

Test	Parameter	FT	RR	GL
		% Diff.[1]	**% Diff.[2]**	**% Diff.[2]**
Standard Parameters	**Al_2O_3**	46.1	-10.6	-33.7
	CaO	14.3	48.9	-8.77
	Fe_2O_3	-93.0	-27.9	-24.3
	K_2O	-55.5	-44.9	131
	MgO	-68.5	-20.7	59.9
	Na_2O	231	-50.8	25.6
	P_2O_5	-56.5	-45.1	26.0
	SiO_2	2.53	-12.7	40.9
	SO_3	-56.5	-37.9	9.14
	TiO_2	-35.7	23.7	58.7
	Parameter	**% Diff.[1]**	**% Diff.[2]**	**% Diff.[2]**
	As	-88.1	-40.0	-31.7
	Cd	-18.8	NA	NA
	Cl	-76.1	-50.2	-18.0
	Co	-89.9	4.19	19.8
	Cr	-56.6	285	55.7
	Cu	-20.3	-91.1	-91.7
	Hg	12.0	56.2	5.51
	Mo	-85.7	273	-60.7
	Ni	-93.7	540	18.5
	Pb	-88.9	-51.1	-53.6
	Se	NA	NA	NA
	V	-81.1	-6.47	26.2
	Zn	-96.8	-85.0	-61.2

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP**

4.4.4.5 Forest Trimmings Trial Burn (FT)

Coal, petroleum coke, waste tires, and waste plastics were the conventional fuels utilized during the FT burn. In addition, forest trimmings were utilized as the alternative fuel. All fuels were sampled and tested by the external laboratory. Tables 4.31 and 4.32 show the results from all fuels utilized during the FT trial burn. The conventional fuels were presented previously, but are shown again for comparison purposes.

Note from Table 4.31, of all the fuels, forest trimmings have the lowest percentage of carbon and sulfur. This is expected based on Section 2.3.4.3. Conversely, forest trimmings have the highest percentage of moisture and oxygen. Recall from Section 2.3.4.3 that biomass such as forest trimmings typically have high moisture contents as they are fibrous materials. Forest trimmings also have the lowest heating value, while tires have the highest. Petroleum coke has the highest percentages of fixed carbon, carbon, and sulfur, but has the lowest volatile matter and oxygen content. Coal has the largest percentage of ash.

From Table 4.32, forest trimmings have the highest concentration of several parameters, such as K_2O, P_2O_5 and SiO_2. Conversely, Cl and SO_3 concentrations in forest trimmings were the lowest of all fuels. This may be beneficial from an operational standpoint, as excess Cl can lead to kiln buildups. Concentrations of Fe_2O_3 and Zn in the tires were extremely high compared to the other fuels. However, the iron in tires is expected to be high due the steel belts.

Though forest trimmings were the alternative fuel utilized during this burn, they were blended with plastics to form an alternative solid fuel (ASF) blend. On average, the cement plant estimated that the ASF blend consisted of approximately 57% plastics and 43% forest trimmings.

Table 4.31: ELR – Proximate, ultimate, and combustion analysis of all fuels from FT burn

Test	**Parameter**	**Coal**	**Coke**	**Tires**	**Plastics**	**FT**
		Value (wt. %)	**Value (wt. %)**	**Value (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**
Proximate Analysis	**Ash**	28.3	10.2	18.2	11.2	15.2
	Fixed Carbon	46.5	74.0	27.6	7.57	14.3
	Moisture[3]	1.33	0.340	0.320	6.35	47.0
	Volatile Matter	25.3	15.8	54.3	81.2	70.6
Ultimate Analysis	**Carbon**	61.6	78.5	72.7	53.8	48.7
	Hydrogen	3.13	3.15	4.85	5.40	3.89
	Nitrogen	0.950	1.02	0.480	0.815	0.953
	Oxygen	2.94	1.56	1.63	28.3	31.3
	Sulfur	3.11	8.78	2.21	0.405	0.053
Heat Value[4] **(BTU/lb)**		10872	11723	13757	9636	7818

Notes: [3] **As-received**
[4] **Dry Basis**

The ASF blend results from the proximate, ultimate, and combustion analyses are shown in Table 4.33. The sufficient number of specimens allowed a normality test to determine how closely the data follow a normal distribution. Note that all parameters follow a normal distribution except the moisture and sulfur. Note that not all ASF values fall between the two individual values of the plastics and forest trimmings. For instance, the heating values for plastics and forest trimmings from Table 4.31 are 9,636 and 7,818 BTU/lb, respectively. The ASF heating value shown in Table 4.33 is 10,100 BTU/lb. This is most likely attributed to the variability in plastics.

Table 4.32: ELR – Standard parameters of all fuels from FT burn

Test	Parameter	Coal	Coke	Tires	Plastics	FT
		Value (wt. %)	**Value (wt. %)**	**Value (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**
Standard Parameters	**Al_2O_3**	20.7	12.7	0.776	26.9	9.3
	CaO	8.91	19.1	3.03	29.4	15.4
	Fe_2O_3	11.2	7.14	76.2	0.614	4.59
	K_2O	2.23	1.47	0.261	0.213	3.66
	MgO	1.12	1.17	0.390	1.44	1.80
	Na_2O	0.207	0.194	0.552	13.4	0.300
	P_2O_5	0.186	0.120	0.119	0.181	0.922
	SiO_2	45.0	28.8	3.80	22.3	60.3
	SO_3	9.17	26.4	4.58	3.17	0.618
	TiO_2	1.00	0.563	0.285	2.27	0.891
	Parameter	**Value (ppm)**	**Value (ppm)**	**Value (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**
	As	167	192	7.61	11.0	24.3
	Cd	< 5	< 5	< 5	6.50	6.00
	Cl	129	107	1415	91.0	31.7
	Co	44.0	40.0	490	32.0	16.3
	Cr	104	< 10	286	69.0	104
	Cu	148	165	1300	2332	10397
	Hg	0.334	0.167	0.030	0.044	0.068
	Mo	49.0	199	9.31	44.0	27.0
	Ni	81.0	3690	< 10	66.5	29.3
	Pb	31.0	436	13	69.5	119
	Se	3.00	< 2	< 2	NR	< 2
	V	246	9340	38	151	149
	Zn	77.0	300	77200	340	2023

Notes: **NA - Not Applicable** **NR - Not Reported**

Table 4.33: ELR – Proximate, ultimate, and combustion analysis of ASF blend (forest trimmings and plastics) from FT burn

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Proximate Analysis	**Ash**	9.21	31.0	> 0.250
	Fixed Carbon	10.6	39.1	> 0.250
	Moisture[3]	27.6	60.4	0.077[1]
	Volatile Matter	80.2	7.00	> 0.250
Ultimate Analysis	**Carbon**	52.5	12.7	0.177
	Hydrogen	5.12	21.4	0.244
	Nitrogen	0.922	32.8	> 0.250
	Oxygen	32.0	23.2	> 0.250
	Sulfur	0.189	70.9	< 0.005[1]
Heat Value[4] **(BTU/lb)**		10100	18.1	0.216

Notes: [1] **Not Normally Distributed** [3] **As-received**
[2] **Anderson-Darling Statistics** [4] **Dry Basis**

Table 4.34 shows the standard parameters of the ASF blend. Based on the normality test, it can be seen that results from most parameters do not follow a normal distribution. Also, as previously mentioned, many ASF values do not fall between the individual values of the plastics and forest trimmings. Again, this is most likely due to the variability in plastics and the fact that few individual plastic specimens were tested during this burn.

Table 4.34: ELR –Standard parameters of ASF blend (forest trimmings and plastics) from FT burn

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Standard Parameters	**Al_2O_3**	14.0	42.4	> 0.250
	CaO	20.9	48.4	0.207
	Fe_2O_3	2.82	105	< 0.005[1]
	K_2O	1.31	79.2	< 0.005[1]
	MgO	1.85	30.6	0.131
	Na_2O	4.36	164	< 0.005[1]
	P_2O_5	0.459	43.0	0.016[1]
	SiO_2	46.0	30.4	< 0.005[1]
	SO_3	1.18	163	< 0.005[1]
	TiO_2	3.72	180	< 0.005[1]
	Parameter	**Avg. (ppm)**	**C.V. (%)**	**P-Value[2]**
	As	36.4	101	0.008[1]
	Cd	6.56	8.04	< 0.005[1]
	Cl	75.1	70.9	< 0.005[1]
	Co	26.3	71.7	< 0.005[1]
	Cr	387	300	< 0.005[1]
	Cu	20979	132	< 0.005[1]
	Hg	0.082	163	< 0.005[1]
	Mo	52.2	197	< 0.005[1]
	Ni	25.3	77.0	0.041[1]
	Pb	929	340	< 0.005[1]
	Se	ND	NA	NA
	V	275	138	< 0.005[1]
	Zn	2758	187	< 0.005[1]

Notes: **[1] Not Normally Distributed** **NA - Not Applicable**
[2] Anderson-Darling Statistics **ND- Not Detected**

4.4.4.6 Railway Ties Trial Burn (RR)

Coal, petroleum coke, and waste plastics were the conventional fuels utilized during the RR burn. In addition, railway ties were utilized as the alternative fuel. All fuels were sampled and tested by the external laboratory. Tables 4.35 and 4.36 show the external laboratory results from all fuels utilized during the RR trial burn. The conventional fuels were presented previously, but are shown again for comparison purposes.

Note from Table 4.35 that railway ties have the highest moisture content, which is expected of fibrous material. Also, the heating value of the railway ties, as well as the carbon and sulfur contents are seen to be the lowest of any other fuel during this burn.

The standard parameters from all fuels tested during the RR burn are listed in Table 4.36. Railway ties contain the highest percentage of several major and minor parameters such as CaO, MgO, and Zn. Recall from Section 2.5, if excess concentrations of MgO and Zn are incorporated into the cement, several adverse effects on concrete performance and strength could result.

As with the forest trimmings, the shredded railway ties were blended with plastics to form an alternative solid fuel (ASF) blend. On average, the ASF blend consisted of approximately 59% plastics and 41% railway ties. The ASF blend was the primary alternative fuel fed into the kiln, and was therefore sampled the most frequent. Eight ASF samples were collected per day during the RR burn. Discrete samples were tested by the external laboratory.

Table 4.35: ELR – Proximate, ultimate, and combustion analysis of all fuels from RR burn

Test	**Parameter**	**Coal** **Value (wt. %)**	**Coke** **Value (wt. %)**	**Plastics** **Avg. (wt. %)**	**RR** **Avg. (wt. %)**
Proximate Analysis	**Ash**	24.7	12.3	8.57	7.49
	Fixed Carbon	50.6	71.1	7.63	14.2
	Moisture [3]	1.67	0.680	1.74	28.4
	Volatile Matter	24.7	16.6	83.8	78.3
Ultimate Analysis	**Carbon**	64.7	76.3	52.6	50.3
	Hydrogen	2.99	2.76	5.71	4.99
	Nitrogen	0.983	1.07	1.21	0.880
	Oxygen	4.44	0.223	31.7	36.2
	Sulfur	2.14	7.26	0.213	0.158
Heat Value [4] **(BTU/lb)**		11199	13281	9725	8572

Notes: [3] **As-received**

[4] **Dry Basis**

The ASF blend results from the proximate, ultimate, and combustion analyses are shown in Table 4.37. The sufficient number of specimens allowed a normality test to determine how closely the data follow a normal distribution. Note that few parameters follow a normal distribution. As seen in the FT burn, not all ASF values fall between the two individual values of the plastics and railway ties. For instance, the heating values for plastics and railway ties from Table 4.35 are 9,725 and 8,572 BTU/lb, respectively. The ASF heating value shown in Table 4.37 is 9,767 BTU/lb. Once again, this is most likely due to the variability in plastics and the fact that only a small number of individual plastic specimens were tested.

Table 4.36: ELR – Standard parameters of all fuels from RR burn

Test	**Parameter**	**Coal**	**Coke**	**Plastics**	**RR**
		Value (wt. %)	**Value (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**
Standard Parameters	**Al_2O_3**	21.7	11.9	23.9	6.13
	CaO	10.1	22.3	39.0	43.1
	Fe_2O_3	8.76	5.27	4.38	7.75
	K_2O	2.53	1.37	0.325	0.802
	MgO	1.24	1.15	2.21	5.52
	Na_2O	0.273	0.179	2.21	0.519
	P_2O_5	0.157	0.120	0.258	0.223
	SiO_2	49.5	27.8	21.0	28.4
	SO_3	4.51	27.3	2.01	4.38
	TiO_2	1.02	0.55	2.35	0.541
	Parameter	**Value (ppm)**	**Value (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**
	As	130	116	38.2	28.8
	Cd	< 6	< 6	< 6	< 6
	Cl	114	124	334	321
	Co	37.6	36.1	107	216
	Cr	306	107	2970	388
	Cu	577	544	1135	1374
	Hg	1.01	0.900	0.272	0.182
	Mo	38.2	210	429	889
	Ni	175	1435	1576	266
	Pb	32.0	68.4	198	105
	Se	< 2	< 2	<2	< 2
	V	659	5919	160	127
	Zn	91.4	175	1228	15648

Notes: **NA - Not Applicable**

Table 4.37: ELR – Proximate, ultimate, and combustion analysis of ASF blend (railway ties and plastics) from RR burn

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Proximate Analysis	**Ash**	9.01	39.9	0.015[1]
	Fixed Carbon	12.5	24.7	> 0.250
	Moisture[3]	21.6	47.0	< 0.005[1]
	Volatile Matter	78.5	4.64	> 0.250
Ultimate Analysis	**Carbon**	53.1	12.6	0.017[1]
	Hydrogen	5.66	6.61	0.041[1]
	Nitrogen	1.13	39.6	< 0.005[1]
	Oxygen	30.9	17.1	0.203
	Sulfur	0.210	63.6	< 0.005[1]
Heat Value[4] **(BTU/lb)**		9767	9.48	> 0.250

Notes: [1] **Not Normally Distributed** [3] **As-received**
[2] **Anderson-Darling Statistics** [4] **Dry Basis**

The standard parameters of the ASF blend from the RR burn are shown in Table 4.38. Based on the normality test, it can be seen that results from most parameters do not follow a normal distribution. Also, as previously mentioned, many ASF values do not fall between the individual values of the plastics and forest trimmings. Again, this is most likely due to the variability in plastics and the fact that few individual specimens were tested.

Table 4.38: ELR –Standard parameters of ASF blend (railway ties and plastics) from RR burn

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Standard Parameters	**Al_2O_3**	13.7	86.9	< 0.005[1]
	CaO	33.2	30.3	> 0.250
	Fe_2O_3	10.9	54.7	< 0.005[1]
	K_2O	0.786	27.6	0.085[1]
	MgO	3.23	43.4	< 0.005[1]
	Na_2O	1.85	67.3	< 0.005[1]
	P_2O_5	0.370	71.1	0.022[1]
	SiO_2	28.5	31.8	> 0.250
	SO_3	2.97	34.9	> 0.250
	TiO_2	1.73	76.7	< 0.005[1]
	Parameter	**Avg. (ppm)**	**C.V. (%)**	**P-Value[2]**
	As	59.9	-375	< 0.005[1]
	Cd	< 6	NA	NA
	Cl	883	216	< 0.005[1]
	Co	285	90.6	< 0.005[1]
	Cr	3445	194	< 0.005[1]
	Cu	2138	80.0	0.007[1]
	Hg	0.414	29.2	< 0.005[1]
	Mo	215	105	< 0.005[1]
	Ni	1025	107	< 0.005[1]
	Pb	425	99.9	< 0.005[1]
	Se	< 2	NA	NA
	V	148	38.7	< 0.005[1]
	Zn	14798	49.3	> 0.250

Notes: **[1] Not Normally Distributed** **NA - Not Applicable**

[2] Anderson-Darling Statistics

4.4.4.7 Liquid Glycerin Trial Burn (GL)

Coal, petroleum coke, and waste plastics were the conventional fuels utilized during the GL burn. In addition, liquid glycerin was utilized as the alternative fuel. This was the first *liquid* fuel to be utilized in the entire alternative fuel study. Therefore, modifications were made at the cement plant to accommodate its use. All fuels were sampled by the cement plant and tested by the external laboratory. The results from all fuels utilized during the GL trial burn are shown in Tables 4.39 and 4.40. The conventional fuels were presented previously, but are shown again for comparison purposes.

From Table 4.39, glycerin is seen to possess the highest contents of hydrogen and oxygen relative to all other fuels used. Glycerin also has the lowest percentages of carbon and nitrogen. From Table 4.41, note the extremely high concentrations of Na_2O and P_2O_5 for glycerin. If incorporated into the cement, concentrations of this magnitude may have adverse effects on concrete setting time and strength. Also, the Cl content is much higher than any other fuel utilized during this study. This may lead to ring formations or buildup in the kiln. However, no known problems occurred during the burn operation.

Though glycerin was not blended with the waste plastics, glycerin samples were collected at the same frequency as the ASF sample earlier discussed. Discrete specimens were tested by the external laboratory, and the results are shown in Tables 4.41 and 4.42. Sufficient data allowed a normality test to be conducted on the results. Results from this normality test are also shown. As indicated by the high C.V., the glycerin results are quite variable. Segregation of the liquid material was noticed during the burn. The variation seen is possibly due to improper mixing of the glycerin prior to injection.

Table 4.39: ELR – Proximate, ultimate, and combustion analysis of all fuels from GL burn

Test	Parameter	Coal	Coke	Plastics	GL
		Value (wt. %)	**Value (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**
Proximate Analysis	**Ash**	23.8	13.0	9.59	6.02
	Fixed Carbon	50.4	71.9	11.2	ND
	Moisture [3]	1.12	0.580	18.9	16.4
	Volatile Matter	25.8	15.1	79.2	ND
Ultimate Analysis	**Carbon**	63.8	72.5	49.6	39.4
	Hydrogen	3.23	2.77	5.58	6.19
	Nitrogen	1.07	1.14	0.954	0.143
	Oxygen	6.76	4.74	34.1	46.8
	Sulfur	1.44	5.81	0.228	1.40
Heat Value [4] **(BTU/lb)**		11483	13347	8448	9241

Notes: [3] **As-received** **ND - Not Detected**

[4] **Dry Basis**

Table 4.40: ELR – Standard parameters of all fuels from GL burn

Test	Parameter	Coal	Coke	Plastics	GL
		Value (wt. %)	**Value (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**
Standard Parameters	**Al_2O_3**	21.8	6.89	17.7	0.211
	CaO	10.7	29.2	23.9	0.627
	Fe_2O_3	7.57	3.25	4.60	2.42
	K_2O	2.36	0.742	1.36	1.10
	MgO	1.25	1.35	4.46	0.288
	Na_2O	0.250	0.793	5.63	40.4
	P_2O_5	0.180	0.173	0.593	8.58
	SiO_2	43.7	16.1	34.0	0.835
	SO_3	10.7	39.4	3.53	44.4
	TiO_2	1.05	0.37	3.01	0.016
	Parameter	**Value (ppm)**	**Value (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**
	As	162	46.8	43.5	44.5
	Cd	< 6	< 6	< 6	< 6
	Cl	123	103	549	2727
	Co	37.0	33.6	122	57.1
	Cr	70.0	< 10	1200	1880
	Cu	868	79.3	1053	366
	Hg	0.523	0.496	0.184	0.016
	Mo	29.0	149	45.2	174
	Ni	85.0	1669	292	129
	Pb	25.0	73.2	188	215
	Se	3.00	< 2	< 2	<2
	V	323	6988	216	72.5
	Zn	121	167	3171	172

Table 4.41: ELR – Proximate, ultimate, and combustion analysis of glycerin

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Proximate Analysis	**Ash**	6.02	49.6	$< 0.005^1$
	Fixed Carbon	ND	NA	NA
	Moisture[3]	16.4	52.4	0.064^1
	Volatile Matter	ND	NA	NA
Ultimate Analysis	**Carbon**	39.4	20.3	$< 0.005^1$
	Hydrogen	6.19	14.6	0.172
	Nitrogen	0.143	30.7	> 0.250
	Oxygen	46.8	13.6	$< 0.005^1$
	Sulfur	1.40	59.6	> 0.250
Heat Value[4] **(BTU/lb)**		9241	36.2	$< 0.005^1$

Notes:

[1] Not Normally Distributed

[2] Anderson-Darling Statistics

[3] As-received

[4] Dry Basis

NA - Not Applicable

ND - Not Detected

Table 4.42: ELR –Standard parameters of glycerin

Test	Parameter	Avg. (wt. %)	C.V. (%)	P-Value[2]
Standard Parameters	**Al_2O_3**	0.211	164	< 0.005[1]
	CaO	0.627	72.4	0.030[1]
	Fe_2O_3	2.42	117	< 0.005[1]
	K_2O	1.10	147	< 0.005[1]
	MgO	0.288	78.4	< 0.005[1]
	Na_2O	40.4	21.0	< 0.005[1]
	P_2O_5	8.58	181	< 0.005[1]
	SiO_2	0.835	161	< 0.005[1]
	SO_3	44.4	34.2	< 0.005[1]
	TiO_2	0.016	129	< 0.005[1]
	Parameter	**Avg. (ppm)**	**C.V. (%)**	**P-Value[2]**
	As	44.5	74.4	> 0.250
	Cd	< 6	NA	NA
	Cl	2727	76.9	> 0.250
	Co	57.1	267	<0.005[1]
	Cr	1880	292	<0.005[1]
	Cu	366	146	<0.005[1]
	Hg	0.016	218	<0.005[1]
	Mo	174	73.5	<0.005[1]
	Ni	129	64.7	0.018[1]
	Pb	215	121	<0.005[1]
	Se	<2	NA	NA
	V	72.5	194	<0.005[1]
	Zn	172	123	<0.005[1]

Notes: [1] **Not Normally Distributed** **NA - Not Applicable**

[2] **Anderson-Darling Statistics**

4.4.5 Chemical Composition of Clinker

Clinker is the primary output of the kiln process. Eight clinker samples were collected per day during each burn. Composite specimens were tested by the cement plant, external laboratory, and the cement plant's specialty laboratory. Tables 4.43a and 4.43b provide summary statistics for clinker composition determined by the cement plant. Based on the C.V. in these two tables, all parameters appear to be consistent during each burn. Sufficient data were available to perform a normality test to determine how closely the data follow a normal distribution. Aside from the RR burn, most data appear to follow a normal distribution.

The percent difference of the trial burns relative to their respective baseline burn is shown in Table 4.44. The percent differences for several primary parameters are plotted in Figure 4.6. A t-test was conducted to determine if the percent difference is considered statistically significant, as indicated by the p-value shown in Table 4.44. Several parameters are considered significantly different from their baseline burns. Recall the four primary oxides, CaO, SiO_2, Al_2O_3, and Fe_2O_3, discussed in Chapter 2. From the GL burn, all four are significantly different from those tested during the B-CCP burn. Also, the Bogue compounds are seen to differ greatly from all trial burns to their baseline burn. The difference in C_4AF was significant for each trial burn. The greatest difference is seen in the MgO content during the GL burn. As seen earlier, the MgO contents of the kiln feed and CKD were highest during the GL burn. This was determined by both the cement plant and external laboratory, which explains its abundance in the clinker.

Table 4.43a: CPR – Summary statistics of chemical composition of clinker for FT and B-CCTP burns

Parameter	FT			B-CCTP		
	Avg. (wt. %)	C.V. (%)	P-Value[2]	Avg. (wt. %)	C.V. (%)	P-Value[2]
Al_2O_3	5.24	2.42	> 0.250	4.83	3.02	> 0.250
CaO	64.7	0.337	> 0.250	65.0	0.369	> 0.250
Fe_2O_3	3.40	2.06	> 0.250	3.40	2.86	> 0.250
K_2O	0.621	8.65	> 0.250	0.543	6.58	> 0.250
MgO	3.24	1.71	> 0.250	3.37	2.87	0.016[1]
Na_2O	0.083	8.11	< 0.005[1]	0.094	6.50	< 0.005[1]
Na_2O_{eq}	0.492	7.89	0.207	0.450	6.35	0.146
SiO_2	21.1	0.693	> 0.250	21.3	0.986	> 0.250
SO_3	1.21	26.7	0.076[1]	1.17	20.4	0.154
Free CaO	0.795	76.4	< 0.005[1]	1.39	49.3	0.0561[1]
C_3S	62.4	3.03	0.245	65.1	3.43	0.113
C_2S	13.6	12.3	> 0.250	12.0	18.3	> 0.250
C_3A	8.15	3.59	0.087[1]	7.05	5.84	0.008[1]
C_4AF	10.3	2.05	0.022[1]	10.3	2.88	0.021[1]

Notes: [1] **Not Normally Distributed**

[2] **Anderson-Darling Statistics**

Table 4.43b: CPR –Summary statistics of chemical composition of clinker for B-CCP, RR, and GL burns

Parameter	B-CCP			RR			GL		
	Avg. (wt. %)	**C.V. (%)**	**P-Value[2]**	**Avg. (wt. %)**	**C.V. (%)**	**P-Value[2]**	**Avg. (wt. %)**	**C.V. (%)**	**P-Value[2]**
Al_2O_3	5.02	3.74	0.246	5.14	6.12	< 0.005[1]	5.15	1.78	> 0.250
CaO	65.4	0.637	> 0.250	63.3	4.09	< 0.005[1]	64.7	0.490	0.040[1]
Fe_2O_3	3.32	2.28	> 0.250	3.38	4.72	< 0.005[1]	3.45	1.55	> 0.250
K_2O	0.537	9.94	0.045[1]	0.586	8.95	> 0.250	0.521	9.61	0.187
MgO	2.82	1.47	> 0.250	3.02	7.33	< 0.005[1]	3.99	4.96	0.007[1]
Na_2O	0.135	11.3	0.094[1]	0.115	14.8	< 0.005[1]	0.147	17.8	0.034[1]
Na_2O_{eq}	0.488	9.03	0.028[1]	0.501	8.96	0.191	0.490	9.90	0.224
SiO_2	21.3	0.723	0.091[1]	20.9	4.54	< 0.005[1]	20.7	1.23	0.135
SO_3	1.18	21.0	> 0.250	1.24	31.1	< 0.005[1]	0.963	23.9	0.148
Free CaO	1.28	24.41	> 0.250	1.27	64.6	< 0.005[1]	1.07	36.4	> 0.250
C_3S	66.3	4.62	0.026[1]	59.3	6.71	< 0.005[1]	66.4	3.17	> 0.250
C_2S	11.0	22.9	0.021[1]	15.3	25.4	< 0.005[1]	9.39	23.0	> 0.250
C_3A	7.69	5.46	0.185	7.90	7.30	0.120	7.82	2.58	> 0.250
C_4AF	10.1	2.28	> 0.250	10.3	4.72	> 0.250	10.5	1.55	> 0.250

Notes: [1] **Not Normally Distributed**

[2] **Anderson-Darling Statistics**

Table 4.44: CPR – Percent difference and statistical significance for clinker relative to baseline

Parameter	**FT**		**RR**		**GL**	
	% Diff.[1]	**P-Value**[4]	**% Diff.**[2]	**P-Value**[4]	**% Diff.**[2]	**P-Value**[4]
Al_2O_3	8.50	0.00[3]	2.36	0.647	2.59	0.004[3]
CaO	-0.536	0.00[3]	-3.25	0.00[3]	-1.10	0.00[3]
Fe_2O_3	0.023	0.968	1.75	0.606	3.78	0.00[3]
K_2O	14.4	0.00[3]	9.09	0.005[3]	-2.99	0.477
MgO	-3.98	0.00[3]	7.25	0.020[3]	41.6	0.00[3]
Na_2O	-10.9	0.00[3]	-14.5	0.002[3]	9.28	0.00[3]
Na_2O_{eq}	9.34	0.00[3]	2.58	0.403	0.391	0.364
SiO_2	-0.876	0.001[3]	-1.56	0.008[3]	-2.52	0.00[3]
SO_3	2.86	0.991	5.52	0.062[3]	-18.1	0.009[3]
Free CaO	-42.9	0.00[3]	-0.829	0.355	-16.3	0.035[3]
C_3S	-4.24	0.00[3]	-10.6	0.00[3]	0.104	0.579
C_2S	12.9	0.928	39.5	0.129	-14.4	0.034[3]
C_3A	15.5	0.00[3]	2.80	0.00[3]	1.72	0.162
C_4AF	-0.001	0.002[3]	1.75	0.00[3]	3.78	0.00[3]

Notes:

[1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

[3] **Significantly Different**

[4] **Wilcoxin Rank Sum Test**

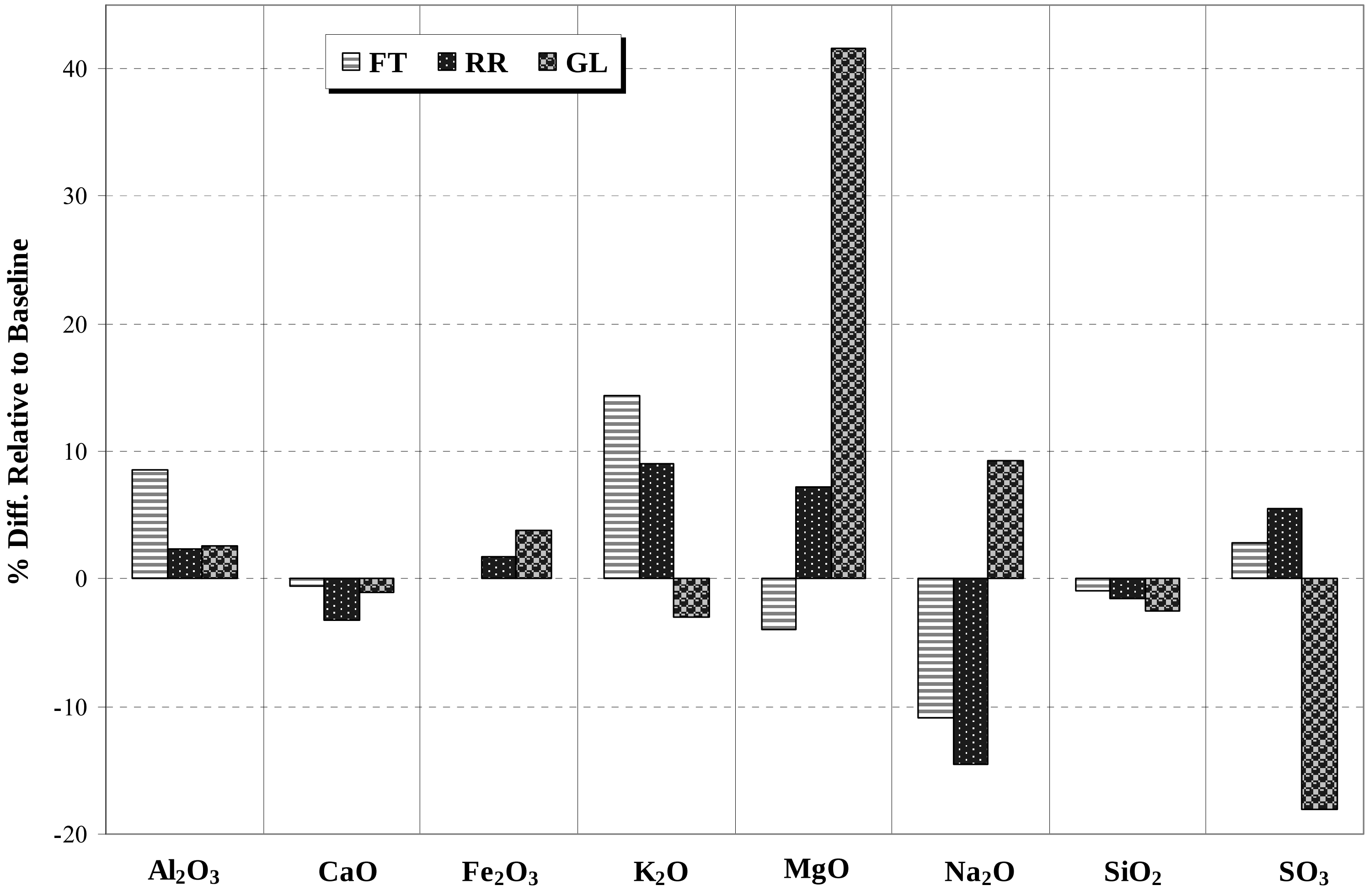


Figure 4.6: CPR – Percent difference in clinker composition relative to baseline

Clinker samples were used to prepare 24-hour composite specimens, which were tested by the external laboratory. The standard parameters are shown in Table 4.45 along with the percent difference of each trial burn relative to their baseline. Unfortunately, sufficient data was not available conduct the t-test, though several results agree with the cement plant findings. For instance, The MgO content of the GL clinker was higher than all other burns. This is most likely because kiln feed and CKD had the greatest concentration of MgO during the GL burn, as explained earlier. In addition, concentrations of K_2O during the FT burn, and SO_3 during the RR burn were higher than all other burns. The P_2O_5 content was greatest during the GL burn and appears to be significantly higher than its baseline. The greatest difference was seen in the FT moisture content, but the cement plant did not test this parameter to confirm this finding. However, the moisture content for the FT samples were still very low at an average of 0.028%.

Also from Table 4.45, several trends regarding percent difference were not consistent between the cement plant and external laboratory results. For instance, the cement plant reported a decrease in Na_2O from the FT to B-CCTP burn, shown in Table 4.44. The external laboratory shows an increase in this parameter. During the RR burn, trends in Fe_2O_3 and SiO_2 differ between the two testing parties. Percent differences in Fe_2O_3, K_2O, and Na_2O during the GL burn also differ. These differences may be due to variable compositions inherent in the types of samples tested by each laboratory.

Composite specimens were also sent to the cement plant's specialty laboratory where a Rietveld analysis was conducted to determine the major clinker phases. Results are shown in Table 4.46. The GL clinker is seen to exhibit the greatest percentage of C_3S and C_3A but the lowest C_2S and C_4AF. Several differences are seen between the trial burns and their baseline. The most apparent difference is the C_2S content of the RR clinker. The average increased from 17.4% during the B-CCP burn, to 24.7% during the RR burn. The practical significance of these clinker phases will depend on the physical properties of the cement, which will be discussed in the following section.

Table 4.45: ELR – Chemical composition of clinker and percent difference relative to baseline for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg. (wt. %)	**% Diff.^{1}**	**Avg. (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**	**% Diff.^{2}**	**Avg. (wt. %)**	**% Diff.^{2}**
Al_2O_3	4.96	2.89	4.82	4.97	5.04	1.56	5.15	3.64
CaO	64.0	-2.29	65.5	65.3	64.6	-1.07	64.5	-1.16
Fe_2O_3	3.42	5.77	3.23	3.46	3.41	-1.30	3.37	-2.68
K_2O	0.592	30.6	0.453	0.460	0.557	21.2	0.494	7.38
MgO	3.47	-7.10	3.74	3.16	3.41	7.89	4.28	35.3
Na_2O	0.098	39.5	0.070	0.120	0.071	-41.0	0.098	-18.6
P_2O_5	0.057	-1.04	0.058	0.056	0.061	9.01	0.071	27.1
SiO_2	21.3	4.05	20.5	20.7	21.0	1.46	20.5	-0.807
SO_3	1.39	14.2	1.22	1.18	1.40	18.2	0.995	-15.9
TiO_2	0.197	73.9	0.113	0.193	0.182	-5.34	0.266	38.3
Moisture	0.028	3236	0.001	0.028	0.048	70.8	0.002	-94.4
LOI	0.237	143	0.097	0.146	0.036	-75.5	0.091	-37.5
Parameter	**Avg. (ppm)**	**% Diff.^{1}**	**Avg. (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**	**% Diff.^{2}**	**Avg. (ppm)**	**% Diff.^{2}**
As	21.5	-14.0	25.0	23.0	29.0	25.8	24.2	4.92
Cd	ND	NA	5.33	ND	< 5	NA	< 5	NA
Cl	505	539	79.0	217	175	-19.3	151	-30.6
Co	16.0	-13.5	18.5	16.7	18.0	7.94	17.8	7.00
Cr	162	101	80.8	544	458	-15.8	37.2	-93.2
Cu	232	151	92.2	524	87.0	-83.4	63.8	-87.8
Hg	0.081	NA	< 0.01	0.392	0.010	-97.4	0.033	-91.6
Mo	11.5	109	5.50	7.54	10.0	32.6	5.53	-26.6
Ni	22.0	-73.5	83.2	39.6	31.0	-21.7	23.5	-40.7
Pb	28.3	51.1	18.8	19.6	17.0	-13.4	44.3	126
Se	< 2	NA	< 2	< 2	< 2	NA	< 2	NA
V	89.3	-1.02	90.2	95.6	95.0	-0.613	92.4	-3.35
Zn	86.0	-18.1	105	198	119	-39.9	54.5	-72.5

Notes: **^{1} Relative to B-CCTP** **NA - Not Applicable**

^{2} Relative to B-CCP **ND - Not Detected**

Table 4.46: SLR – Rietveld analysis of clinker and percent difference relative to baseline

Property	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg. (wt. %)	**% Diff.**[1]	**Avg. (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**	**% Diff.**[2]	**Avg. (wt. %)**	**% Diff.**[2]
C_3S	57.6	-2.74	59.2	65.4	56.5	-13.6	65.7	0.432
C_2S	23.6	10.3	21.4	17.4	24.7	41.8	14.9	-14.5
C_3A	3.03	-10.7	3.39	3.05	3.4	10.3	3.8	25.6
C_4AF	12.1	8.95	11.1	10.7	11.3	5.10	10.4	-2.80

Notes: **[1] Relative to B-CCTP**

[2] Relative to B-CCP

4.4.6 Chemical Composition of Cement

Portland cement is the final product of the manufacturing process. Ten cement samples were collected after the grinding period for each burn. Composite specimens were tested by the cement plant, external laboratory, and the cement plant's specialty laboratory. Tables 4.47a and 4.47b provide summary statistics for cement composition determined by the cement plant. Recall from Chapter 3, limestone was added during the grinding stage of all burns except the FT burn. This is seen in the form of CO_2 in the cement, which is included in the tables. Since no limestone was added during the FT burn, this value is shown to be zero. Based on the low C.V. values in these two tables, most of the cement data appear to be consistent during each burn. Though FT cement was the only burn containing more than ten data points, a normality test was conducted on all cement due to the importance of this material. Aside from the FT burn, most data appear to follow a normal distribution.

The percent difference of the trial burns relative to their respective baseline is listed in Table 4.48. Several of these parameters are plotted in Figures 4.7 and 4.8. As with the normality test, a t-test was conducted on all trial burns even though FT was the only burn with a sufficient amount of data. The four primary oxides of the GL cement are seen to change significantly as compared to its baseline. This was also seen in the clinker discussed in the previous section. The Bogue compounds are also seen to differ greatly compared to the baseline burns. All four compounds were determined to be significantly different for the RR cement. In all trial burns, the compound showing the greatest difference was C_2S, which was significantly different for each burn.

Table 4.47a: CPR –Summary statistics of chemical composition of cement for FT and B-CCTP burns

Parameter	FT			B-CCTP		
	Avg. (wt. %)	**C.V. (%)**	**P-Value[2]**	**Avg. (wt. %)**	**C.V. (%)**	**P-Value[2]**
Al_2O_3	4.91	1.89	> 0.250	4.86	2.38	> 0.250
CaO	62.7	0.731	> 0.250	63.0	0.428	> 0.250
CO_2	0.00	NA	NA	1.03	12.7	> 0.250
Fe_2O_3	3.25	0.715	> 0.250	3.30	1.31	0.012[1]
K_2O	0.593	3.14	< 0.005[1]	0.502	5.16	> 0.250
MgO	3.14	1.60	0.063[1]	3.43	5.48	> 0.250
Na_2O	0.080	7.59	< 0.005[1]	0.094	5.83	0.014[1]
Na_2O_{eq}	0.469	1.93	< 0.005[1]	0.424	4.28	> 0.250
SiO_2	19.8	2.04	0.020[1]	19.8	1.01	0.059[1]
SO_3	2.92	10.5	0.076[1]	3.16	2.71	> 0.250
Free CaO	1.35	59.1	< 0.005[1]	1.52	7.41	0.184
LOI	1.31	18.7	> 0.250	1.55	7.61	> 0.250
C_3S	58.8	4.41	> 0.250	54.8	4.80	> 0.250
C_2S	12.4	22.5	0.046[1]	15.4	16.5	> 0.250
C_3A	7.52	3.03	> 0.250	7.37	1.86	> 0.250
C_4AF	9.88	0.705	> 0.250	10.1	1.20	< 0.005[1]
Blaine SSA (m^2/kg)	401	2.81	> 0.250	394	1.81	0.110

Notes:

[1] Not Normally Distributed

[2] Anderson-Darling Statistics

Table 4.47b: CPR –Summary statistics of chemical composition of cement for B-CCP, RR, and GL burns

Parameter	B-CCP			RR			GL		
	Avg. (wt. %)	C.V. (%)	P-Value[2]	Avg. (wt. %)	C.V. (%)	P-Value[2]	Avg. (wt. %)	C.V. (%)	P-Value[2]
Al_2O_3	4.66	1.27	> 0.250	4.80	2.49	> 0.250	4.74	1.64	> 0.250
CaO	63.4	0.160	> 0.250	63.1	0.520	0.025[1]	63.0	0.285	0.231
CO_2	1.30	0.00	NA	1.30	0.00	NA	1.30	0.00	NA
Fe_2O_3	3.15	0.574	0.005[1]	3.23	1.81	> 0.250	3.27	1.79	> 0.250
K_2O	0.529	4.77	> 0.250	0.534	4.44	> 0.250	0.461	5.46	0.027[1]
MgO	2.61	2.06	0.148	2.78	2.75	> 0.250	3.66	1.50	> 0.250
Na_2O	0.120	9.32	0.079[1]	0.106	5.06	< 0.005[1]	0.129	8.52	> 0.250
Na_2O_{eq}	0.468	4.28	> 0.250	0.457	3.79	0.122	0.432	5.19	> 0.250
SiO_2	19.9	0.61	> 0.250	20.2	0.66	> 0.250	19.3	1.66	0.038[1]
SO_3	3.20	5.79	> 0.250	3.20	7.76	> 0.250	3.23	5.46	0.243
Free CaO	1.19	21.3	0.177	1.08	38.2	0.110	1.03	28.7	0.212
LOI	2.29	5.05	> 0.250	2.17	7.01	> 0.250	1.91	27.3	0.138
C_3S	55.2	2.00	> 0.250	51.0	5.41	0.044[1]	57.4	4.49	0.188
C_2S	15.3	7.34	> 0.250	19.3	12.2	0.078[1]	12.0	23.7	0.106
C_3A	7.02	1.84	> 0.250	7.27	3.11	> 0.250	7.04	3.14	> 0.250
C_4AF	9.60	0.574	< 0.005[1]	9.83	1.81	> 0.250	9.94	1.79	> 0.250
Blaine SSA (m^2/kg)	388	3.18	0.209	386	3.20	> 0.250	385	1.01	> 0.250

Notes:

[1] Not Normally Distributed

[2] Anderson-Darling Statistics

Table 4.48: CPR – Percent difference and statistical significance for cement relative to baseline for trial burns

Parameter	**FT**		**RR**		**GL**	
	% Diff.[1]	**P-Value**	**% Diff.[2]**	**P-Value**	**% Diff.[2]**	**P-Value**
Al_2O_3	0.906	1.00	3.09	0.031[3]	1.73	0.031[3]
CaO	-0.545	0.125	-0.517	0.109	-0.723	0.031[3]
CO_2	-100	0.063[3]	0.00	1.00	0.00	1.00
Fe_2O_3	-1.77	0.125	2.44	0.031[3]	3.51	0.031[3]
K_2O	18.0	0.063[3]	1.02	0.703	-12.9	0.031[3]
MgO	-8.40	0.125	6.49	0.031[3]	40.3	0.031[3]
Na_2O	-15.2	0.250	-11.9	0.031[3]	7.08	0.125
Na_2O_{eq}	10.6	0.063[3]	-2.29	0.844	-7.75	0.125
SiO_2	0.193	0.063[3]	1.28	0.031[3]	-3.11	0.063[3]
SO_3	-7.7	0.188	-0.134	0.688	0.990	0.438
Free CaO	-11.1	0.250	-9.14	1.00	-12.9	1.00
LOI	-15.7	0.188	-5.00	0.156	-16.5	0.313
C_3S	7.37	0.063[3]	-7.66	0.063[3]	3.87	0.219
C_2S	-19.1	0.063[3]	26.1	0.031[3]	-21.6	0.094[3]
C_3A	2.03	0.813	3.58	0.031[3]	0.378	0.563
C_4AF	-1.86	0.125	2.44	0.031[3]	3.51	0.031[3]
Blaine SSA (m^2/kg)	1.83	0.063[3]	-0.557	0.563	-0.870	0.313

Notes:
[1] Relative to B-CCTP
[2] Relative to B-CCP
[3] Significantly Different
[4] Wilcoxin Rank Sum Test

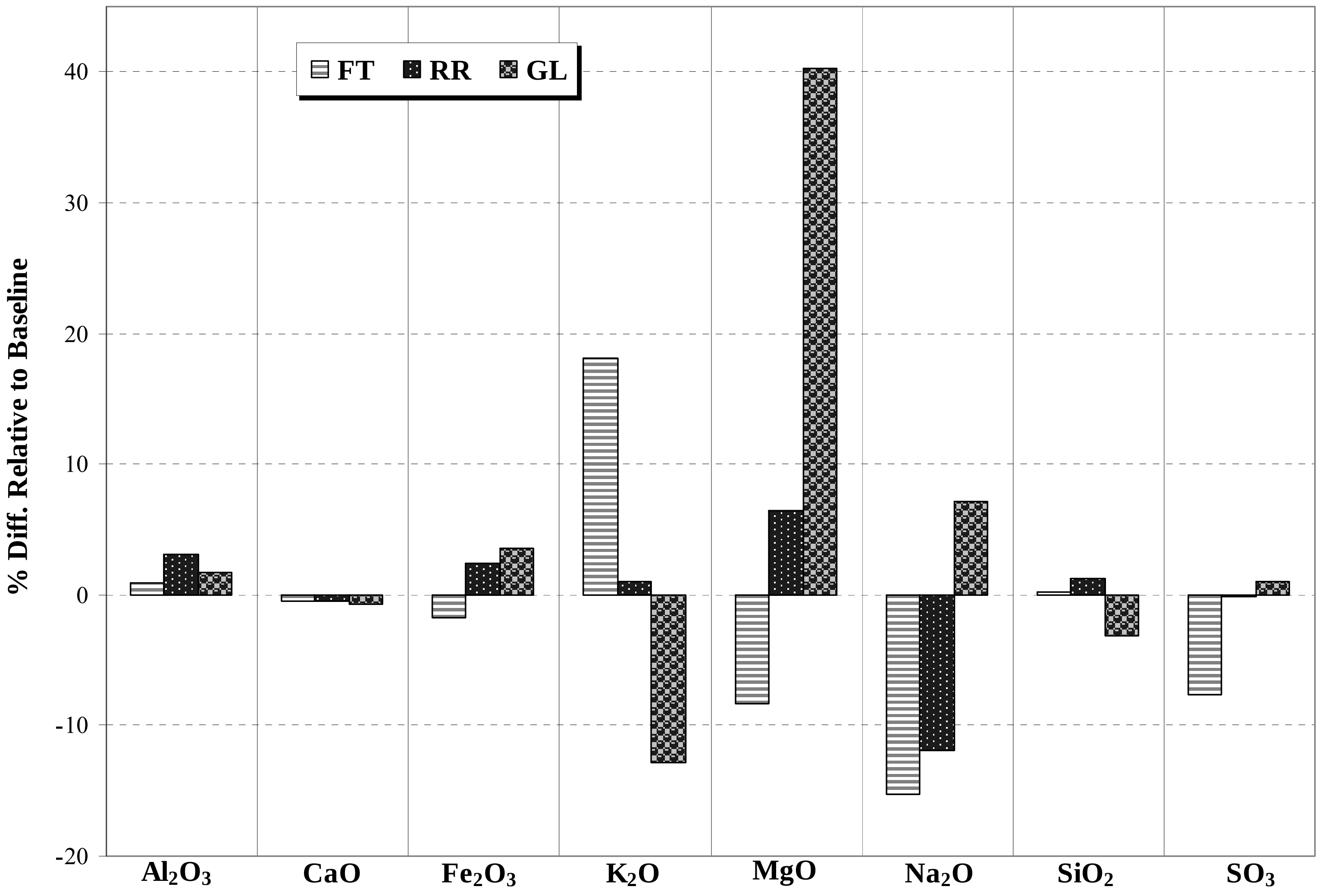


Figure 4.7: CPR – Trial burns, percent difference in cement composition relative to baseline

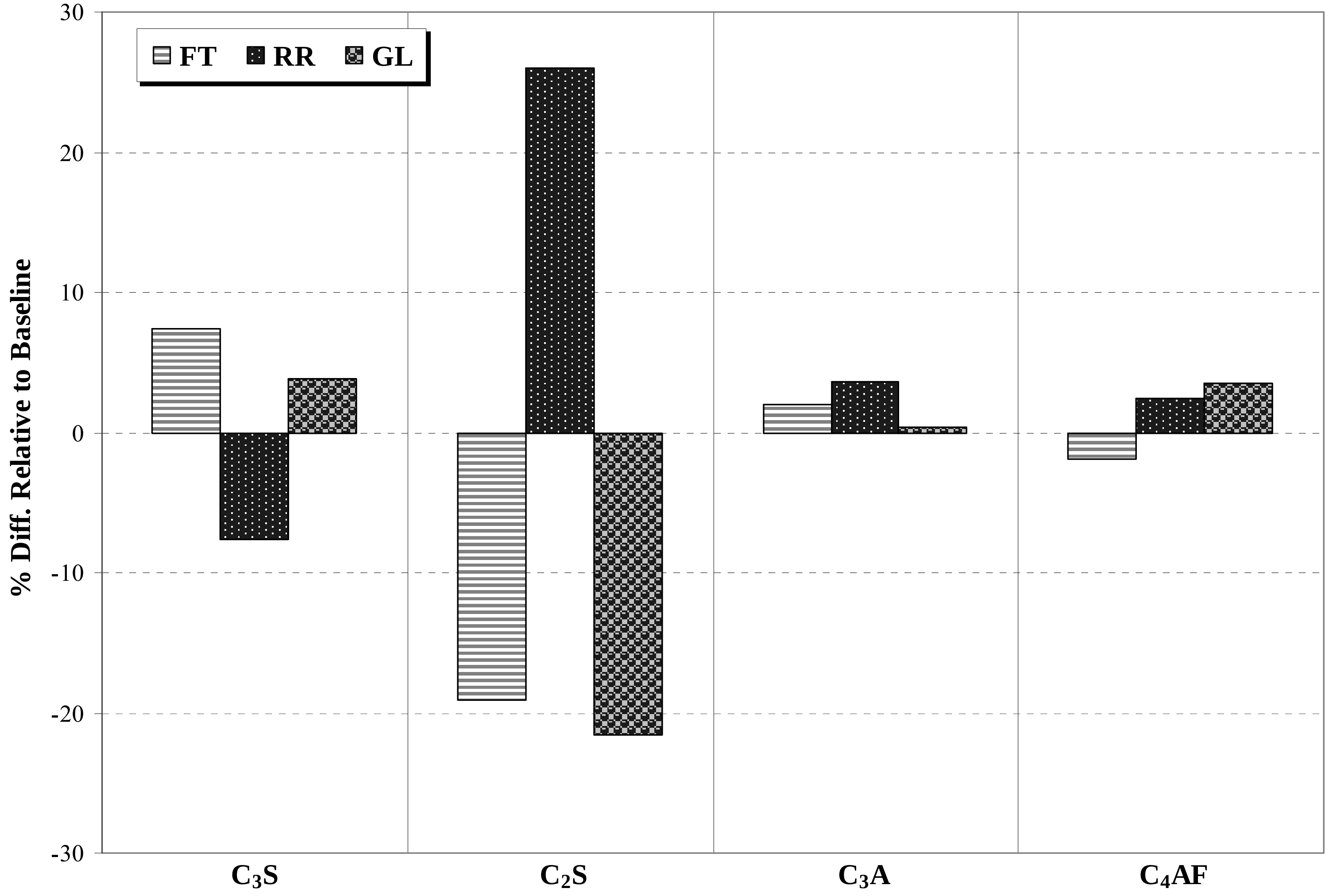


Figure 4.8: CPR – Percent difference in cement Bogue compounds relative to baseline

Cement samples were also used to prepare 24-hour composite specimens, which were tested by the external laboratory. The standard parameters are shown in Tables 4.49a and 4.49b along with the percent difference of each trial burn relative to their baseline. Unfortunately, sufficient data were not available to obtain any statistical parameters, such as C.V. and p-values. Bogue compounds were not determined by the external laboratory, but were calculated using the equations of ASTM C 150 (2007). The CO_2 generated from the added limestone was accounted for during these calculations. These compounds are shown in Table 4.49a.

One notable change shown in Table 4.49a is the increased P_2O_5 content from the GL cement. As discussed in Section 4.4.4.7, this was likely due to the glycerin fuel. Recall from Section 2.5.4, excessive P_2O_5 levels may inhibit the formation of C_3S. Although sources disagreed as to what percentage of P_2O_5 is considered excessive, reductions in C_3S were not seen in Tables 4.48 or 4.49a. The practical significance of this increase in P_2O_5 is discussed in Section 4.4.7 and 4.4.8.

Many external laboratory results agree with those determined by the cement plant. For instance, Al_2O_3, K_2O, and C_3A contents were the highest for the FT cement, as per both testing laboratories. Once again, the MgO content of the GL cement was the highest, with a value of 4.28% as reported by the external laboratory.

As with the clinker, several trends regarding percent difference were not consistent between the cement plant and external laboratory. From Table 4.48, the cement plant reported a decrease in Fe_2O_3, Na_2O, C_2S, and C_4AF and an increase in C_3S between the FT and B-CCTP burns. According to the external laboratory in Table 4.49a, the opposite trend is seen for each of these parameters. Trends in Na_2O and SO_3 differ between the two agencies during the RR burn. The cement plant reported an increase in Na_2O for the GL cement relative to the baseline. The external laboratory reported a decrease in Na_2O. As previously mentioned, these various trends may be due to the fact that different samples were tested and inherent variability may cause differences in results.

Note that the SO_3 content for FT cement was lower than the baseline's, as reported by both testing agencies. Also, note from the previous section that both laboratories reported a higher SO_3 content in the clinker from the FT burn. This indicates that less gypsum or sulfate was ground with the clinker to produce the FT cement. Recall from Section 2.6 that insufficient sulfate content may adversely affect hydration. This is especially expected since the C_3A content is high for the FT cement. The practical significance of this finding is discussed later in this chapter.

Composite specimens were also sent to the cement plant's specialty laboratory where a Rietveld analysis was conducted to determine the principle cement compounds. The Rietveld analysis is typically more accurate than the equations from ASTM C 150 (2007). Results are shown in Table 4.50. Note that C_3S and C_4AF were highest in the FT cement, C_3S and C_3A were highest in the GL cement, and C_2S and C_4AF were lowest in the GL cement.

In comparing results from Table 4.50 with the Bogue compounds calculated by the cement plant, several differences are noticed. For the percent difference in FT cement relative to its baseline, the trends reported by the cement plant were opposite from those reported by the specialty laboratory in all four compounds. The main similarity is that the

GL cement has the lowest C_2S percentage as reported by both the cement plant and their specialty laboratory.

In comparing results from Table 4.50 with those calculated from the external laboratory's results, many more similarities are seen. Regarding the trends between the trial burns and their baseline, differences were seen only in C_3A of the FT cement and C_4AF of the GL cement. All other trends were consistent between the specialty and external laboratories. Both entities agree that the GL cement has the highest C_3S and lowest C_2S contents. Both also agree that the FT cement has the lowest C_3S and the highest C_2S contents.

Few trends are consistent among the cement plant, the external laboratory, and specialty laboratory. One such trend is that C_3S was decreased and C_2S, C_3A, and C_4AF were increased in the RR cement. In the GL cement, C_2S was decreased and C_3A was increased. The GL cement yielded the lowest C_2S content of all other cement. The C_3S content of the GL cement was increased, as reported by all testing agencies, despite the increased P_2O_5 content in the GL cement.

For the purposes of this study, it is necessary that the results and/or trends are consistent between all available testing agencies. Otherwise, conclusive evidence is not available to attribute any effect to the fuels being utilized. However, in the case of the principle cement compounds previously discussed, the Rietveld analysis conducted by the specialty laboratory is known to produce accurate results. It is of some importance to note the similarities between the specialty laboratory and either of the other entities' results. Such results may encourage practical significance, assuming supporting evidence is gathered form the remaining results of this chapter.

Table 4.49a: ELR – Chemical composition of cement and percent difference relative to baseline for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg. (wt. %)	**% Diff.**[1]	**Avg. (wt. %)**	**Avg. (wt. %)**	**Avg. (wt. %)**	**% Diff.**[2]	**Avg. (wt. %)**	**% Diff.**[2]
Al_2O_3	4.96	6.87	4.64	4.61	4.82	4.69	4.82	4.69
CaO	62.6	-1.14	63.3	64.1	64.1	-0.056	63.5	-0.853
Fe_2O_3	3.18	2.27	3.11	3.20	3.30	3.18	3.21	0.450
K_2O	0.497	13.6	0.437	0.482	0.456	-5.46	0.447	-7.27
MgO	3.31	-1.11	3.34	2.94	3.17	7.65	4.28	45.2
Na_2O	0.095	30.2	0.073	0.145	0.095	-34.2	0.095	-34.4
P_2O_5	0.056	-1.25	0.056	0.047	0.051	8.25	0.059	24.6
SiO_2	20.6	6.31	19.4	19.3	20.0	3.73	18.4	-4.71
SO_3	2.88	-10.8	3.23	2.91	3.01	3.49	2.99	2.94
TiO_2	0.206	55.4	0.133	0.179	0.174	-2.82	0.241	35.1
Moisture	0.171	224	0.053	0.209	0.00	-100	0.357	70.7
LOI	1.37	-33.3	2.06	1.83	0.603	-67.0	1.77	-2.88
C_3S	51.7	-13.6	59.8	63.7	56.2	-11.8	66.7	4.65
C_2S	20.2	91.8	10.5	7.22	14.9	107	2.38	-67.0
C_3A	7.78	10.3	7.05	6.80	7.20	5.89	7.35	8.06
C_4AF	9.67	2.27	9.46	9.73	10.0	3.18	9.77	0.450
TOC	0.154	179	0.055	1.30	0.353	-72.8	0.047	-96.4

Notes:

[1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

Table 4.49b: ELR – Chemical composition of cement and percent difference relative to baseline for all burns

Parameter	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg. (ppm)	**% Diff.[1]**	**Avg. (ppm)**	**Avg. (ppm)**	**Avg. (ppm)**	**% Diff.[2]**	**Avg. (ppm)**	**% Diff.[2]**
As	18.7	-16.4	22.3	22.0	21.7	-1.56	24.5	11.3
Cd	4.67	NA	5.67	< 6	< 5	NA	< 6	NA
Cl	160	38.6	116	189	138	-27.2	124	-34.2
Co	15.3	2.22	15.0	18.2	16.3	-10.3	15.0	-17.6
Cr	138	70.4	81.0	476	485	1.84	52.3	-89.0
Cu	106	13.5	93.7	486	237	-51.1	113	-76.8
Hg	0.06	NA	< 0.01	0.01	1.27	17218	0.00	-72.7
Mo	8.33	11.1	7.50	5.13	6.00	72.6	4.86	-5.39
Ni	21.3	3.23	20.7	31.6	30.7	-2.99	22.2	-29.8
Pb	17.0	6.25	16.0	12.4	15.3	23.8	17.2	39.0
Se	< 2.3	NA	< 2	<2	< 2	NA	<2	NA
V	82.3	2.49	80.3	95.9	94.0	-1.93	81.6	-14.8
Zn	86.7	-4.8	91.0	212	148	-30.2	51.9	-75.5

Notes: [1] **Relative to B-CCTP** **NA - Not Applicable**

[2] **Relative to B-CCP** **NR - Not Reported**

Table 4.50: SLR – Rietveld analysis of cement and percent difference relative to baseline

Property	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Value (wt. %)	**% Diff.[1]**	**Value (wt. %)**	**Value (wt. %)**	**Value (wt. %)**	**% Diff.[2]**	**Value (wt. %)**	**% Diff.[2]**
C_3S	50.6	-7.92	55.0	54.3	52.9	-2.49	60.8	12.0
C_2S	25.5	26.9	20.1	21.6	23.5	8.77	13.4	-38.0
C_3A	3.11	-12.8	3.57	3.05	3.34	9.52	4.26	39.8
C_4AF	11.5	4.49	11.0	10.4	10.8	3.87	10.3	-1.16

Notes: [1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

4.4.7 Physical Properties of Cement

Physical properties of the cement were determined by both the cement plant and Auburn University. All tests conducted by Auburn University were also conducted by the cement plant, with the exception of drying shrinkage development of paste prisms. Air in mortar and Blaine specific surface area were tested only by the cement plant.

ASTM specifications provide a maximum permissible error between average test results for both a single operator (single-laboratory) and for multiple operators (multi-lab). These limits represent the likelihood of a particular test result being repeated, and are in place to ensure precision between test results. The precision requirements for several tests of cement physical properties are shown in Table 4.51. All results determined by the cement plant and Auburn University must be within the multi-lab requirements in order to be considered valid. The percent differences in trial burn results relative to their baseline were compared to both single-lab and multi-lab requirements to determine the level of practical significance.

Table 4.51: Single-lab and multi-lab precision requirements for cement physical properties

Property	ASTM Specification	Single-lab	Multi-lab
Autoclave Expansion	C 151 (2005)	0.07 %[1]	0.09 %[1]
Cube flow	C 109 (2007)	21.8 %	33.7 %
Cube strength		10.7 %	18.7 %
Dry shrinkage	C 596 (2007)	0.0007 in./in.[1]	25.0 %

Notes: [1] **Difference in the average of two results**

Results from the cement plant and Auburn University are shown in Tables 4.52 and 4.53, respectively. Both tables show the properties determined, the average values, and the percent difference for the trial burns relative to their corresponding baseline. Note that the percent difference can be deceiving when the mean is a small value, as is the case for the autoclave expansion.

For the properties determined by both entities, percent differences are plotted in Figures 4.9 and 4.10. Though several differences can be seen between the two entities, many of these differences are small, and all meet the requirements of ASTM for multi-lab precision as shown in Table 4.51. One exception is the cube flow for the FT cement. The cement plant and Auburn University determined a cube flow of 100% and 67.2%, respectively, which yields a percent difference of 39.2%. The maximum allowed by ASTM C 109 (2007) is 33.7%. This may be because all tests performed by the cement plant are conducted on 24-hour composite samples, whereas Auburn University only conducts tests on a single 3-day composite sample. This may also be due to human error by one or both parties.

Table 4.52: CPR – Physical properties of cement and percent difference relative to baseline for all burns

Property	**FT**		**B-CCTP**	**B-CCP**	**RR**		**GL**	
	Avg.	**% Diff.[1]**	**Avg.**	**Avg.**	**Avg.**	**% Diff.[2]**	**Avg.**	**% Diff.[2]**
Air in Mortar (%)	4.60	-14.2	5.36	6.30	6.45	2.38	7.20	14.3
Blaine Specific Surface Area (m^2/kg)	394	0.00	394	385	384	-0.390	385	-0.130
Autoclave Expansion (% Exp.)	0.080	36	0.059	0.070	0.056	-21	0.094	34
Cube Flow (%)	100	-0.398	100	115	116	0.435	106	-7.83
Compressive Strength (MPa)								
1 day	15.5	-5.34	16.3	16.4	15.8	-3.66	14.0	-14.6
3 day	25.2	-2.34	25.8	23.5	24.3	3.41	23.8	1.49
7 day	33.3	3.93	32.0	30.5	29.2	-4.27	31.9	4.76
28 day	45.7	9.59	41.7	41.5	41.3	-0.483	41.4	-0.121
Normal Consistency (%)	25.4	0.794	25.2	25.2	25.2	0.00	25.1	-0.199
Gillmore Initial Set (min.)	135	0.00	135	NR	NR	NA	NR	NA
Gillmore Final Set (min.)	225	-16.7	270	NR	NR	NA	NR	NA
Vicat Initial Set (min.)	85.2	-11.7	96.4	103	127	23.4	126	22.9
Vicat Final Set (min.)	203	-17.3	246	248	210	-15.2	240	-3.03

Notes:
[1] Relative to B-CCTP
[2] Relative to B-CCP
NA - Not Applicable
NR - Not Reported

Table 4.53: AUR – Physical properties of cement and percent difference relative to baseline for all burns

Property	FT		B-CCTP	B-CCP	RR		GL	
	Avg.	**% Diff.[1]**	**Avg.**	**Avg.**	**Avg.**	**% Diff.[2]**	**Avg.**	**% Diff.[2]**
Autoclave Expansion (% Exp.)	0.065	7.50	0.060	0.020	0.040	50.00	0.12	500
Cube Flow (%)	67.2	-18.6	82.6	104	107	2.99	118	14.0
Compressive Strength (MPa)								
1 day	14.6	-6.4	15.6	14.7	15.4	4.76	13.6	-7.48
3 day	26.0	-2.6	26.7	26.6	23.4	-12.0	22.2	-16.54
7 day	36.4	8.3	33.6	31.3	30.7	-1.92	27.2	-13.10
28 day	38.6	4.0	37.1	38.4	37.7	-1.82	35.4	-7.81
Normal Consistency (%)	24.6	-3.15	25.4	25.4	25.3	-0.394	24.5	-3.54
Gillmore Initial Set (min.)	130	-3.70	135	88.0	116	31.8	120	36.36
Gillmore Final Set (min.)	220	-2.22	225	178	181	1.69	195	9.55
Vicat Initial Set (min.)	140	10.2	127	97	101	4.12	110	13.40
Vicat Final Set (min.)	225	4.65	215	157	157	0.00	185	17.83
Drying Shrinkage (%)								
7 day	-0.049	-1.5	-0.050	-0.049	-0.049	-0.51	-0.048	-3.5
14 day	-0.075	4.2	-0.072	-0.075	-0.074	-1.7	-0.069	-7.4
21 day	-0.086	6.8	-0.081	-0.088	-0.088	0.00	-0.084	-4.6
28 day	-0.095	6.1	-0.089	-0.089	-0.088	-0.56	-0.094	5.6

Notes:

[1] Relative to B-CCTP **NA - Not Applicable**

[2] Relative to B-CCP **NR - Not Reported**

One consistent trend seen between the two testing agencies is the increase in autoclave expansion of the GL cement relative to its baseline, which is most likely due to the increased MgO content in the GL cement. According to the CPR results, GL was seen to expand by 0.094%, and B-CCP expanded by 0.056%, yielding a difference in percent expansion of 0.024. According to AUR, the difference in percent expansion was 0.10. From Table 4.51, the single-lab precision for autoclave expansion is 0.07. Although AUR results exceed this limit, CPR results do not. Therefore, the increase in autoclave expansion for the GL cement is of no practical significance.

The cube strength results from the cement plant and Auburn University are plotted in Figures 4.11 and 4.12, respectively. Both entities show that FT has similar early-age and long-term strengths as compared to its baseline. However, the greatest difference is 9.59% at 28-days as shown in Table 4.52, which is less than the single-lab limit provided in Table 4.51. Therefore, these results are within the repeatability of the test, meaning the change in compressive strength for the FT cement relative to its baseline is of no practical significance. Both testing party results for the RR cement indicate that its compressive strength development is similar to its baseline burn's results. The only result that is of practical significance is a reduction in early-age compressive strengths for the GL burn. This may be partially due to the increased P_2O_5 content seen in the liquid glycerin, as well as many other changes in the GL cement's chemical composition, as discussed in Section 4.4.6.

The dry shrinkage results collected by Auburn University are plotted in Figure 4.13. According to Table 4.51, it may be concluded that the drying shrinkage results for all burns are very similar, as all results are well within the limits of repeatability.

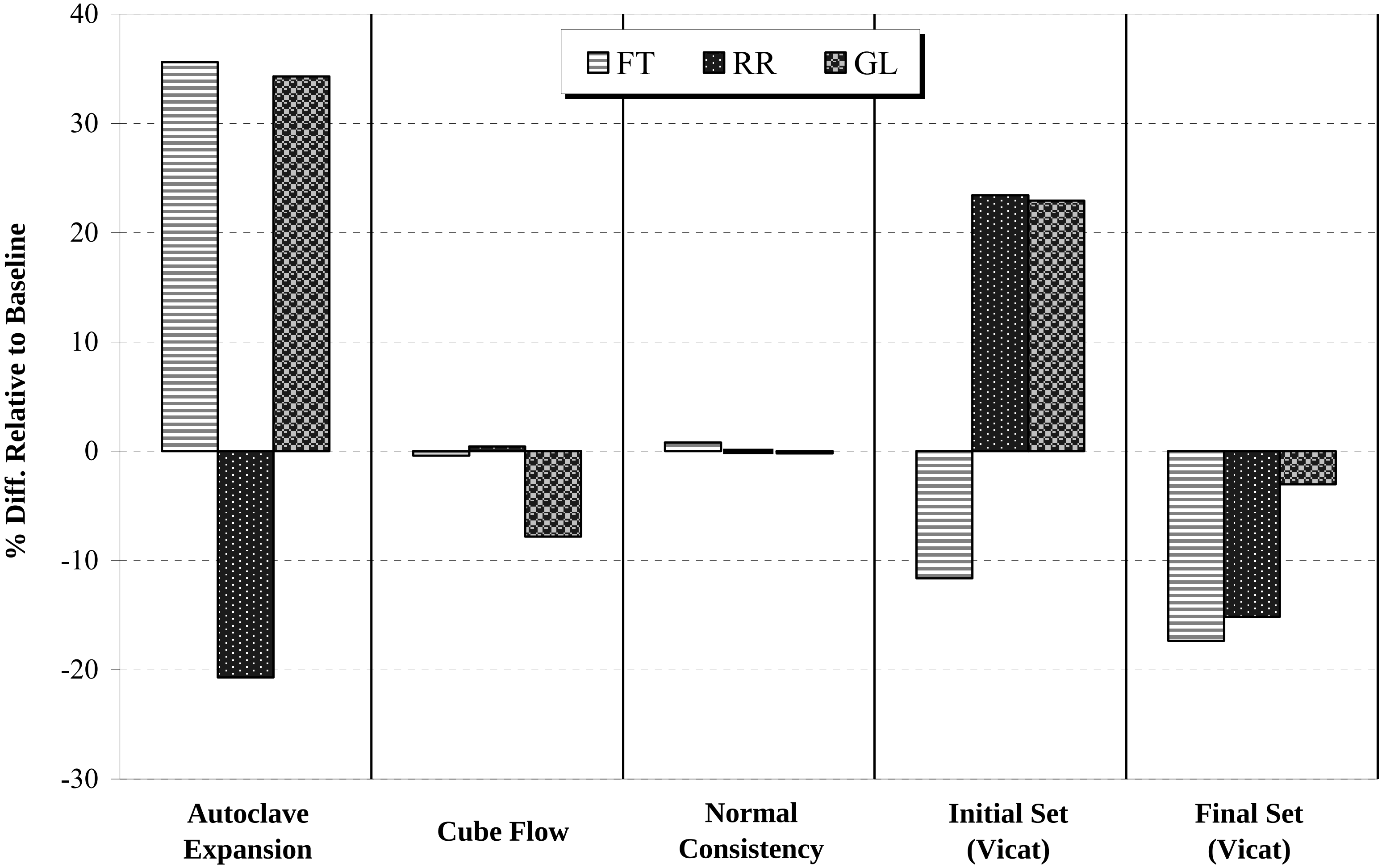


Figure 4.9: CPR – Percent difference of cement physical properties relative to baseline

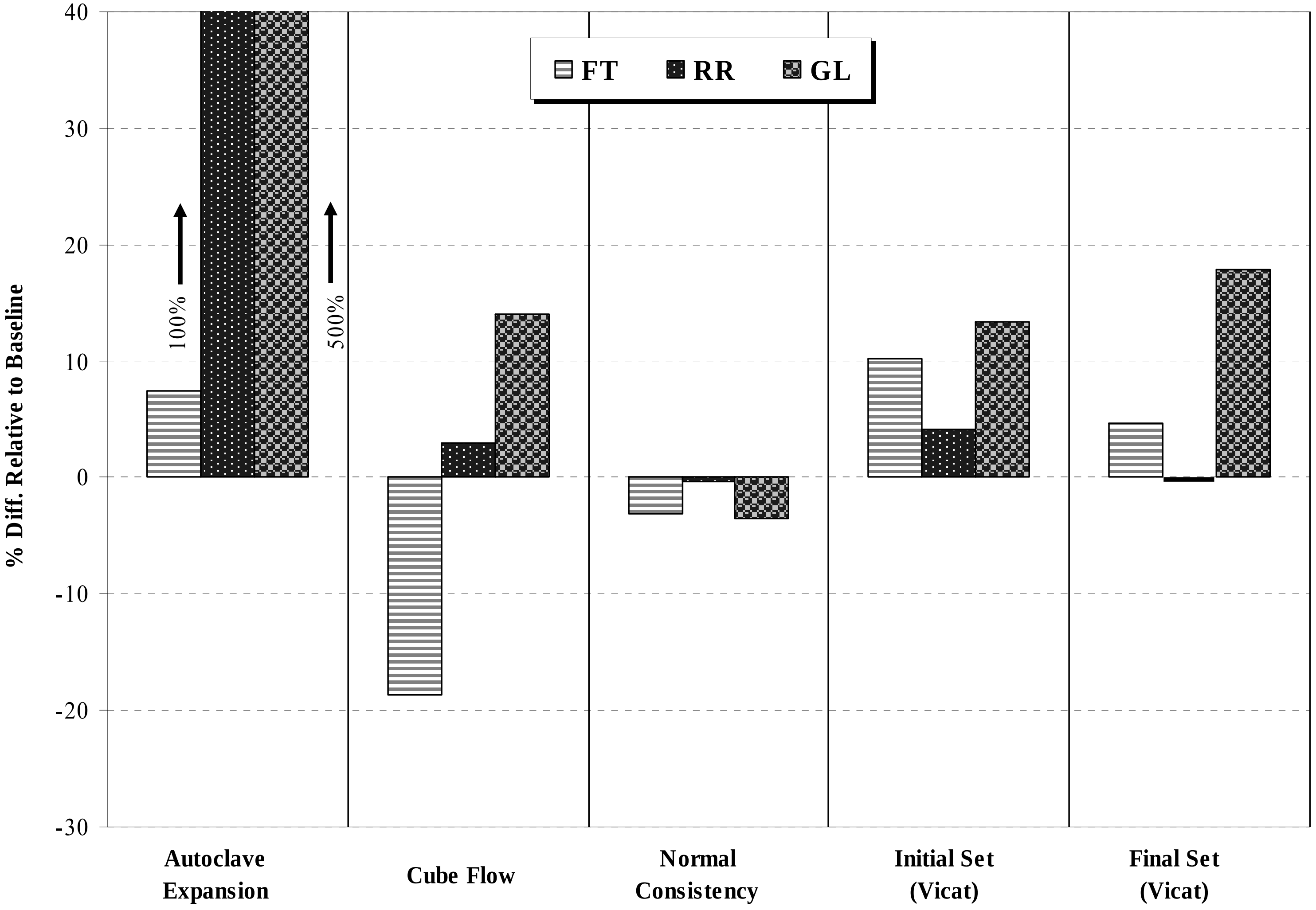


Figure 4.10: AUR – Percent difference of cement physical properties relative to baseline

The final physical property determined is the particle size distribution. This was done by laser diffraction at the cement plant’s specialty laboratory, and the results are shown in Figure 4.14. All cements seem to have a nearly identical distribution, which indicates that all cements were ground to the same particle size by the plant. Any difference in behavior is thus not due to differences in particle size distribution.

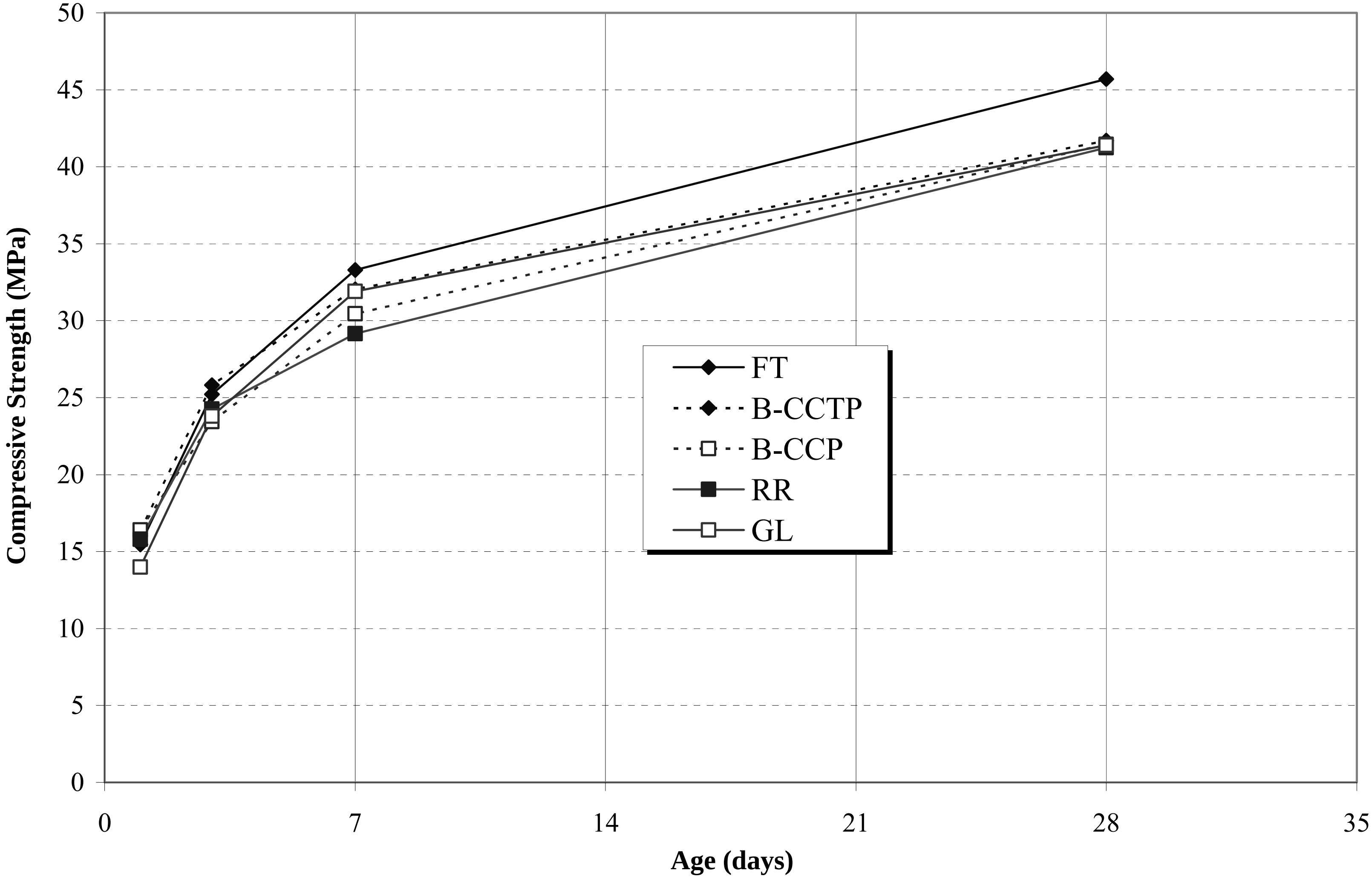


Figure 4.11: CPR –Compressive strength of mortar cubes for all burns

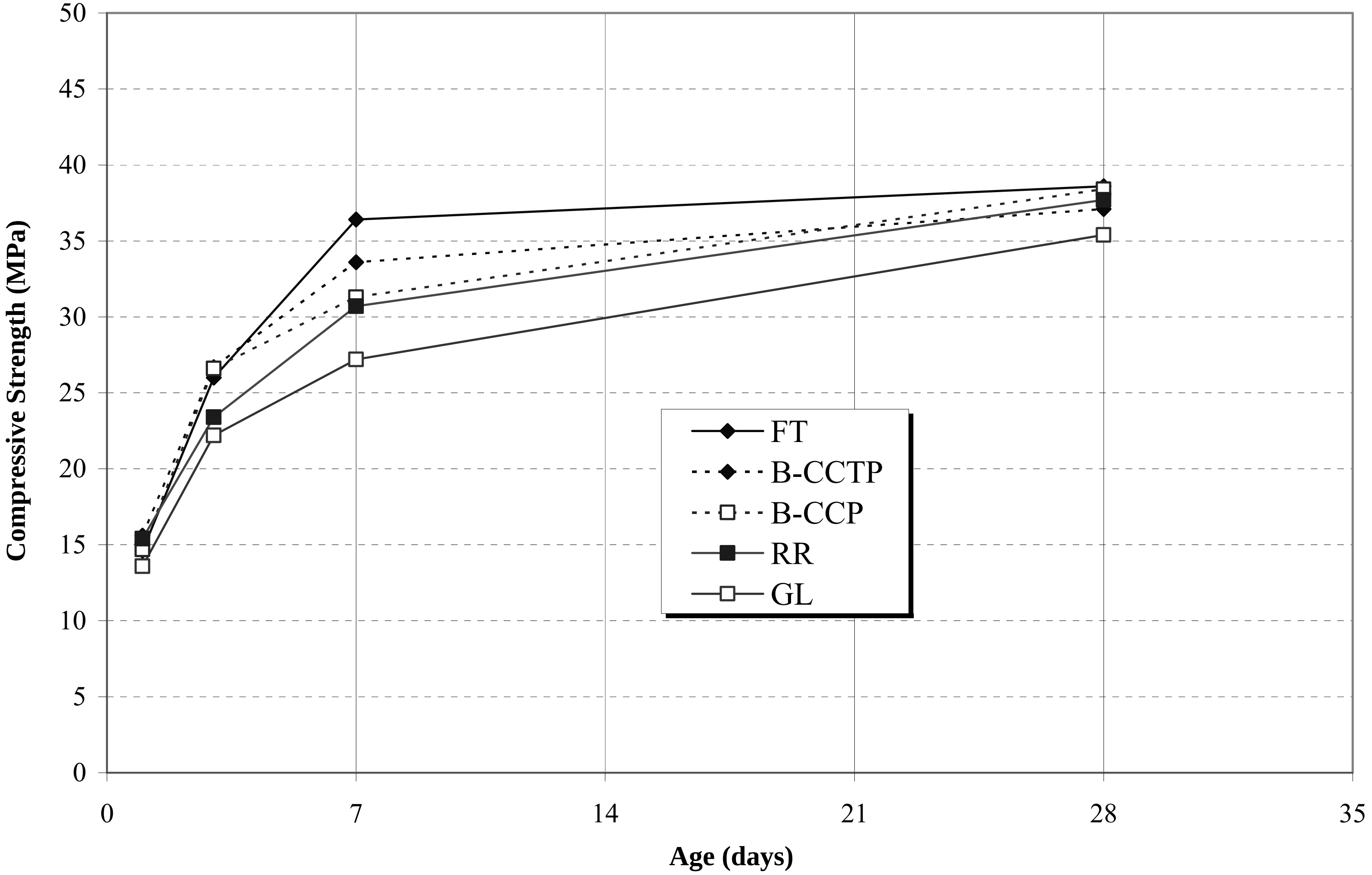


Figure 4.12: AUR – Compressive strength of mortar cubes for all burns

*Note: Values expressed as positive

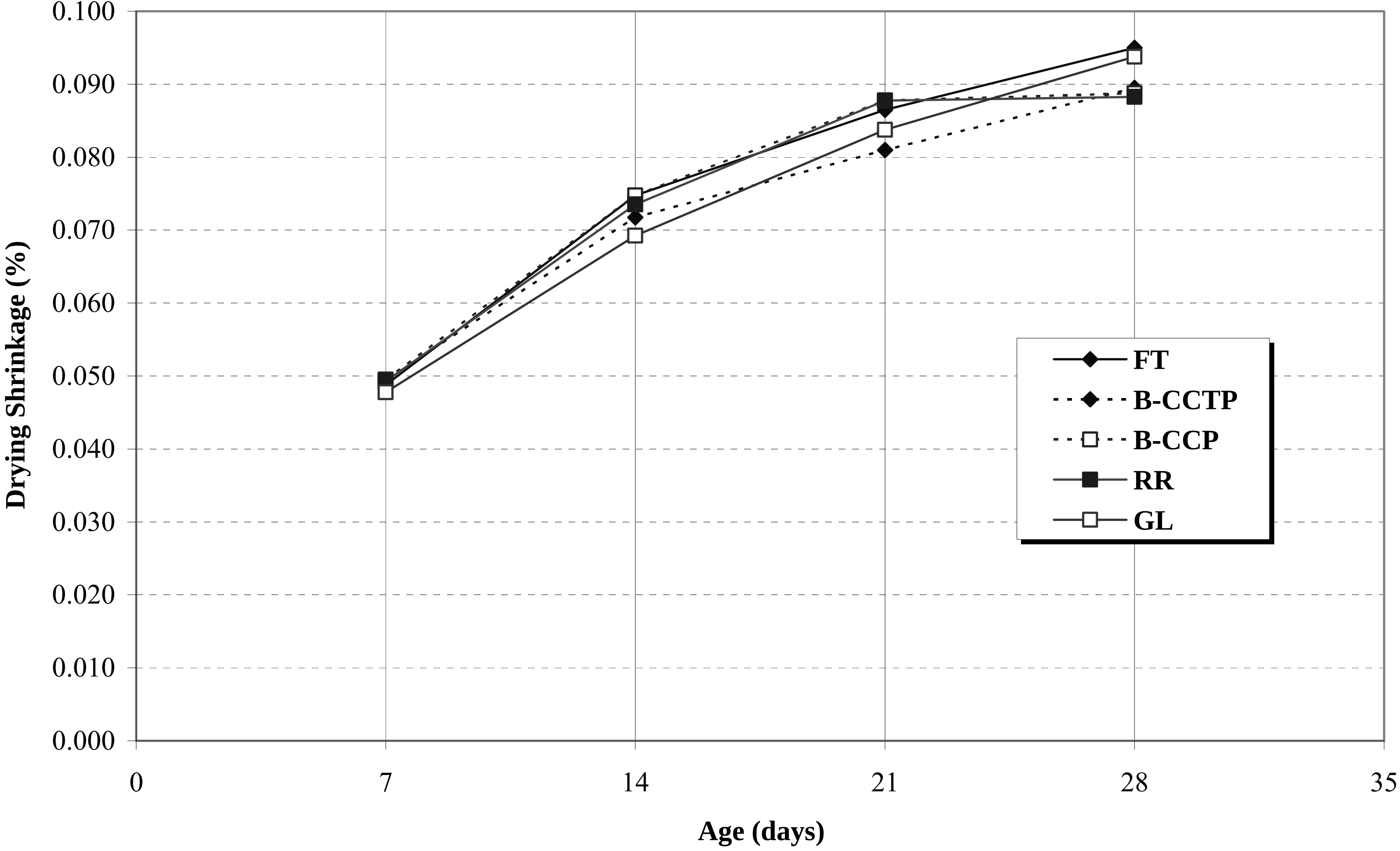


Figure 4.13: AUR – Drying shrinkage development of mortar prisms for all burns

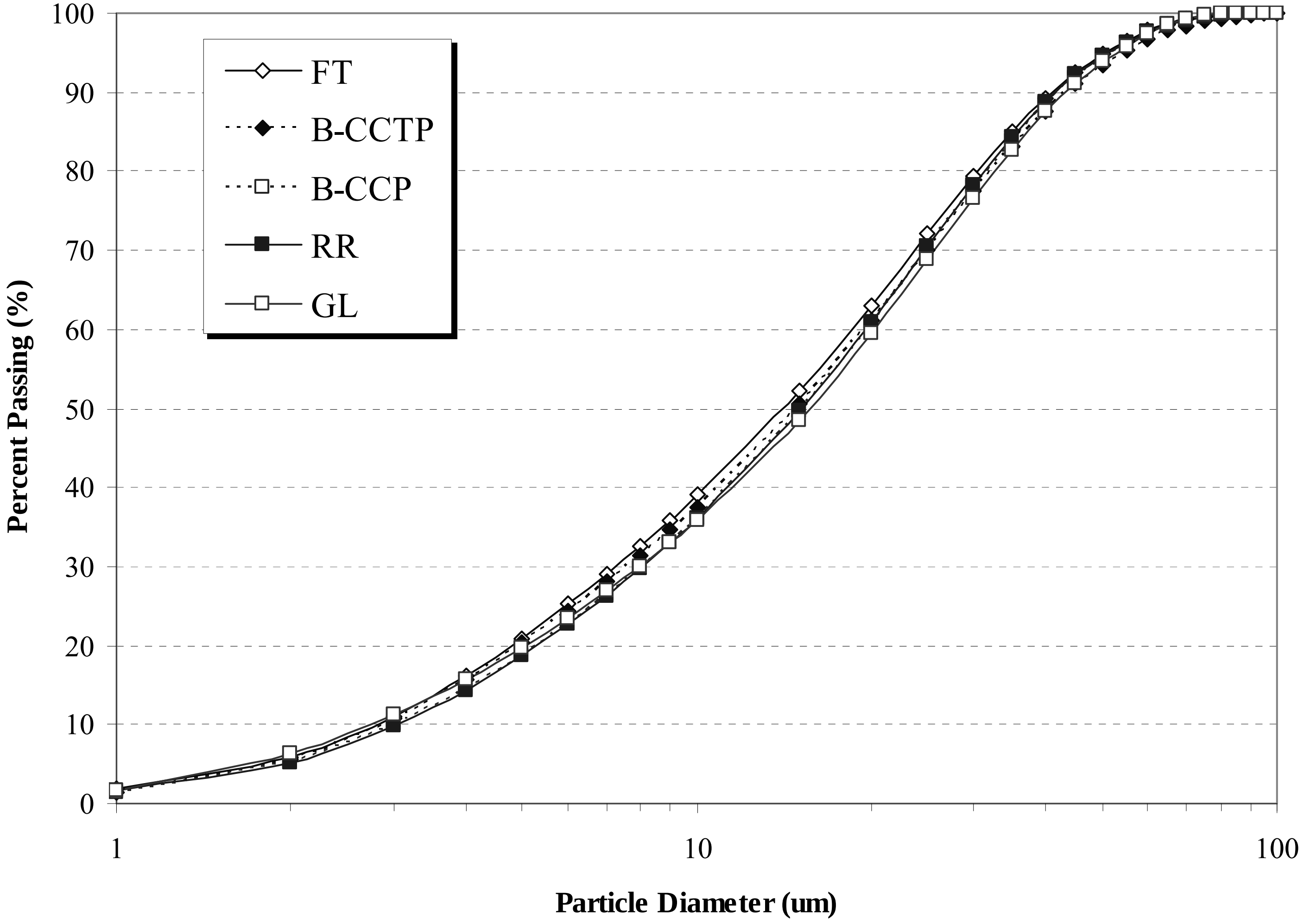


Figure 4.14: SLR – Particle size distribution of cement for all burns

4.4.7.1 Admixture Study

An admixture study was initiated during this phase of the study to examine the effects of chemical admixtures on hydration, flow, and setting time properties of the cement produced from alternative fuels. Three cement pastes were prepared from each cement: one control paste containing no admixture, one containing an accelerating admixture, and one containing a retarding admixture. The accelerating admixture used was *WR Grace Daraset 200*, with a dosage of 35.0 oz/cwt. The retarding admixture used was *WR Grace Daracem 19*, with a dosage of 14.5 oz/cwt. Refer to Section 3.4.2.1 for further details on the testing methods used.

A summary of the flow and setting time results from each paste mixture are provided in Table 4.54. Also shown is the percent difference relative to the control mixture (containing no admixture). The percent differences for flow and setting times are also plotted in Figures 4.15 and 4.16, respectively. Note that the flow was increased significantly for all pastes mixed with the retarder. This change in flow was greatest for GL and least for FT. The accelerator had seemingly little effect on flow.

From Figure 4.16, results are as expected. For all pastes, the accelerator decreased setting times, and the retarder increased setting times. Note that these are final setting times as initial set was not recorded. The accelerator seems to have the greatest effect on GL and least on FT. The retarder seems to have the greatest effect on RR and the least on GL.

Table 4.54: AUR – Summary results for flow and final setting time for all burns

Parameter	Paste	Control	Accelerator	% Diff.[1]	Retarder	% Diff.[1]
Flow (%)	**FT**	242	234	-3.27	372	53.7
	B-CCTP	238	238	-0.294	370	55.2
	B-CCP	237	238	0.253	367	54.7
	RR	236	240	1.65	387	63.9
	GL	246	243	-0.9	406	65.3
Final Set (min.)	**FT**	353	242	-31.4	512	45.0
	B-CCTP	355	200	-43.7	557	56.9
	B-CCP	354	215	-39.3	534	50.8
	RR	356	209	-41.3	567	59.3
	GL	427	227	-46.8	540	26.5

Notes: [1] **Relative to Control Paste**

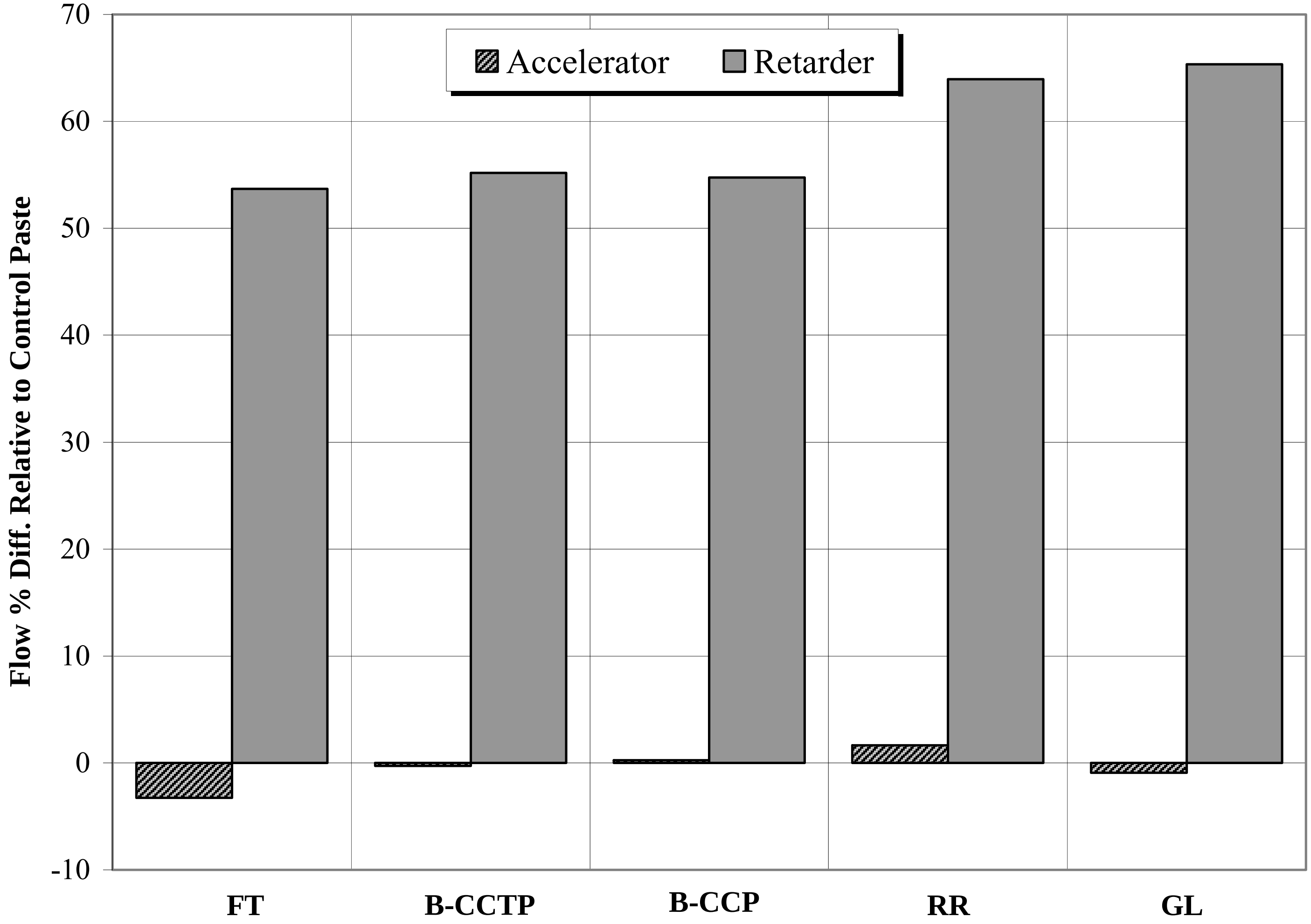


Figure 4.15: AUR – Percent difference in flow relative to control paste for all burns

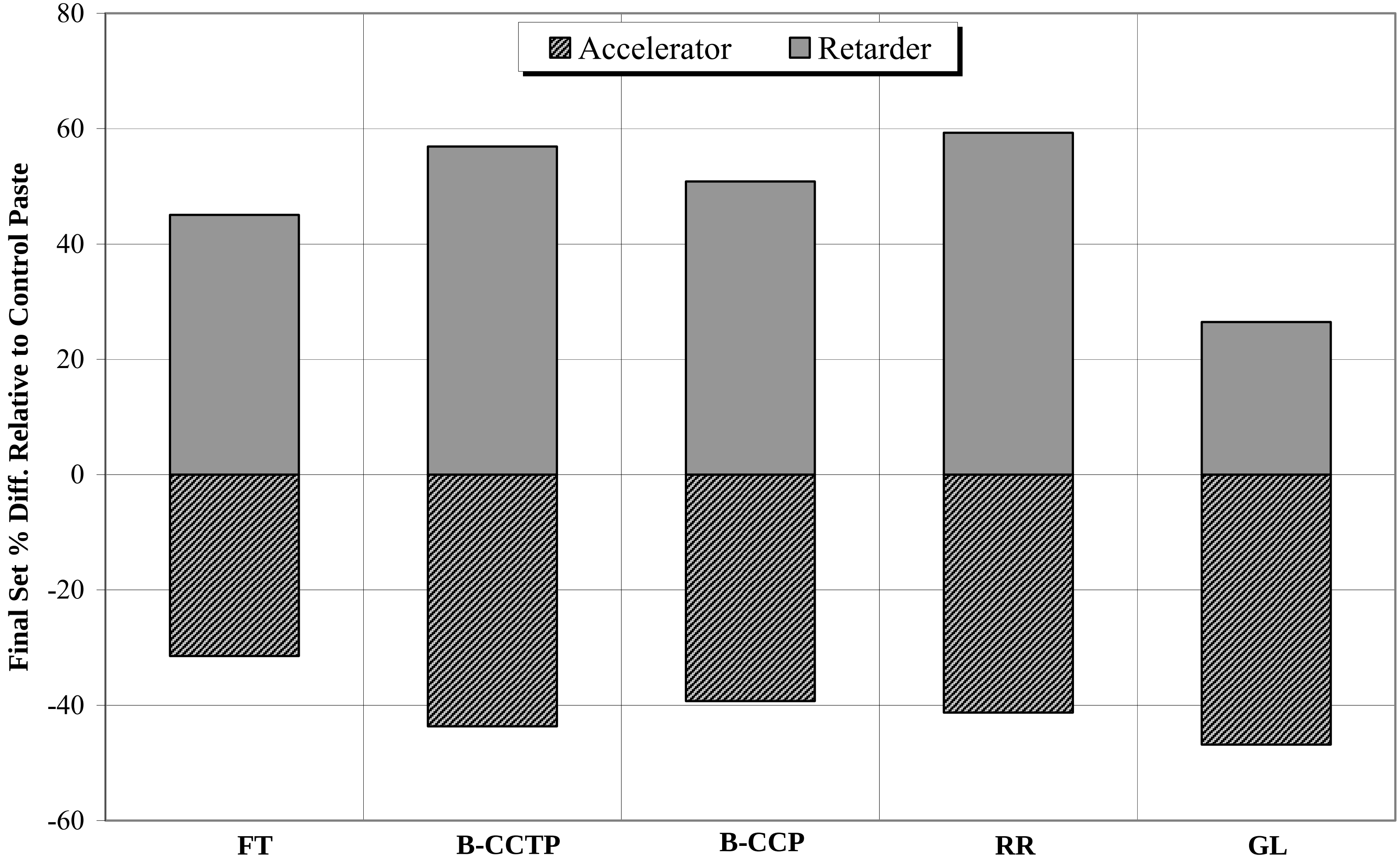


Figure 4.16: AUR – Percent difference in final setting time relative to control paste for all burns

The percent difference in flow and setting times for each of the trial burns with respect to their corresponding baseline burn is shown in Table 4.55. These results are also plotted in Figures 4.17 and 4.18 for flow and final set, respectively. The pastes made with cement from the trial burns are seen to be fairly consistent with their baseline. The greatest difference is seen in the final set for the FT paste mixed with the accelerating admixture, which set 21% later than the B-CCTP paste. This indicates that this dosage of accelerator was not as effective with the FT cement as it was with its baseline cement. The final set for GL cement's control paste increased significantly relative to B-CCP. This was also seen in the cement's physical properties shown in Figure 4.10.

Table 4.55: AUR – Percent difference in flow and final setting time relative to baseline

Test	**Mixture**	**FT**	**RR**	**GL**
		% Diff.[1]	**% Diff.[2]**	**% Diff.[2]**
Flow	Control	1.51	-0.548	3.46
	Accelerator	-1.52	0.841	2.23
	Retarder	0.541	5.36	10.5
Final Set	Control	-0.563	0.565	20.6
	Accelerator	21.0	-2.79	5.58
	Retarder	-8.08	6.18	1.12

Notes: [1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

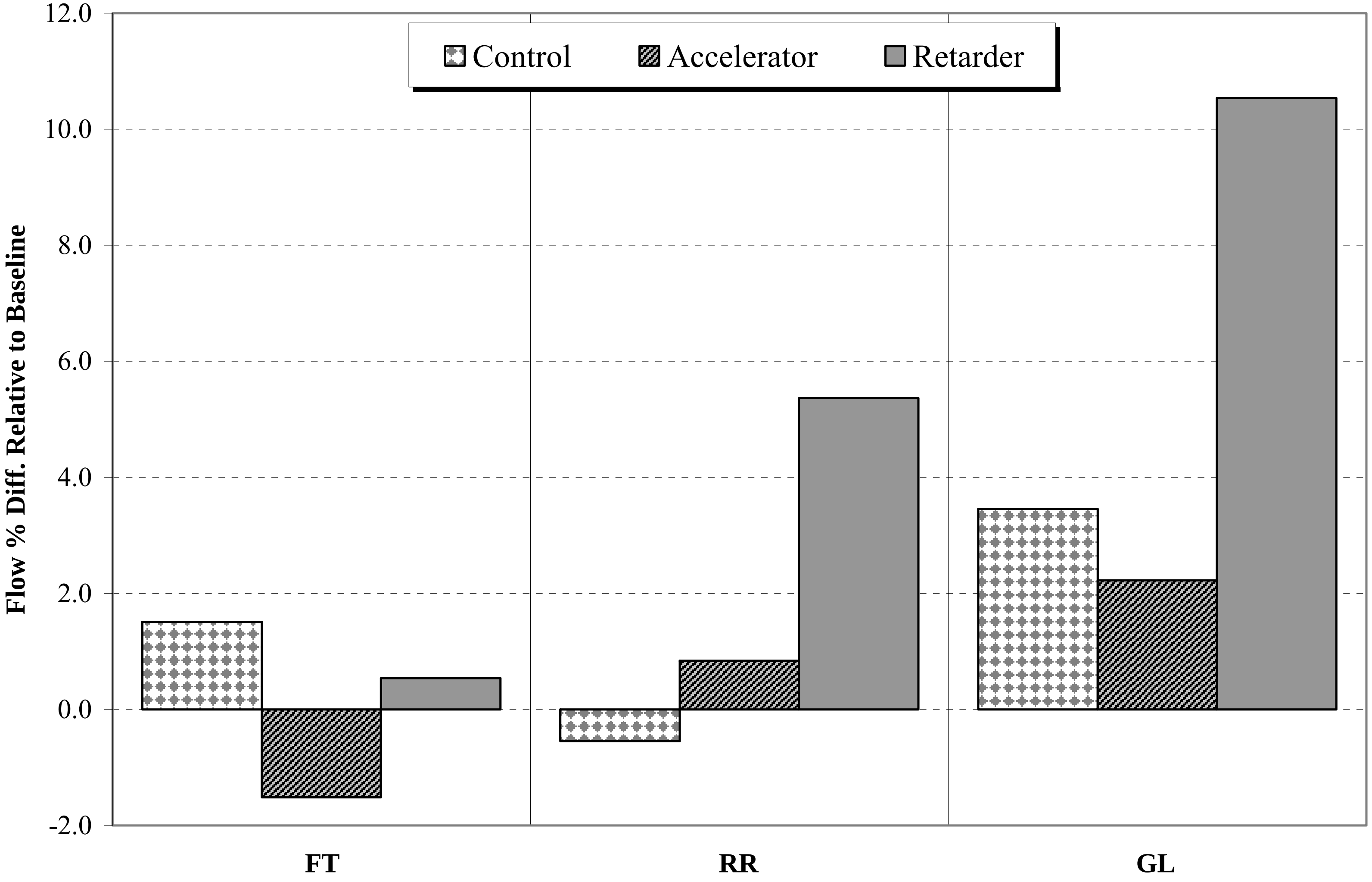


Figure 4.17: AUR – Percent difference in flow relative to baseline for trial burns

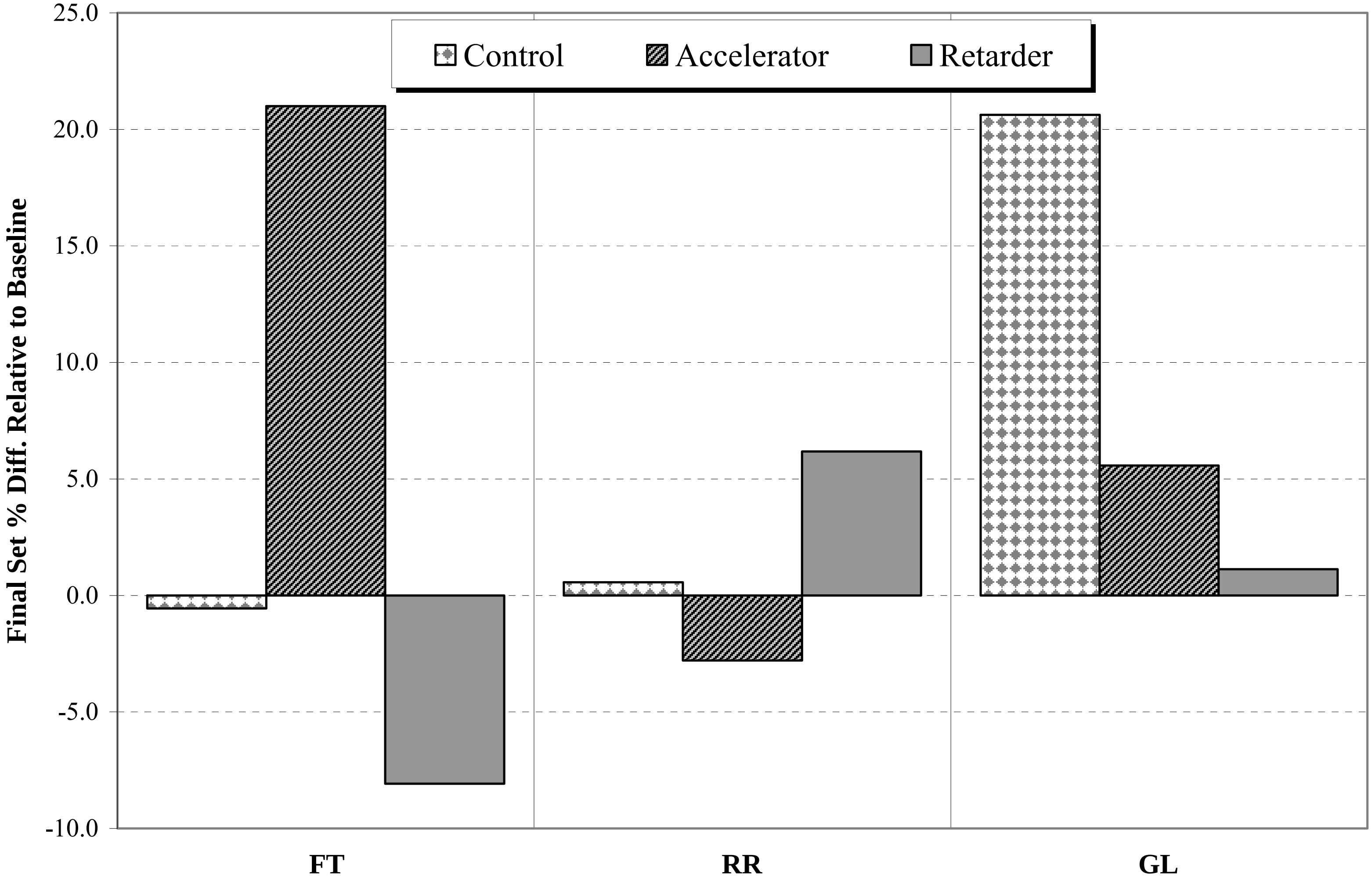


Figure 4.18: AUR – Percent difference in final setting time relative to baseline for trial burns

The hydration process of each paste mixture was also monitored using the *TAM Air* isothermal calorimeter. It took approximately ten minutes from mixing to initiate the test, so the *initial* C_3A hydration peak was not captured. Each paste was monitored for forty-eight hours, but emphasis is placed on the first twenty-four hours of hydration. Heat flow was recorded in fifteen-minute intervals to produce a hydration curve for each paste mixture.

Results are shown in Figures 4.19 through 4.23. Each figure represents one cement with hydration curves for the three paste mixtures. A grey shaded circle is located along each curve, indicating the time of final set as determined earlier. Each figure is plotted on the same scale for comparison purposes. In each figure, the maximum rate of hydration occurs first in the accelerating mixture and last in the retarding mixture. This indicates that hydration progression is proportional to the setting time, which is correct as setting is caused by the development of sufficient hydration products.

Throughout the remainder of this section, several references are made regarding the C_3S and C_3A peaks. Though the *initial* peak is caused by C_3A, it was not fully captured, and thus will not be mentioned from this point forward. The C_3S peak refers to first peak fully captured (Stage III from Figure 3.16). The C_3A peak refers to the second peak fully captured (Stage IV from Figure 3.16).

Note that the three FT paste mixtures do not follow many of the typical trends seen in the other cements. Aside from the FT paste, all mixtures containing the accelerator have the highest peak heat flow, and all containing the retarder have the lowest peak heat flow. For the FT paste, the mixture containing the retarder produced the highest peak heat flow. However, the heat generated from this mixture was consistent with the other cements, so the difference lies with the behavior of its control and accelerating paste results. Notice the heat produced from all accelerated paste mixtures is well above 5.0 W/kg, with the exception of FT. Early-age heat of hydration development is primarily due to C_3S and C_3A. From Tables 4.49a and 4.50, the C_3S content for the FT cement is lower than the other cements. This may have inhibited the early-age heat development seen in this paste.

Another difference in the FT paste is the shape of the hydration curves. Aside from the FT mixtures, the C_3S peak in each mixture is greater than the C_3A peak in the same mixture. The difference in FT may be attributed to the principle cement compounds shown in Tables 4.50a and 4.51 and a possible sulfate imbalance. FT cement is seen to possess high C_3A and low C_3S and SO_3 percentages. Recall from Section 2.6, mixtures high in C_3A typically require additional SO_3 to regulate cement hydration at early ages (Chen and Juenger 2009). This increase in the C_3A peak could be a result of insufficient gypsum in the cement, which could also lead to setting problems.

The hydration curves for the RR paste are shown in Figure 4.22. The control mixture curve fell between the other two curves, as expected. The retarding mixture was nearly identical to the control mixture, only shifted to the right by about four hours. All mixtures for the RR and B-CCP were nearly identical. As discussed in the previous section, the C_3S content of the RR cement was less than that of its baseline. This resulted in a slight reduction in heat during the C_3S peaks of each RR mixture shown in Figure 4.22.

The hydration curves for the GL paste are shown in Figure 4.23. All hydration curves are very similar those from its baseline. Compared to the B-CCP paste, the width of C_3A peak on the GL accelerator curve appears to be more drawn out. As mentioned earlier, the C_3A content of the GL cement was higher than that of its baseline. More C_3A would cause this reaction to occur for a longer period of time, as shown in Figure 4.23.

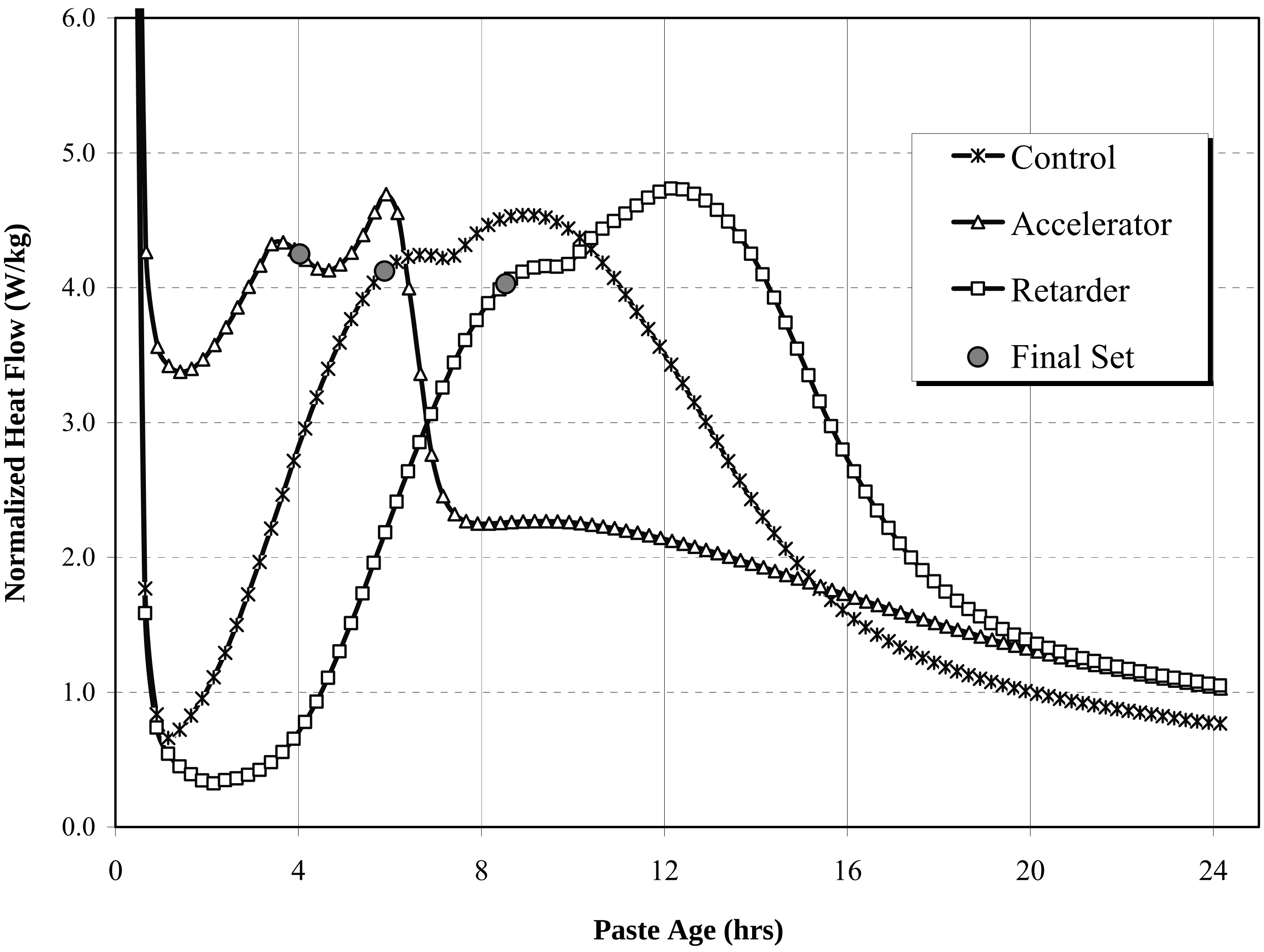


Figure 4.19: AUR – Hydration curves and final setting times for FT paste

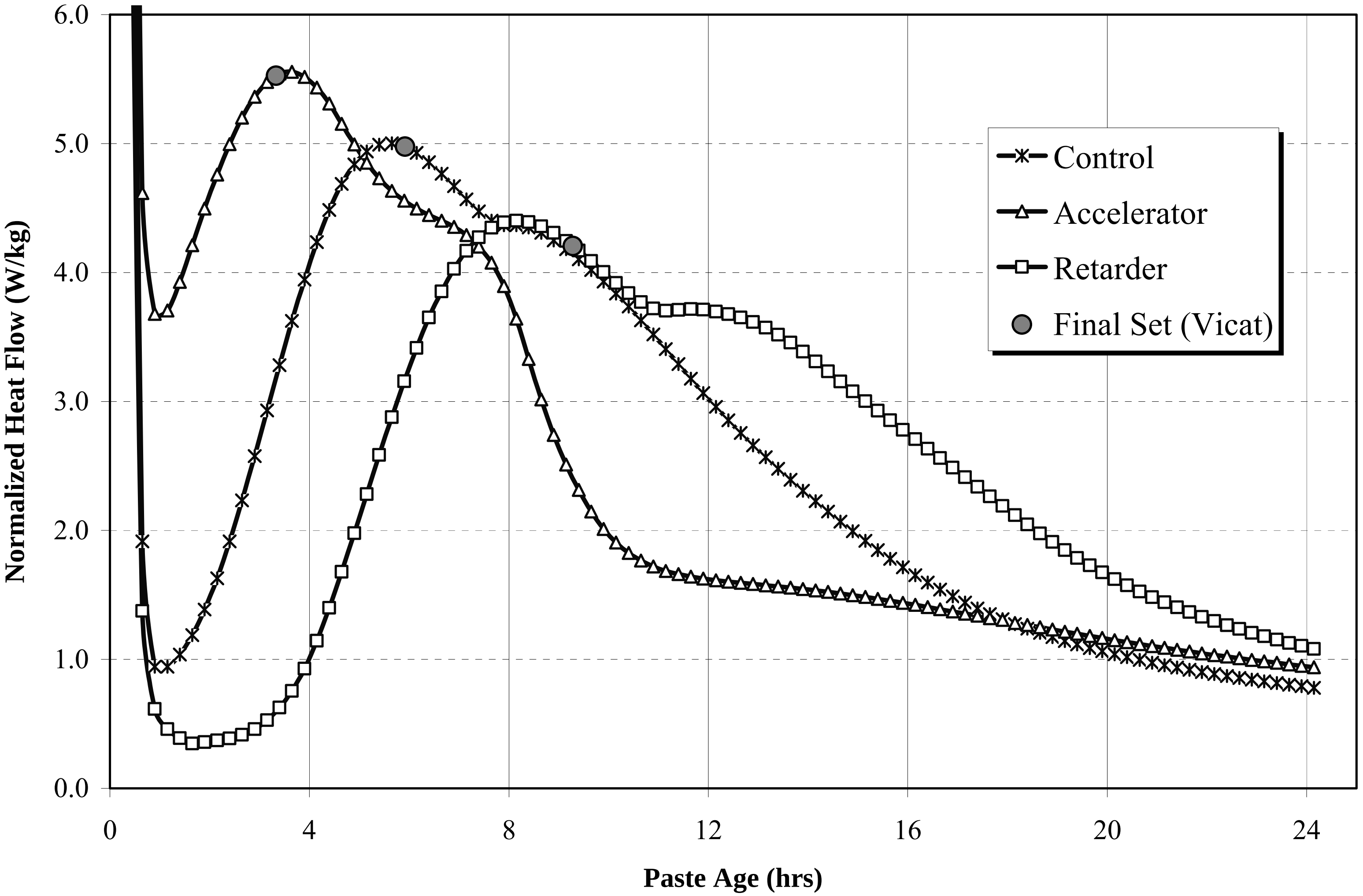


Figure 4.20: AUR – Hydration curves and final setting times for B-CCTP paste

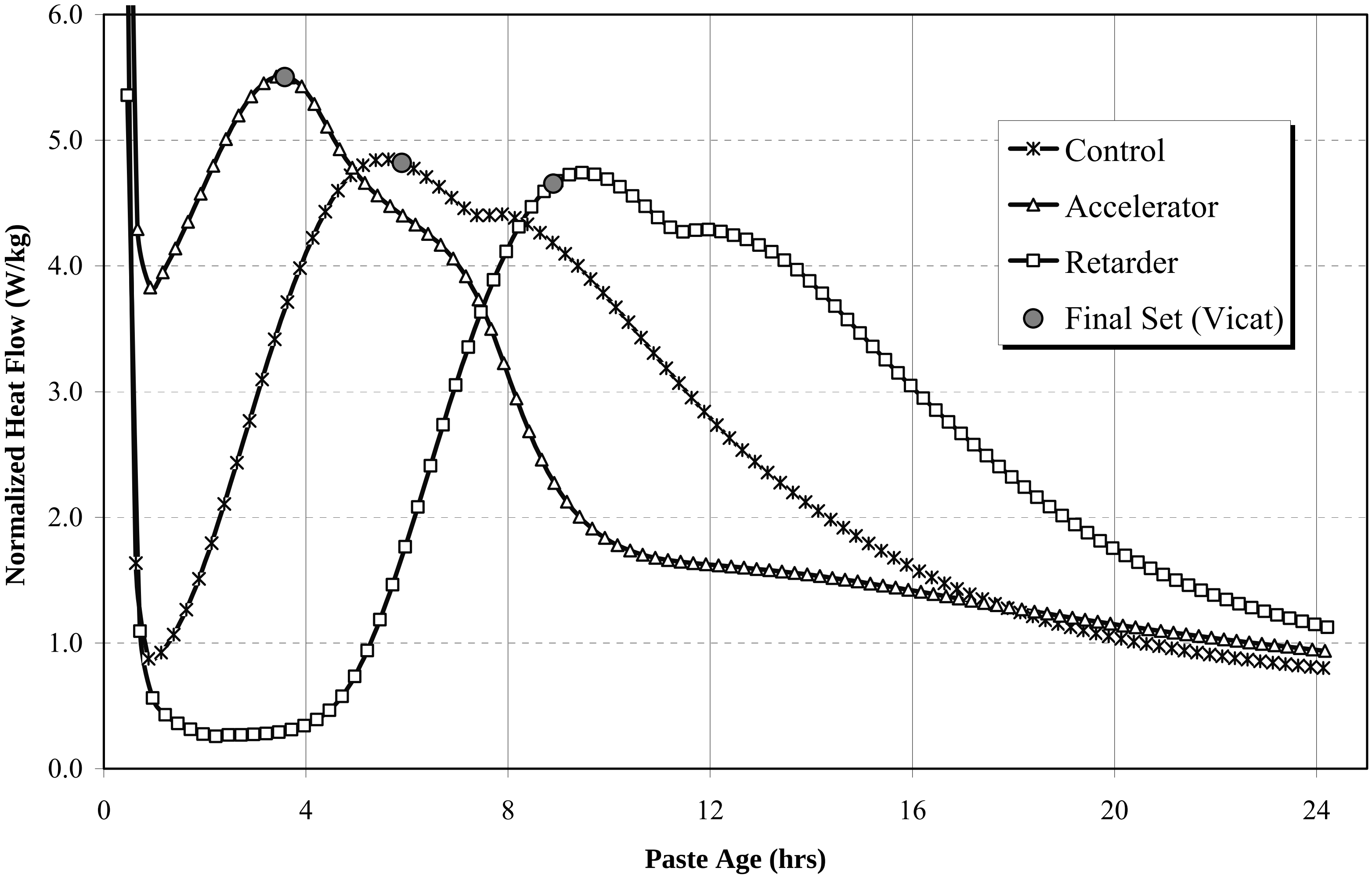


Figure 4.21: AUR – Hydration curves and final setting times for B-CCP paste

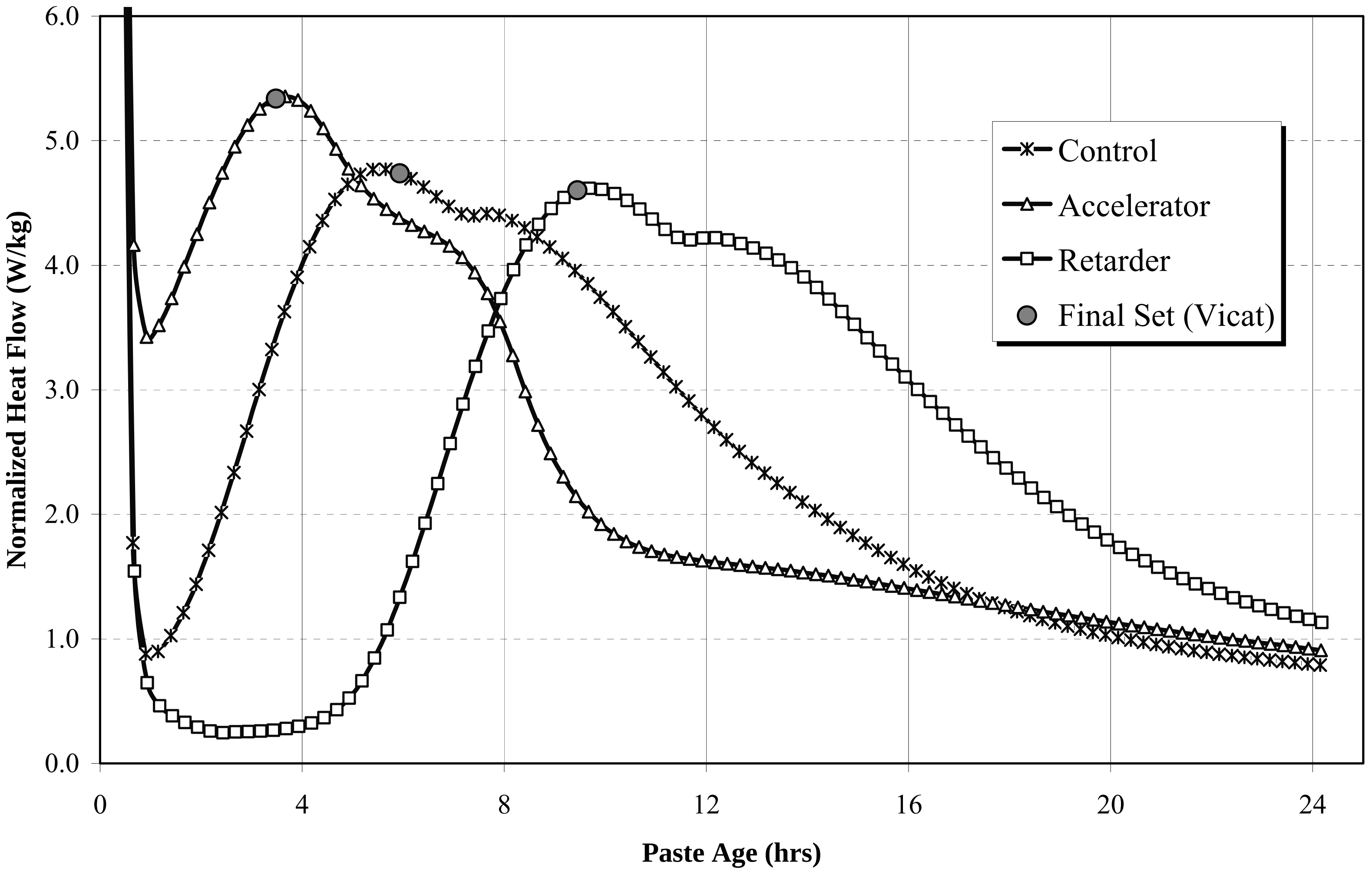


Figure 4.22: AUR – Hydration curves and final setting times for RR paste

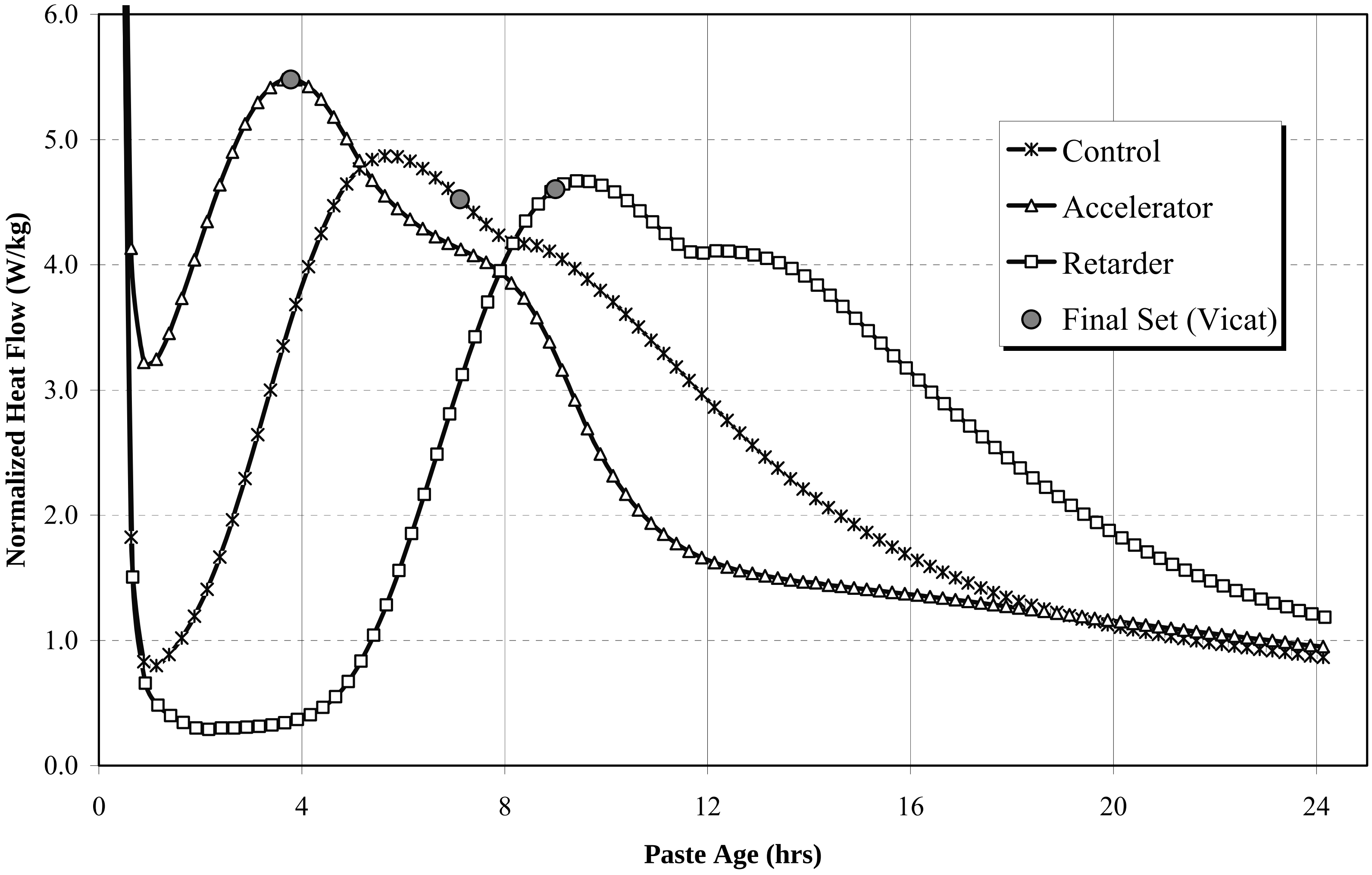


Figure 4.23: AUR – Hydration curves and final setting times for GL paste

4.4.8 Properties of Concrete

As discussed in Chapter 3, cement was collected from each burn in order to prepare two different concrete mixtures, Mix A and Mix B. The water-cement ratio (w/c) and mixture proportions were different for both mixtures. For this reason, results from each mixture cannot be compared directly. However, similar trends must be noticed in both mixtures before the level of practical significance can be established. Therefore, all results from Mix A and Mix B will be provided before they are discussed.

As discussed in Section 4.4.7, ASTM specifications also provide precision limitations on physical properties of concrete. The single-lab and multi-lab requirements for several physical properties determined by Auburn University are shown in Table 4.56. The percent difference in trial burn results relative to their baseline will be compared to the values in Table 4.56. This will be used to determine the level of practical significance in the concrete results. Note that all precision requirements are provided by ASTM specifications except for initial and final setting times. ASTM C 403 (2008) provides this precision in terms of difference in setting times. A study recently conducted by Weakley (2009) reports these precision requirements in terms of percent difference, which is thought to be more accurate.

4.4.8.1 Concrete Mix A

Mix A was a conventional concrete mixture with a w/c of 0.44. Mixture proportions were shown in Table 3.7. Further details of mixing and testing methods were discussed in Section 3.4.3. All physical properties were determined at Auburn University

Table 4.56: Single-lab and multi-lab precision for concrete physical properties

Property	ASTM Specification	Single-lab	Multi-lab
Total air content	C 192 (2007)	0.8 %[1]	1.1 %[1]
Slump		50.8 mm (2.0 in.) [1]	71.1 mm (2.8 in.) [1]
Unit weight		40.0 kg/m^3 (2.5 lb/ft^3) [1]	64.1 kg/m^3 (4.0 lb/ft^3) [1]
Initial set	Weakley (2009)	4.8 %[3]	10.7 %[3]
Final set		3.9 %[3]	7.4 %[3]
Compressive strength	C 39 (2005)	7.9 % [2]	14 %
Splitting tensile strenth	C 496 (2004)	14%	
Permeability	C 1202 (2007)	42 %	51 %
Dry shrinkage	C 157 (2006)	0.0137 % [1]	

Notes:

[1] Difference in the average of two results

[2] Based on three cylinders

and results are shown in Table 4.57. The percent difference for each trial burn relative to their baseline burn is also shown.

The first five properties shown are known as fresh concrete properties (total air content through final set), which were determined while the concrete was its fresh state. Since Mix A was broken into two batches, several properties were evaluated for both batches to ensure consistency. All properties met the single laboratory requirements set forth by ASTM specifications. The percent difference for these fresh concrete properties is plotted in Figure 4.24.

Compressive strength of concrete is heavily dependent on the total air content of the mixture. According to ACI (1992), “Incorporation of entrained air may reduce strength at a ratio of 5 to 7 percent for each percent of air.” Therefore, compressive strengths were normalized with respect to the air content to better compare results. The air-corrected compressive strength results are shown in Table 4.58 along with the percent difference relative to the baseline. Values are also plotted in Figure 4.25. A conservative correction of 5% was used to determine these values. Note that only the trial burns were corrected in order to obtain theoretical compressive strengths that assume the total air content for each trial burn was equal to that of its baseline.

Table 4.57: AUR – Physical properties and percent difference relative to baseline for Mix A concrete for all burns

Property	FT		B-CCTP	B-CCP	RR		GL	
	Avg.	% Diff.[1]	Avg.	Avg.	Avg.	% Diff.[2]	Avg.	% Diff.[2]
Total Air Content (%)	4.3	43.3	3.0	3.3	4.4	33.3	5.5	66.7
Slump (mm)	44.45	26.8	35.05	50.8	50.8	0.0	86.4	70.0
Unit Weight (kg/m^3)	2419	-1.2	2448	2432	2431	-0.066	2358	-3.1
Initial Set (Min.)	264	9.5	241	249	226	-9.2	301	20.9
Final Set (Min.)	363	12.0	324	344	309	-10.2	381	10.8
Compressive Strength (MPa)								
1 day	12.3	-28.7	17.2	18.2	16.5	-9.6	15.1	-17.2
3 day	20.3	-21.1	25.7	25.7	25.1	-2.3	23.0	-10.3
7 day	29.6	-5.9	31.5	30.5	28.2	-7.5	26.8	-12.1
28 day	37.9	-4.7	39.8	38.2	35.1	-8.1	33.4	-12.5
91 day	44.6	-0.4	44.8	43.3	41.0	-5.2	36.8	-15.0
Splitting Tensile Strength (MPa)								
1 day	1.7	-22.4	2.1	2.2	2.1	-1.9	2.1	-2.7
3 day	2.6	-12.6	3.0	3.1	2.8	-8.1	2.5	-18.5
7 day	3.0	-10.7	3.3	3.1	2.9	-6.3	2.9	-7.8
28 day	3.8	1.4	3.7	3.6	3.5	-2.7	3.5	-2.8
91 day	4.0	-0.2	4.0	4.2	3.6	-13.9	3.8	-9.9
Permeability @ 91 days (Coulombs)	1732	-5.0	1823	2652	2248	-15.2	CIP	NA

Notes:

[1] Relative to B-CCTP **NA - Not Applicable**

[2] Relative to B-CCP **CIP - Collection in Progress**

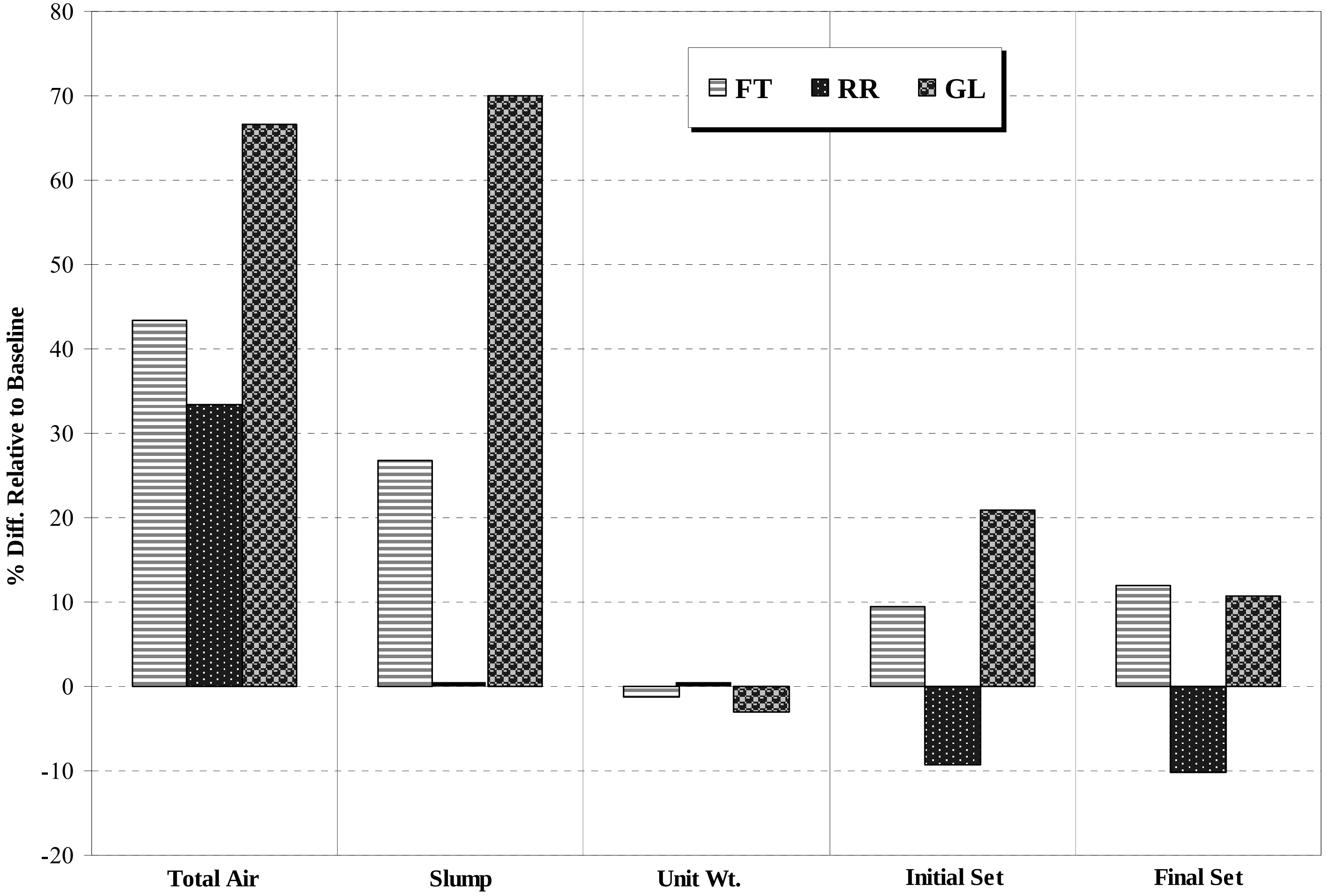


Figure 4.24: AUR – Percent difference in physical properties relative to baseline for Mix A concrete for trial burns

Table 4.58: AUR – Air-Corrected compressive strength and percent difference relative to baseline for Mix A concrete

Concrete Age (days)	**FT**		**RR**		**GL**	
	Avg.[3] (MPa)	**% Diff.[1]**	**Avg.[3] (MPa)**	**% Diff.[2]**	**Avg.[3] (MPa)**	**% Diff.[2]**
1	13.1	-24.1	17.4	-4.6	16.8	-8.1
3	21.6	-15.9	26.4	3.0	25.5	-0.5
7	31.5	0.2	29.8	-2.4	29.7	-2.4
28	40.4	1.5	37.0	-3.1	37.1	-2.8
91	47.5	6.1	43.3	0.0	40.8	-5.7

Notes: [1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

[3] **Air-Corrected**

Splitting tensile strength was tested in accordance with ASTM C 496 (2004) and results are plotted in Figure 4.26. Drying shrinkage development was also tested by Auburn University. Results are shown in Table 4.59 and plotted in Figure 4.27. Note that all shrinkage results are reported as a positive value. The percent length change is relative to the original length. The percent difference is listed for the trial burns relative to their corresponding baseline burn.

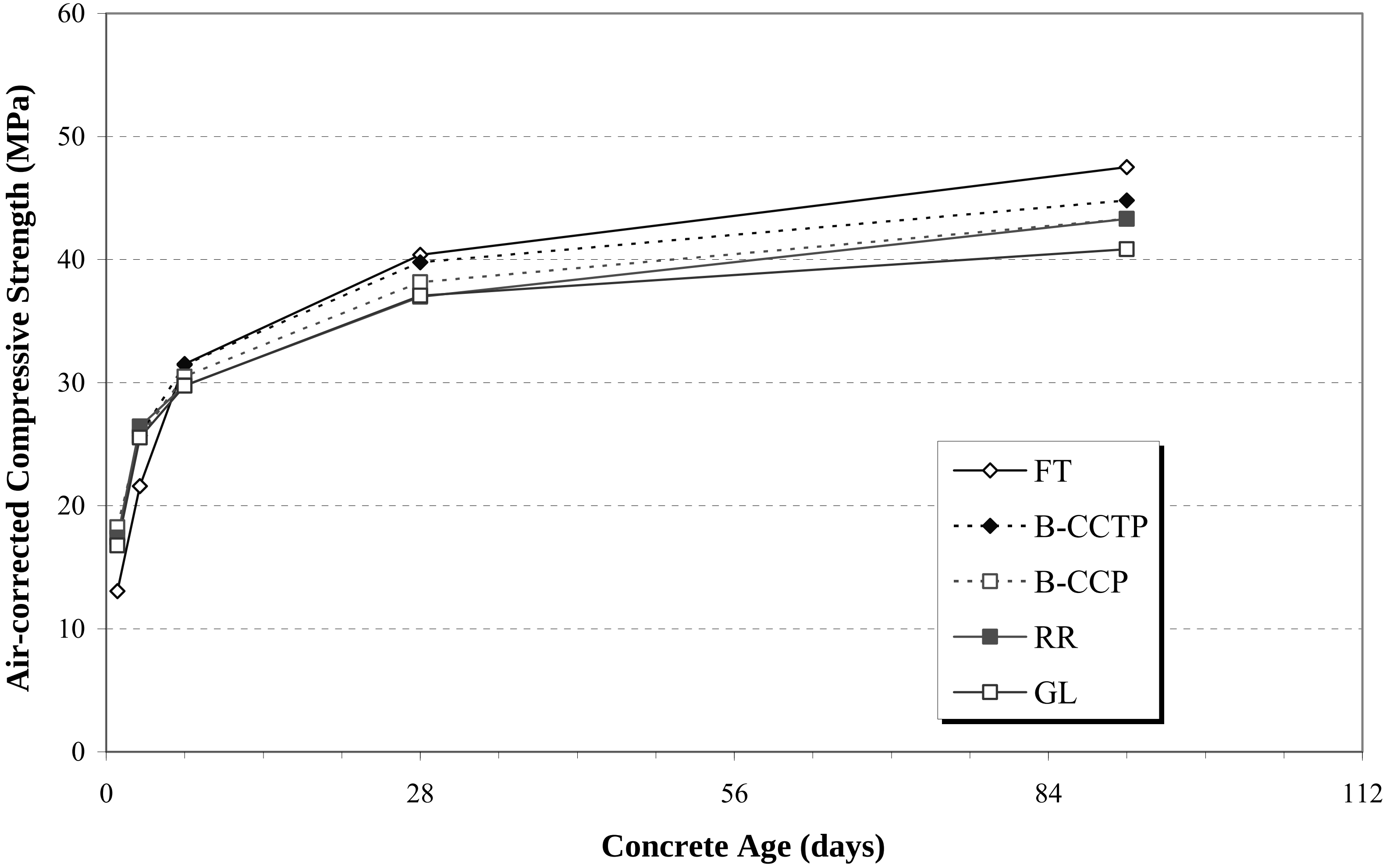


Figure 4.25: AUR – Air-corrected compressive strength for Mix A concrete for all burns

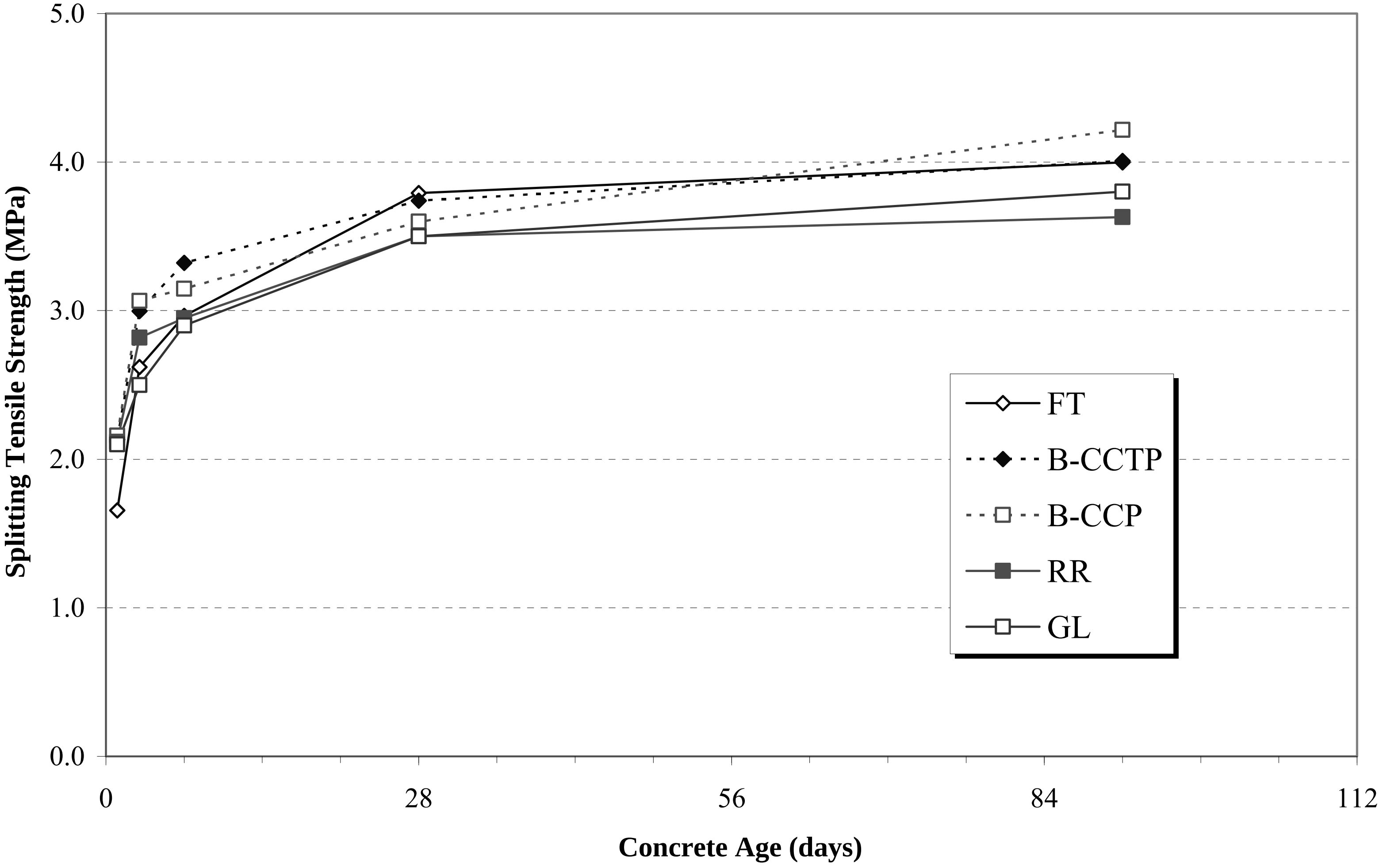


Figure 4.26: AUR – Splitting tensile strength for Mix A concrete for all burns

Table 4.59: AUR – Drying shrinkage development and percent difference relative to baseline for Mix A concrete for all burns

Drying Age (days)	FT		B-CCTP	B-CCP	RR		GL	
	Length Change (%)	% Diff.[1]	Length Change (%)	Length Change (%)	Length Change (%)	% Diff.[2]	Length Change (%)	% Diff.[2]
4	0.016	6.7	0.015	0.013	0.012	-5.1	0.011	-12.8
7	0.019	-5.0	0.020	0.017	0.020	17.6	0.013	-21.6
14	0.029	2.4	0.028	0.024	0.029	17.8	0.021	-15.1
28	0.038	1.8	0.037	0.030	0.036	18.7	0.026	-13.2
56	0.045	0.75	0.045	0.041	0.038	-8.9	0.030	-27.4
112	0.053	2.6	0.052	0.046	0.040	-12.9	0.038	-17.3

Notes:

[1] Relative to B-CCTP

[2] Relative to B-CCP

NA - Not Applicable

CIP - Collection in Progress

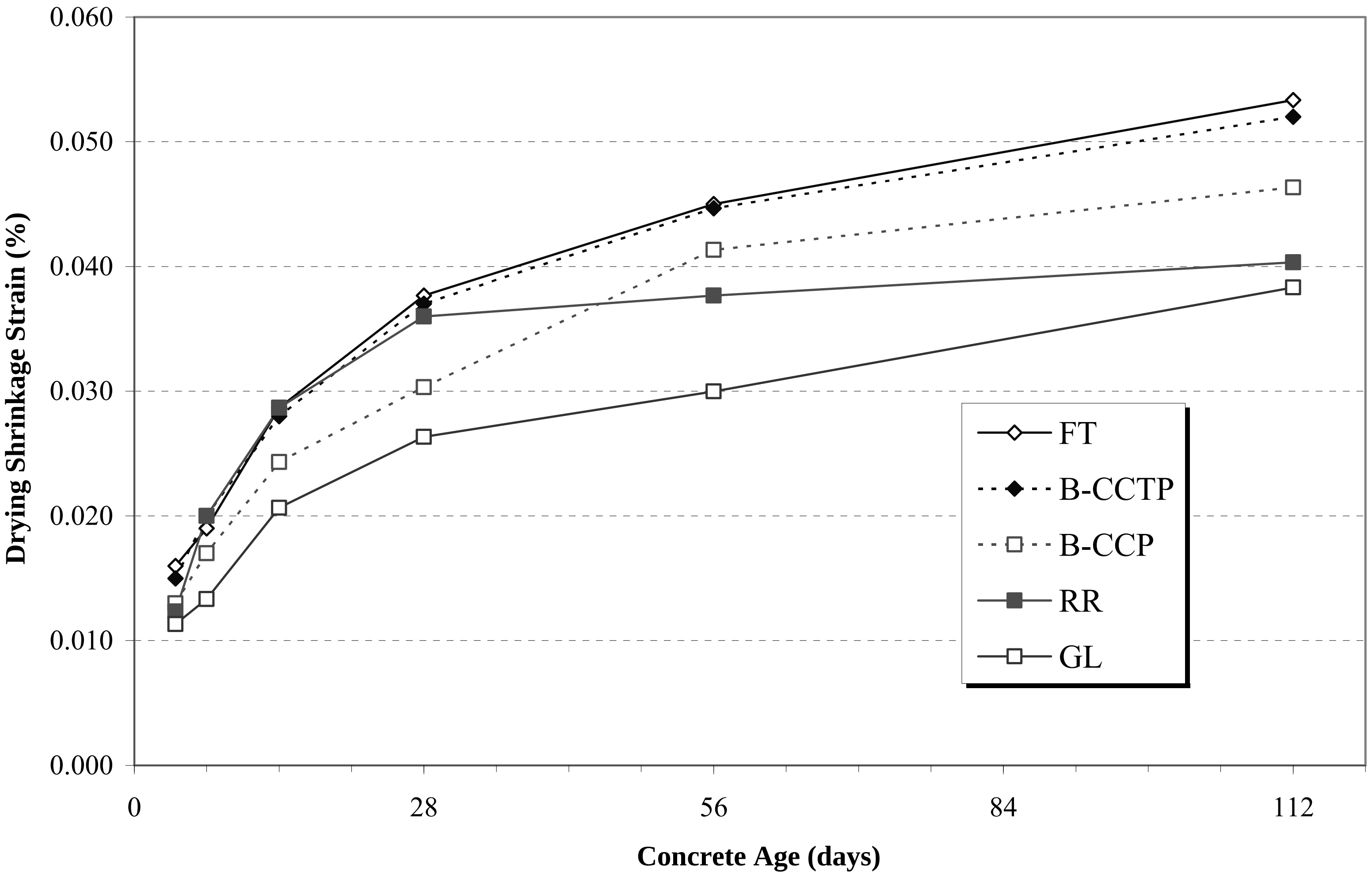


Figure 4.27: AUR – Drying shrinkage development for Mix A concrete for all burns

4.4.8.2 Concrete Mix B

Mix B was a high-strength concrete mixture with a w/c of 0.37. Mix proportions were shown in Table 3.8. All mixing and testing methods were identical to that of Mix A. Refer to Section 3.4.3 for further details of these methods.

All physical properties were determined at Auburn University and results are shown in Table 4.60. Percent differences for each trial burn relative to their baseline burn are also shown, and results are plotted in Figure 4.29. As with Mix A, Mix B was also conducted in two batches. All appropriate fresh properties met the single laboratory requirements set forth by ASTM specifications.

Several trends can be noticed between Mixes A and B from Tables 4.57 and 4.60. For both mixtures, the total air content was higher for all trial burns relative to their baseline. According to Table 4.56, all values are above the single-lab precision limitations, indicating that the total air content for the trial burns is significantly higher than their baseline burns. The same trend was also noticed in the percent air in mortar for the RR and GL burns shown in Table 4.52. As mentioned in Section 2.6.2.4, the effectiveness of an air-entraining admixture may be affected by the alkalinity, carbon content, loss on ignition, or several other chemical properties of the cement. It can be seen from Tables 4.48 and 4.49a that the loss on ignition (LOI) is lower for each of the trial burns relative to their baseline burns, which would lead to an increase in total air content. However, the decrease in LOI is relatively low and is likely not the source for this trend.

During Mix A, the slump was increased for the FT and GL burns. However, the GL slump showed the only increase from Mix B. According to Table 4.56, all values are within the limits of repeatability; hence, all slump values for the trial burns are similar to their baseline.

Unit weight values for all of the trial burns are seen to decrease relative to their respective baseline burns. This is expected since the total air content was increased. As with the total air content, the GL burn showed the only significant decrease in unit weight for both mixtures. The unit weights calculated for the FT and RR burns are close enough to consider them similar.

The setting times for the FT and GL burns were all significantly different from their baseline. During Mix A, the setting times for the FT and GL burns were significantly increased. Note that an increase in setting time means that it took longer to set. The FT cement was seen to have increased levels of K_2O from the fuels and increased Mo and Cr from the raw materials, which would all explain this delayed setting time. However, Mix B shows a decrease in setting times for both the FT and GL burns, indicating that no consistent trend could be established between the two mixtures. Setting times from the RR burn show no significant change in Mix B, but they are seen to decrease for Mix A. However, this trend was not seen from the cement's physical properties shown in Section 4.4.7.

Compressive strength was also tested in accordance with ASTM C 39 (2005). Based on the total air content discussed earlier, compressive strengths for the trial burns are expected to decrease. As discussed in Mix A, it is necessary to correct the compressive strength values to account for the variability in total air content in order to directly compare results between burns. The compressive strengths for each trial burn were normalized to the air content of its corresponding baseline. Air-corrected

Table 4.60: AUR – Physical properties and percent difference relative to baseline for Mix B concrete for all burns

Property	FT		B-CCTP	B-CCP	RR		GL	
	Avg.	% Diff.[1]	Avg.	Avg.	Avg.	% Diff.[2]	Avg.	% Diff.[2]
Total Air Content (%)	6.0	30.4	4.6	3.4	5.3	55.9	5.1	50.0
Slump (mm)	121	-13.6	140	61.0	102	66.7	88.9	45.8
Unit Weight (kg/m^3)	2334	-1.4	2368	2403	2369	-1.4	2360	-1.8
Initial Set (Min.)	254	-8.6	278	261	250	-4.2	231	-11.5
Final Set (Min.)	330	-9.1	363	347	340	-2.0	290	-16.4
Compressive Strength (MPa)								
1 day	22.4	7.1	20.9	21.9	24.0	9.6	22.1	0.8
3 day	32.4	-1.5	32.9	34.0	33.3	-2.0	30.8	-9.5
7 day	37.7	-0.9	38.1	37.1	38.8	4.7	33.5	-9.6
28 day	45.3	3.2	43.9	45.7	46.0	0.6	39.7	-13.1
91 day	51.9	3.5	50.1	50.2	51.5	2.6	44.5	-11.3
Splitting Tensile Strength (MPa)								
1 day	2.7	-4.9	2.8	2.9	2.8	-0.6	2.6	-9.2
3 days	3.6	-2.3	3.7	3.6	3.5	-0.8	3.6	0.7
7 days	3.6	-11.4	4.1	3.8	4.0	2.9	3.7	-3.7
28 days	4.1	-6.2	4.4	4.2	3.9	-6.3	3.7	-11.9
91 days	4.0	-6.5	4.3	4.3	4.1	-4.5	4.0	-7.4
Permeability @ 91 days (Coulombs)	1340	-13.4	1547	2316	1543	-33.4	1707	-26.3

Notes:

[1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

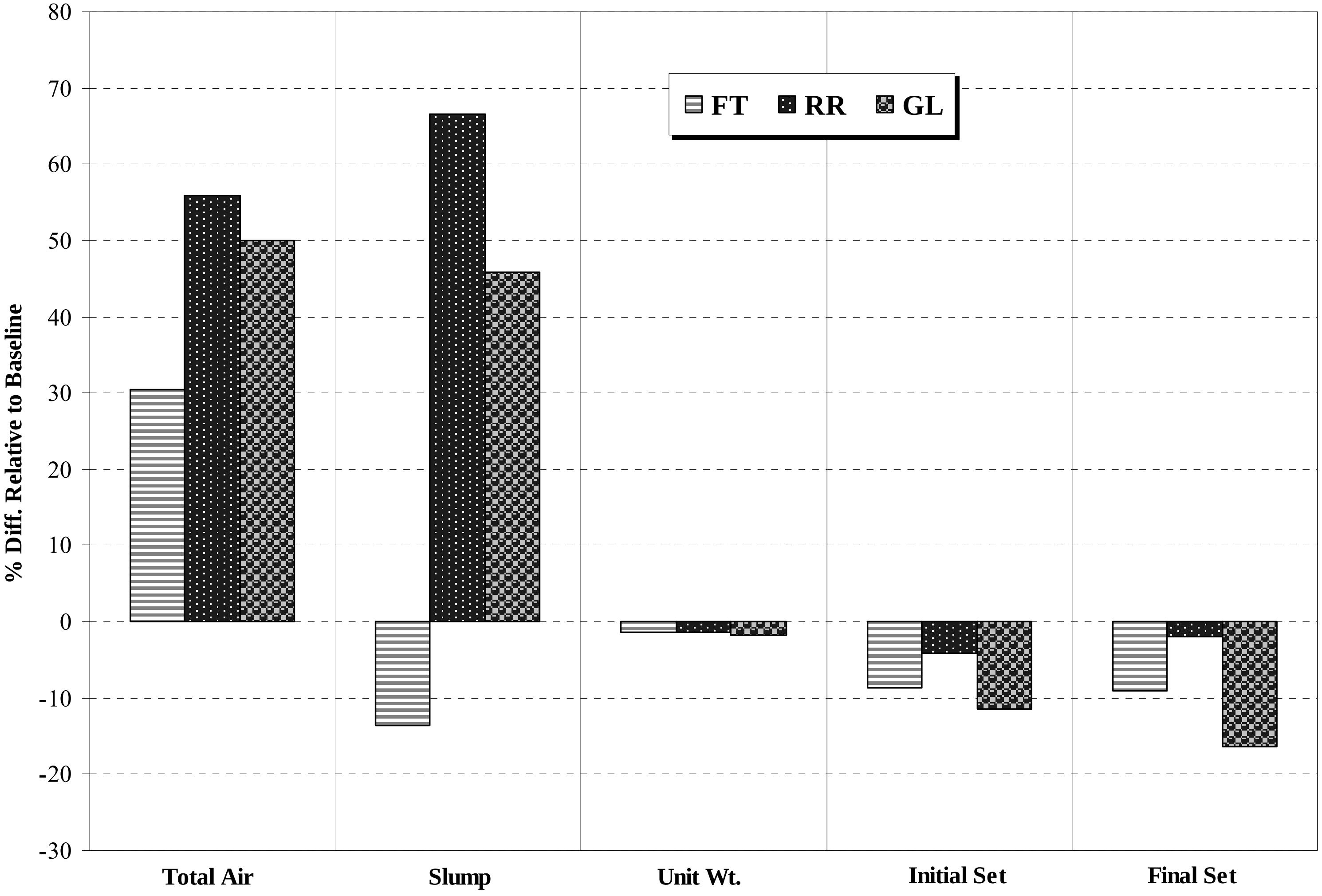


Figure 4.28: AUR – Percent difference in physical properties relative to baseline for Mix B concrete

compressive strengths for the trial burns of Mix B are shown in Table 4.61 along with the percent difference relative to their baseline. These values are also plotted in Figure 4.29. As with Mix A, compressive strengths at 28 days were determined for both batches, and all were within 10%.

Table 4.61: AUR – Air-Corrected compressive strength and percent difference relative to baseline for Mix B concrete

Concrete Age (days)	FT		RR		GL	
	Avg.[3] (MPa)	% Diff.[1]	Avg.[3] (MPa)	% Diff.[2]	Avg.[3] (MPa)	% Diff.[2]
1	23.9	14.6	26.3	20.0	24.0	9.4
3	34.7	5.4	36.5	7.3	33.4	-1.8
7	40.4	6.0	42.5	14.7	36.3	-2.0
28	48.5	10.4	50.4	10.2	43.1	-5.7
91	55.5	10.8	56.4	12.3	48.3	-3.8

Notes: [1] **Relative to B-CCTP**

[2] **Relative to B-CCP**

[3] **Air-Corrected**

From Mix A, the compressive strength of FT is less than B-CCTP at all ages as shown in Table 4.57. Once corrected for air in Table 4.58, only the 1- and 3-day strength are decreased, but this decrease is significant: a 24% reduction in 1-day and 16% reduction in 3-day compressive strengths. Notice the compressive strengths for the mortar cubes shown in Table 4.52 and 4.53. Both results show a slight decrease in early-age strength for the FT cement. However, these values are not corrected for air, but the low percentage of air in mortar would actually exaggerate this trend. The FT compression strength results from Mix B do not show a decrease in early-age strength development. In fact, a significant increase is seen in the air-corrected strength shown in Table 4.61.

However, the majority of test results support the claim that compressive strength development for the FT trial burn is reduced as compared to its baseline.

The compressive strengths for RR during Mix A are lower than B-CCP for all ages. However, when corrected for air, these results are very similar. Once corrected for air, a significant increase in compressive strength was seen in RR during Mix B at all ages. However, no other results support this trend. Therefore, no conclusive evidence indicates a change in the compressive strength development of the RR burn relative to its baseline.

The compressive strengths of GL are significantly lower than B-CCP for all ages, as seen in Mix A. However, when corrected for air in Table 4.58, only the 1-day results are reduced. A significant reduction is also seen in the cube strength as reported by Auburn University in Table 4.53. Though these data were not corrected for air, they support the claim that a reduction in GL compressive strength development is of some significance.

Splitting tensile strength was also tested for Mix B in accordance with ASTM C 496 (2004), and results are plotted in Figure 4.31. Though tensile strength is significantly affected by the air content, it is also dependent on several other properties. Therefore, tensile strengths were not corrected in any way.

FT is seen to exhibit lower tensile strength than its baseline at nearly all ages during both concrete mixtures. Though results from Mix B show little significance, the 1-day tensile strength is more than 22% less than B-CCP, which supports the claim stated earlier that FT exhibits low early-age strength gains as compared to its baseline burn. Recall from Section 2.2.2 that C_2S is typically responsible for early-age strength

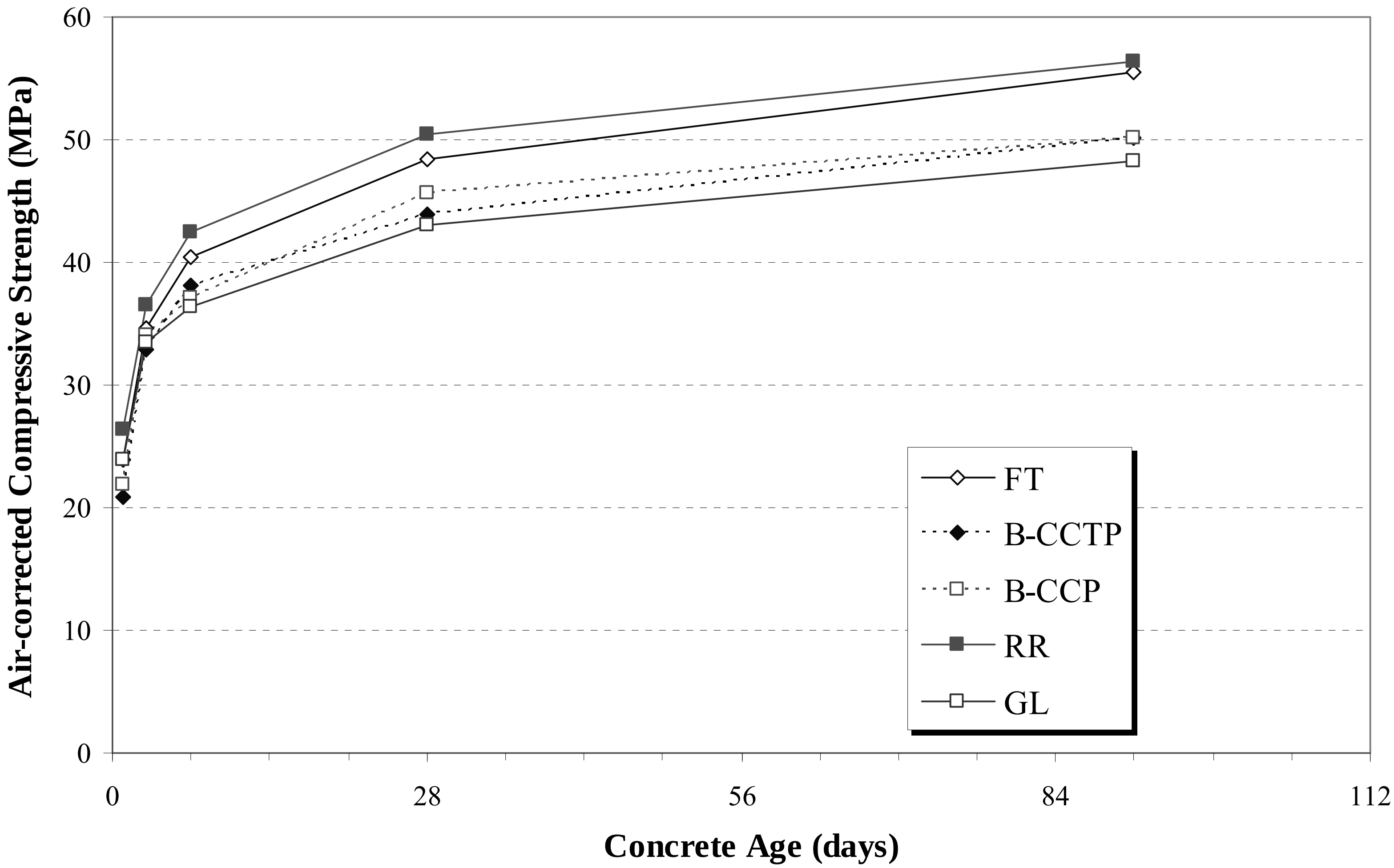


Figure 4.29: AUR – Air-Corrected compressive strength for Mix B concrete for all burns

development. The external and specialty laboratories both reported a decrease in C_2S for the FT cement. This is likely the cause for this trend.

The RR burn shows a reduction in tensile strength development as compared to the B-CCP burn. This was expected due the decreased C_2S values seen in the RR clinker and cement. However, few results show a significant change, and no consistent trends could be established among the testing agencies. Therefore, as seen for compressive strength, the RR burn shows no significant change in strength development relative to the B-CCP burn.

The tensile strength development of the GL concrete was seen to decrease in both mixtures for nearly all ages. Several results have indicated a reduction in strength, especially at early ages. Recall the high MgO content seen in many materials during the GL burn, as discussed throughout this chapter. This has likely contributed to this reduction in strength. Additionally, the high P_2O_5 seen in the GL cement would also explain the reduction in strength. Though certain strength results oppose this trend, particularly the air-corrected compression results in Table 4.61, the majority of results agree that a reduction in GL strength development is of some practical significance. The high P_2O_5 content was a result of the alternative fuel, and therefore, the liquid glycerin is partially responsible for the reduction in strength.

Drying shrinkage development was also tested by Auburn University in accordance with ASTM C157 (2006). Results from Mix B are shown in Table 4.62 and plotted in Figure 4.32. Note that all shrinkage results are reported as positive values. The percent in length change is relative to the original length. All results from Mix A and Mix B are within the limits of repeatability as shown in Table 4.56. This is also consistent with the drying shrinkage development of the mortar prisms discussed in Section 4.4.7. This indicates that drying shrinkage development for all trial burns are similar to their baseline burns.

The 91-day permeability results were the final parameter listed in Table 4.60. Based on ASTM C 1202 (2007), the concrete prepared from the FT and B-CCTP cements are both classified as "*low* chloride ion penetrability", as determined by the results from both mixtures. Both mixtures classify the B-CCP concrete as "*moderate* chloride ion penetrability". RR and GL are both classified as "*low* chloride ion penetrability" according to Mix B, but Mix A denotes RR as having "*moderate* chloride ion penetrability". Permeability results were not determined for the GL burn for Mix A.

All available results from Mixes A and B show a decrease in the permeability for the trial burns relative to their baselines. The largest difference is seen in the RR burn from Mix B, with a decrease of more than 33%. Note from Table 4.56 that two tests results, as performed by a single operator within the same laboratory, should be within 42%. This indicates the extreme variability expected in this test. Therefore, results indicate the change permeability for all trial burns relative to their baseline to be of no practical significance.

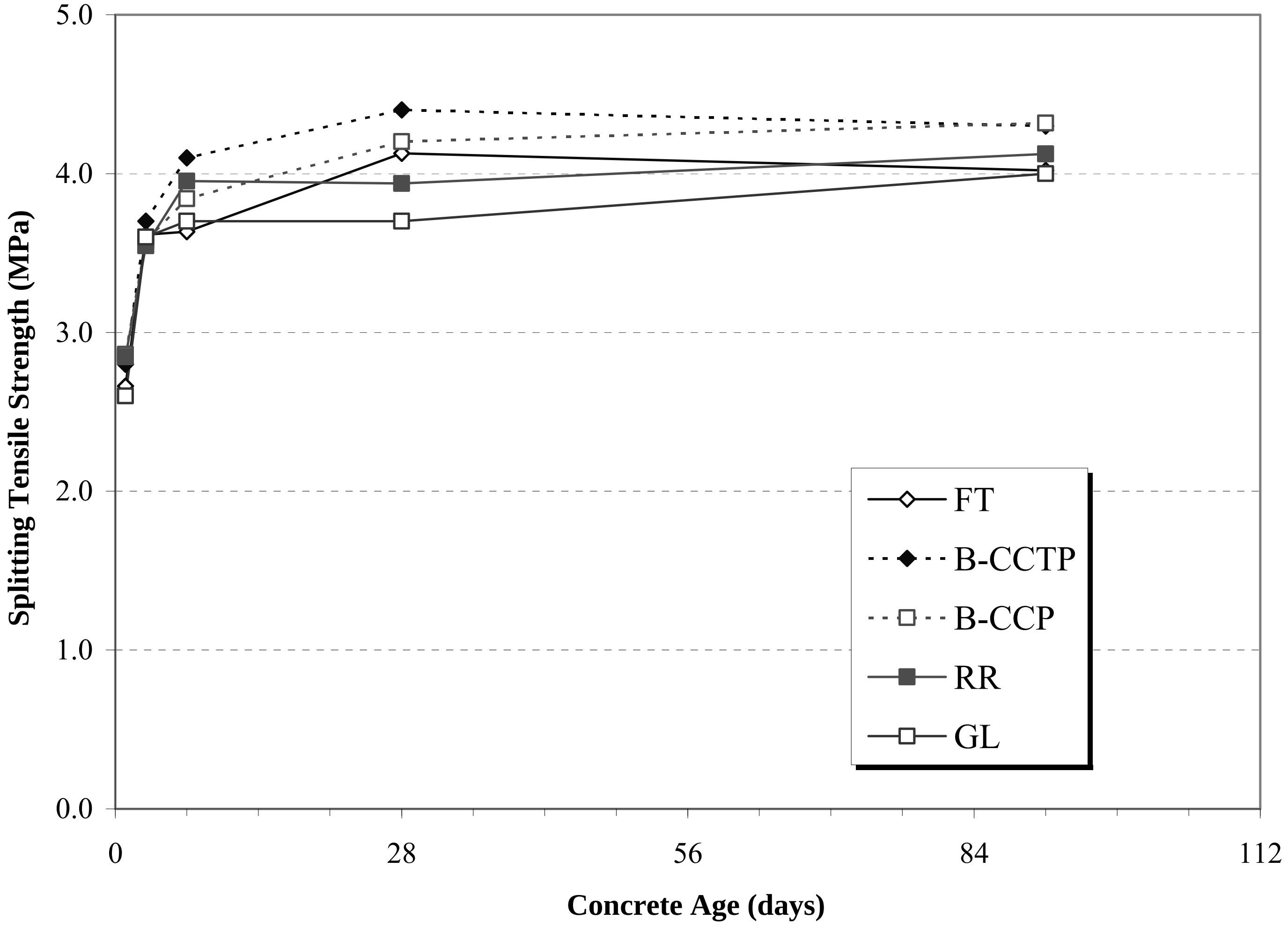


Figure 4.30: AUR – Splitting tensile strength for Mix B concrete for all burns

Table 4.62: AUR – Drying shrinkage development and percent difference relative to baseline for Mix B concrete for all burns

Drying Age (days)	FT		B-CCTP	B-CCP	RR		GL	
	Length Change (%)	% Diff.[1]	Length Change (%)	Length Change (%)	Length Change (%)	% Diff.[2]	Length Change (%)	% Diff.[2]
4	0.011	-23	0.015	0.016	0.014	-15	0.010	-38
7	0.016	12	0.014	0.019	0.015	-17.9	0.016	-16
14	0.024	7	0.023	0.024	0.023	-3	0.021	-11
28	0.032	12	0.028	0.031	0.032	5	0.027	-13
56	0.036	7	0.034	0.037	0.039	4.5	0.031	-17
112	0.042	4	0.041	0.045	0.045	NA	0.038	-16

Notes:

[1] Relative to B-CCTP

[2] Relative to B-CCP

NA - Not Applicable

CIP - Collection in Progress

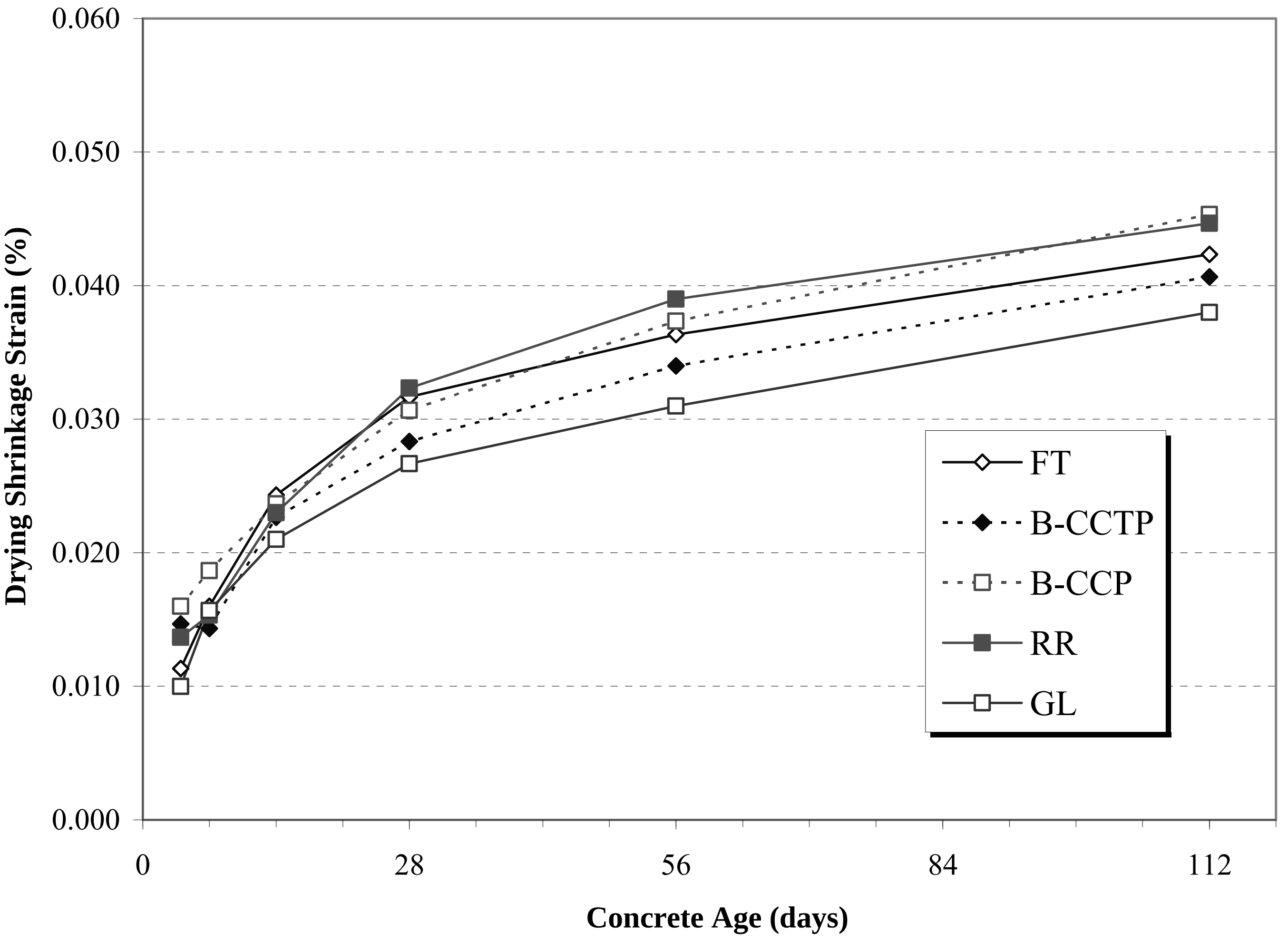


Figure 4.31: AUR – Drying shrinkage development for Mix B concrete for all burns

4.4.9 Plant Emissions

Plant emissions are one of the primary outputs of the manufacturing process. These pollutants are of great concern to the environment, and are closely monitored by the cement plant to ensure they meet the strict limitations set forth by governmental agencies. Emissions are monitored in real time by a Continuous Emissions Monitoring System (CEMS). This certified device measures various pollutants in accordance with Environmental Protection Agency (EPA) requirements. CEMS results were obtained by the cement plant in five-minute intervals.

Emissions were reported in terms of tons per hour released. These results were normalized by Auburn University to account for variation in production rates between the burns. Results are therefore expressed as tons per ton of clinker produced. The summary statistics for these emissions data are shown in Table 4.63. Emission results are also plotted in Figure 4.32.

Emission limits were defined by the Alabama Department of Environmental Management, specified in ADEM (2007). Emission limits were originally expressed in allowable tons per 30-day period, which were converted to allowable tons per ton of clinker produced using production data from each burn. Therefore, each burn had its own limit for the primary emission components, as shown in Table 4.64. Each burn was evaluated individually to verify that all emission limits were satisfied.

Note from Table 4.64 that the RR burn produced the greatest quantity of clinker per hour of operation. Therefore, the ADEM limits calculated for this burn are the lowest of any other burn. Data from Tables 4.63 and 4.64 were used to calculate the percentage of emission levels relative to the ADEM limit for each burn. These results are plotted in

Table 4.63: CPR – Summary statistics of normalized plant emissions for all burns

Emissions		FT	B-CCTP	B-CCP	RR	GL
NO_x (tons/ton clinker)	Average (10^{-4})	11.4	11.8	7.03	7.12	9.59
	Coefficient of Variation (%)	15.4	16.1	26.5	13.6	23.0
	P-Value^2	> 0.250	< 0.005^1	0.083^1	> 0.250	> 0.250
SO_2 (tons/ton clinker)	Average (10^{-6})	25.1	5.07	5.88	12.2	2.50
	Coefficient of Variation (%)	25.1	59.8	44.2	47.8	53.8
	P-Value^2	0.077^1	< 0.005^1	< 0.005^1	0.023^1	0.006^1
VOC (tons/ton clinker)	Average (10^{-6})	26.3	15.5	12.9	17.0	27.5
	Coefficient of Variation (%)	53.7	36.1	20.8	29.0	19.0
	P-Value^2	0.008^1	< 0.005^1	> 0.250	< 0.005^1	> 0.250
CO (tons/ton clinker)	Average (10^{-5})	15.2	25.2	15.3	15.4	43.9
	Coefficient of Variation (%)	18.9	20.7	24.4	14.4	11.1
	P-Value^2	0.179	> 0.250	0.215	> 0.250	0.037^1

Notes: **[1] Not Normally Distributed**
[2] Anderson-Darling Statistics
[3] ADEM (2007)

Figure 4.33. It can be seen that all emission levels are within the ADEM limits specified for each burn. The NO_x emissions from the B-CCTP burn were the closest to the limit, reaching approximately 99% of the ADEM limit. All SO_2 and CO emission values are well within the ADEM limits.

The percent differences in emissions for the trial burns relative to their baseline are shown in Table 4.65. These results are also plotted in Figure 4.34. The Wilcoxin rank-sum test was also conducted to determine if these changes are considered statistically significant, and the results are shown in Table 4.65.

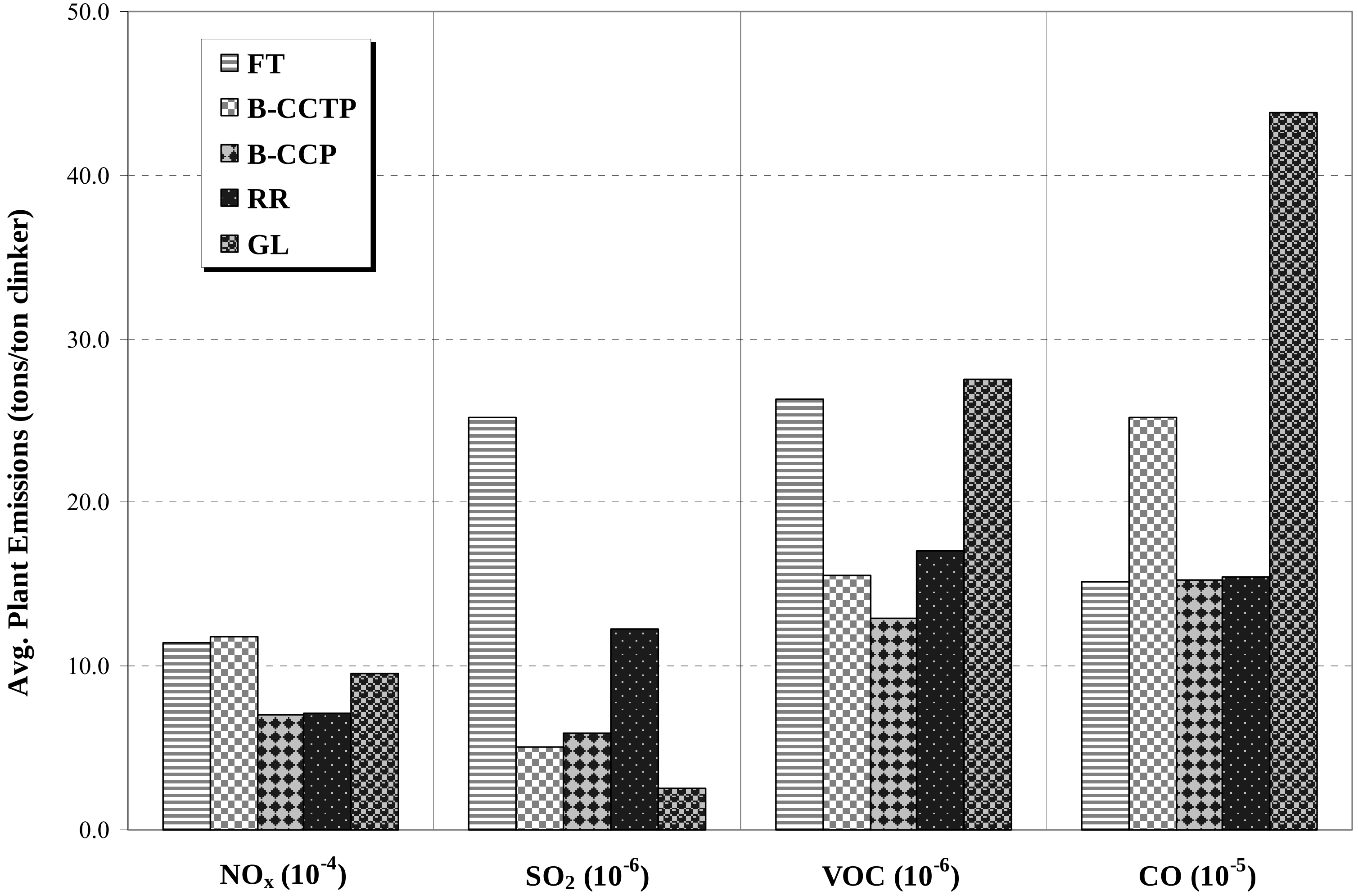


Figure 4.32: CPR – Average of normalized plant emissions for all burns

Table 4.64: ADEM limits for primary emissions during each burn

ADEM (2007) Limits					
Emission		**NOx**	**SO2**	**VOC**	**CO**
Limit (tons/30 days)		221	202	4.80	NA
Limit (tons/hr)		0.307	0.282	0.007	0.002
FT	**tons clinker/hr**	176.8[1]			
	Limit (tons/ton clinker)	1.74E-03	1.59E-03	3.77E-05	2.00E-03
B-CCTP	**tons clinker/hr**	258.0[1]			
	Limit (tons/ton clinker)	1.19E-03	1.09E-03	2.58E-05	2.00E-03
B-CCP	**tons clinker/hr**	336.7[1]			
	Limit (tons/ton clinker)	9.12E-04	8.36E-04	1.98E-05	2.00E-03
RR	**tons clinker/hr**	344.6[1]			
	Limit (tons/ton clinker)	8.91E-04	8.17E-04	1.93E-05	2.00E-03
GL	**tons clinker/hr**	197.8[1]			
	Limit (tons/ton clinker)	1.55E-03	1.42E-03	3.37E-05	2.00E-03
Average Limit (tons/ton clinker)		12.6 (10^{-4})	1150 (10^{-6})	27.3 (10^{-6})	200 (10^{-5})

Notes: **[1] Based on average production data**

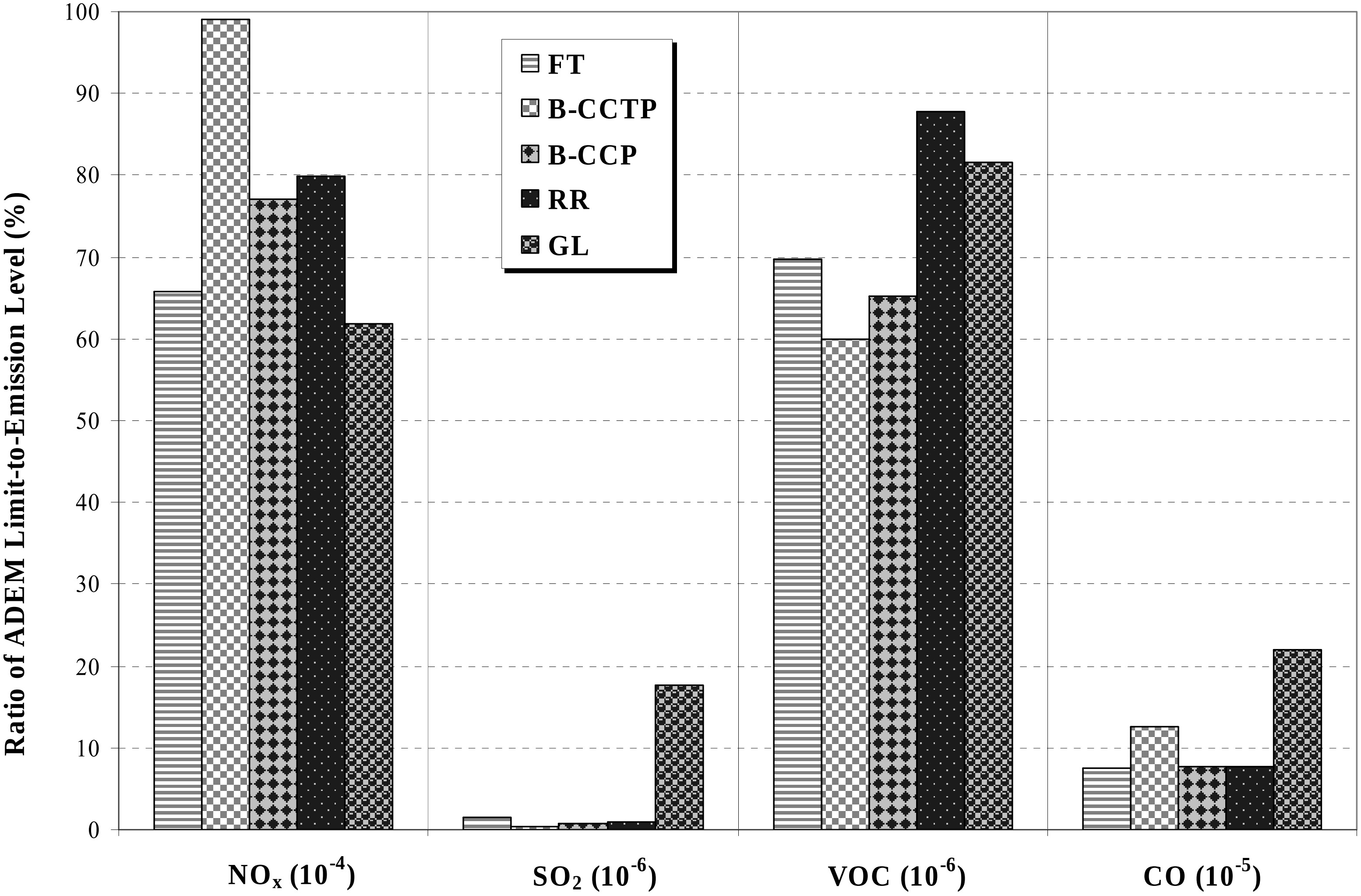


Figure 4.33: ADEM limit-to-Emission level ratio

Note the NO_x emissions from Table 4.63 and Figure 4.32. The baseline burns represent the two extremes, B-CCTP emitting the highest and B-CCP emitting the lowest levels of NO_x. Based on the p-values provided, these are also the only burns whose data are not normally distributed. Though both burns utilizing waste tires emitted more NO_x than those without tires, this is merely coincidence. Tires are seen to contain the lowest percentage of nitrogen compared to all other fuels during the FT burn, as shown in Table 4.31. These are most likely thermal NO_x emissions, which are primarily dependent on kiln temperatures as explained in Section 2.4.2. NO_x emissions from the FT burn are slightly lower than its baseline, and the RR and GL burns were both higher than their baseline. Based on Table 4.65, GL was the only burn with NO_x emissions significantly different from its baseline. However, the glycerin is not thought to be the cause for this. Table 4.38 indicates that the nitrogen content of glycerin is relatively low.

From Tables 4.63 and 4.64, it may be seen that all SO_2 emissions are well below their limits during all burns. Also, based on the C.V. and p-values, SO_2 emissions were highly variable during each burn and none followed a normal distribution. The FT burn emitted the greatest quantity of SO_2 emissions, by far. From Table 4.65, SO_2 emissions were 396% greater during the FT burn as compared to the B-CCTP burn. This may be due to the high sulfur content in many of the fuels utilized during the FT burn. Relative to the other burns, sulfur contents were the highest during the FT burn for all fuels other than coal. Though the FT burn showed the greatest change in SO_2 emissions, all trial burns showed a significant difference relative to their baseline burns. RR emitted 108% more SO_2 emissions, and GL 57% less. However, neither the railway ties nor the glycerin alternative fuels are thought to be the cause of these effects.

The volatile organic compound (VOC) levels from each burn are presented in Table 4.63 and Figure 4.32. VOC levels are seen to vary greatly among all burns, and all but B-CCP and GL are not normally distributed. VOC emissions were the highest during the GL burn, and according to Table 4.65, were 113% higher than the B-CCP burn. Based on the p-values in Table 4.65, VOC emissions were significantly increased for all burns that used alternative fuels. There is no apparent reasoning to explain these effects.

The CO emissions shown in Table 4.63 and Figure 4.32 are all well within the limits for each burn. The C.V. indicates variability in the data, and all follow a normal distribution, except for the GL burn. CO emissions during the RR burn were slightly increased relative to the BCCP burn. According to Figure 4.32, the B-CCTP and GL burns emit the most CO. The CO emissions of the GL burn are 188% higher than its baseline, as indicated in Table 4.65. This is most likely not an effect from the alternative fuel, as glycerin shows the lowest content of carbon compared to the other fuels used during this burn. The CO emissions from the FT burn are 40% lower than B-CCTP. From Table 4.31, the forest trimmings contained the lowest carbon content of any other fuel during this burn. Additionally, the carbon content of the coal was 4.5% lower during the FT burn relative to the baseline burn. Although all remaining fuels contained higher carbon contents during the FT burn, the coal supplied nearly 60% of the energy during this burn, and likely played the greatest role in the reduction of CO levels.

As explained in Section 2.4.1, carbon monoxide is a product of incomplete combustion, due to either insufficient oxygen, or rapid cooling before carbon has completed its oxidation process, which results in the formation of CO rather than CO_2 (Greer et al. 2004; Hendrik and Padovani 2003). This implies that kiln conditions dictate the formation of these emissions, more so than the fuels. However, incomplete combustion of fuels that contain a lower carbon content means that less carbon is available for CO formation. Since the oxygen-to-fuel ratio within the kiln was not collected during the burns, nor was the rate of clinker cooling or CO_2 levels, the specific cause of decreased CO emissions during the FT burn cannot be isolated. Nonetheless, evidence indicates that the use of forest trimmings as an alternative fuel was partly responsible for the reduction in CO emissions.

Table 4.65: CPR – Percent difference and statistical significance of plant emissions

Emissions	**FT**		**RR**		**GL**	
	% Diff.[1]	**P-Value**[4]	**% Diff.**[2]	**P-Value**[4]	**% Diff.**[2]	**P-Value**[4]
NO_x (tons/ton clinker)	-2.96	0.324	1.31	0.890	36.4	< 0.001[3]
SO_2 (tons/ton clinker)	396	< 0.001[3]	108	< 0.001[3]	-57.4	< 0.001[3]
VOC (tons/ton clinker)	69.5	< 0.001[3]	31.5	< 0.001[3]	113	< 0.001[3]
CO (tons/ton clinker)	-39.7	< 0.001[3]	1.15	0.189	188	< 0.001[3]

Notes: [1] **Relative to B-CCTP** [3] **Significantly Different**

[2] **Relative to B-CCP** [4] **Wilcoxin Rank Sum Test**

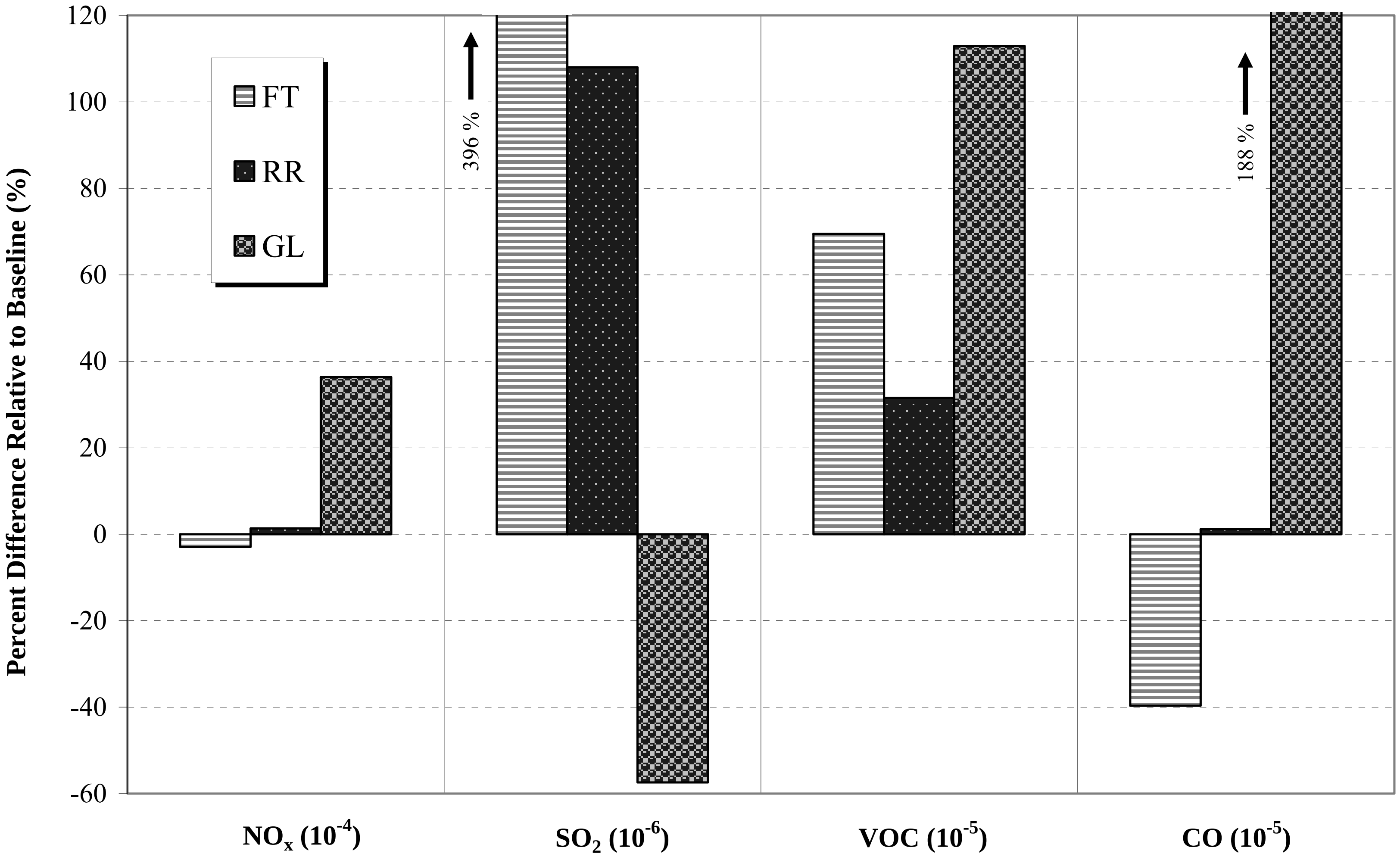


Figure 4.34: CPR – Percent difference in plant emissions relative to baseline

4.5 Concluding Remarks

There are many complex materials, facilities, and processes involved in the production of portland cement, and countless variables may affect both the chemical and physical properties of the final product. Therefore, it is extremely difficult to attribute any changes in cement or concrete properties directly to the utilization of alternative fuels in a facility where many variables are uncontrolled. However, many findings have been gathered regarding the implications of using alternative fuels in the portland cement manufacturing process.

One objective of this study is to evaluate the ability of the cement plant to maintain proper production while consuming forest trimmings, railway crossties, and liquid glycerin. The density of the forest trimmings and railway ties was somewhat of an issue. The amount of material fed through the ASF conveyor system was partially limited by the weight of the ASF. Due to the excessive moisture within these bio-fuels, the ASF density was increased, thus reducing optimum feed rates. It was also difficult to maintain a consistent ASF stream due to the variable chemical composition of plastics, forest trimmings, and railway ties. The liquid glycerin was injected directly into the main burner, so no negative effects were experienced regarding its use.

Another important property of the alternative fuels is their energy content. Relative to the conventional fuels used, the alternative fuels were seen to contain less energy per pound for combustion. The range of as-received energy outputs for each of the fuels utilized during this study were as follows:

1. Coal: 10,730 to 11,500, with an average of 11,170 BTU/lb,
2. Petroleum Coke: 11,683 to 13,756, with an average of 13,120 BTU/lb,
3. Waste Tires: 13,710 to 14,540, with an average of 14,130 BTU/lb,
4. Waste Plastics: 6,850 to 9,530, with an average of 8,720 BTU/lb,
5. Forest Trimmings: 3,491 to 4,959, with an average of 4,140 BTU/lb,
6. Railway Ties: 5,641 to 6,774, with an average of 6,140 BTU/lb, and
7. Liquid Glycerin: 4,307 to 16,684, with an average of 7,730 BTU/lb

Though the liquid glycerin is seen to possess the highest maximum energy content, the average energy for this fuel was only 7,730 BTU/lb. The primary reason for the low energy contents of the forest trimmings and railway ties is their high moisture contents. Also, based on the proximate and ultimate analyses, the combustion properties of the alternative fuels were highly variable. This may also present problems in maintaining consistent production conditions in the kiln.

Although coal and coke provided the majority of the energy used during production, a substantial amount of these nonrenewable fossil fuels were replaced by the combination of waste tires and plastics with the alterative. A considerable amount of waste was diverted from landfills, while incineration needs were reduced, leading to less excess pollutants released into the atmosphere.

The second goal of this study is to determine if the alternative fuels had a direct impact on the chemical properties of the final product. Based on the results reported in Sections 4.4.5 and 4.4.6, several clinker and cement parameters of the three trial burns were significantly different as compared to their corresponding baseline burns. From Section 4.4.2, the kiln feed composition was seen to be fairly consistent, at least more so than the cement and clinker. This would imply that the fuels and the plant's burn conditions in the kiln had some impact on the cement chemistry.

Recall from Section 2.5.4, excessive P_2O_5 levels may inhibit the formation of C_3S. During the GL burn, the concentration P_2O_5 was 25% higher than burn B-CCP (0.059 compared to 0.047 percent by weight), yet all results showed increased C_3S percentages. Although sources disagreed as to what percentage of P_2O_5 is considered excessive, reductions in C_3S were not seen in this study.

Additionally, several of the four primary oxides, Al_2O_3, CaO, Fe_2O_3, and SiO_2 were seen to change significantly during all trial burns. In turn, this led to a significant change in the Bogue compounds of several cements. This would also imply that the fuels and kiln conditions had some impact on the cement chemistry. However, the Bogue compound formations depends on all process input materials, as well kiln temperatures, clinker cooling rate, and several other variables. Additionally, each of the material's properties was seen to vary greatly during each burn. This made it difficult to conclude any changes in the cement's chemistry were a direct result of the addition of one particular fuel. Though the cause for these changes in chemistry is unknown, several performance-related properties were changed as a result.

The third and fourth goals of this study are to evaluate the impact of alternative fuels on the physical properties of cement and concrete. There were several similar physical properties determined for both the cement and concrete. For each test, ASTM provides acceptable levels of precision for the results of both single-operator (single-lab) testing and multiple-operator (multi-lab) testing (refer to Tables 4.51 and 4.56). These limitations indicate the probability of repeatability between test results. These values were compared to the difference in test results between the trial burns and baseline burns to determine a level of practical significance seen. Results within the single-lab limitations were considered similar, thus the change was of no practical significance.

Strength is likely the most important physical property and was determined using several methods. Mortar cubes were prepared and tested in compression for each cement. Additionally, two concrete mixtures were prepared, and sample cylinders were tested, measuring both compressive and tensile strengths. Compressive strengths are highly dependent on the amount of air present within the concrete. Therefore, concrete compressive strength results were corrected for the trial burns to normalize them to the air content of their baseline.

In several strength tests, the FT burn was seen to exhibit strength development similar to its baseline. Final setting times were accelerated, as shown in several results. This may be due to the high alkali equivalency content from the FT cement. Recall from Section 2.5.1 that high levels of Na_2O and K_2O may result from low sulfate content, which, according to Jackson (1998), could result in accelerated setting times. The SO_3 content of the FT cement was in fact low. Insufficient sulfate can also accelerate the formation of C_3A hydration products (Chen and Juenger 2009). This effect was noticed in the admixture study in Section 4.4.7.1.

The physical properties determined from the RR cement and concrete were very similar to that of its baseline. Though the total air content in the concrete was significantly increased, the change in strength development was of little practical significance. Several results indicated that the set times for the paste, mortar, and concrete were similar.

The GL burn had relatively low compressive and tensile strengths at nearly all ages, but particularly during early-age strength development. This trend is seen in several results, and may be attributed to several characteristics. First, the total air content of the GL concrete was consistently high, which is of direct relation to the low strength development. Also, all entities agree that the C_2S content of the GL cement was significantly lower than its baseline. This would explain the reduction in long-term strength. Additionally, the MgO content was noted in several instances to be extremely high. Recall from Section 4.4.6, the high MgO content in RM3, kiln feed, and CKD during the GL burn. As explained in Section 2.5.3, magnesium is known to reduce strength at all ages. Furthermore, the P_2O_5 content of the GL cement was increased relative to the baseline burn. Recall from Section 2.5.4, excess quantities of P_2O_5 may adversely affect hydration parameters and decrease concrete strength. Although the increase in P_2O_5 was not significant, it likely contributed to the delayed setting times and reduced strengths. Low levels of Cr and Zn and the high Pb content of the GL cement also contributed to the delay in initial and final setting times. However, the only change in chemistry of the cement that could be linked to the liquid glycerin fuel was the increase in P_2O_5, which was nearly *fifty* times greater than the amounts found in coal and petroleum coke.

The admixture study was implemented to evaluate additional physical properties of the cement. Flow, setting time, and hydration were monitored to study the effects of chemical admixtures on cement produced with alternative fuels. Based on the results of Section 4.4.7.1, admixtures were seen to have similar effects on all pastes. Therefore, no conclusions were drawn relative to the control mixtures. However, relative to their baseline burn, several trends were thought to be the result of changes in cement chemistry, especially for the FT cement. The FT paste containing the accelerator set 21% later than the B-CCTP paste. This indicated that dosage of accelerator used was not as effective with the FT cement as it was with its baseline cement. However, there was no known cause of this behavior. Compared to the other pastes, the control and accelerated FT pastes had much lower peak heat flows. Tables 4.49a and 4.50, the C_3S content for the FT cement is lower than the other cements, which would indicate a lower early-age hydration development. Also, the C_3S peak in each mixture was greater than the C_3A peak in the same mixture. The difference in FT may be attributed to the principle cement compounds shown in Tables 4.49a and 4.50 and a possible sulfate imbalance. FT cement is seen to possess high C_3A and low C_3S and SO_3 percentages. Mixtures high in C_3A typically require additional SO_3 to regulate cement hydration at early ages (Chen and Juenger 2009). This increase in the C_3A peak could be another result of insufficient gypsum in the cement.

The RR burn was seen have a slightly lower peak heat flow as compared to all B-CCP pastes. This is likely due to the reduced C_3S content as compare to its baseline. Finally, the C_3A peak on the GL accelerator curve appeared to be more drawn out. As mentioned earlier, the C_3A content of the GL cement was higher than that of its baseline. More C_3A would cause this reaction to occur for a longer period of time, as shown in Figure 4.23.

The final objective of this study is to determine whether the utilization of alternative fuels had a direct impact the emissions released during each burn. Although emission levels were highly variable throughout the burns, all remained within the allowable ADEM limits.

In Section 4.4.9, it was first noticed that the highest and lowest NO_x emissions occurred during the two baseline burns, B-CCTP and B-CCP, respectively. Both burns utilizing waste tires were noticed to have the highest NO_x emissions, but it was confirmed that the waste tires were not the cause of this effect. The GL burn showed the only significant increase in NO_x emissions, however, since the glycerin's nitrogen content was relatively low, its use is probably not the cause for the elevated NO_x emissions.

SO_2 emissions were significantly different for all trial burns relative to their baseline. FT and RR had increased SO_2 emissions, while these emissions decreased during the GL burn. The FT burn showed the greatest increase, which was likely caused by the high sulfur content of all fuels used during this burn. However, it is not probable that the forest trimmings, nor any particular alternative fuel, cause the increase in SO_2 emissions.

VOC emissions were significantly increased during all trial burns relative to their baseline. However, a logical explanation for this trend is not apparent. VOC emissions form the GL burn were 113% higher than its baseline burn.

From the CO emissions data, the RR burn was seen to perform similarly to its baseline burn. CO emissions were 40% lower during the FT burn, and 188% higher during the GL burn, and these differences were found to be significant at a 90% confidence interval. The increased CO emissions during the GL burn were not thought to be of any relation to the liquid glycerin, as glycerin has the lowest carbon content of all the fuels used during this burn. The forest trimmings also had the lowest carbon content relative to the other fuels utilized during the FT burn. The coal, which contributed nearly 60% of the energy during the FT burn, and the waste plastics also had lower carbon contents relative to these fuels used during the baseline burn. Therefore, the forest trimmings, coal, and waste plastics were thought to be in some way related to this effect. Unfortunately, the oxygen-to-fuel ratio within the kiln was not monitored during the burns, nor was the rate of clinker cooling or CO_2 emissions, so this finding could not be confirmed. Regardless, evidence indicated that the forest trimmings were partly responsible for the reduction in CO emissions.

Unfortunately, the variable nature of the portland cement production process makes it extremely difficult to directly link the use of alternative fuels to any changes seen. Throughout this chapter, several changes in physical properties and emissions were explained by alterations in chemical properties. Several alterations in chemical properties were explained by a change in the raw materials or fuels utilized. However, the only effect thought to be exclusively attributed to the alternative fuel usage was seen in the GL burn. The glycerin fuel possessed a large quantity of P_2O_5, which likely led to delayed setting times and reduced strength development. Considering the complex nature of cement production and the inherent variability within a full-scale cement manufacturing facility, production was well controlled and consistent overall. Despite the few performance-related effects that proved to be of practical significance, alternative fuels were successfully implemented in the portland cement production process.

Chapter 5

Summary, Conclusions, and Recommendations

5.1 Summary

The production of portland cement involves a variety of raw materials that are chemically fused together in the presence of temperatures approaching 1500 °C. The resulting product, clinker, is ground with sulfates to produce portland cement. An immense quantity of fuel is required to maintain these high temperatures. Traditionally, nonrenewable fossil fuels such as coal, petroleum coke, and natural gas have been used to fuel the operation. Many cement-manufacturing facilities have instigated the use of alternative fuels as a partial replacement of conventional fuel. Previous studies have evaluated several alternative fueling options and their impact throughout the entire portland cement production process, and results indicate many benefits to the industry. However, each alternative fuel introduces new variables into the equation, and each must be evaluated individually to determine its viability as a sufficient fuel replacement option.

Utilizing alternative fuels provides several benefits. As mentioned, the most common fuels used in cement production are nonrenewable fossil fuels. Though still abundant, their supply is slowly being depleted, and costs associated with obtaining these fuels are rising. Alternative fuels commonly consist of waste by-products from other industries. Therefore, a constant supply is easily obtainable from nearly any location. Also, waste production is continuous, providing a sustainable fuel that costs considerably less than conventional fuels. Waste materials are typically disposed of in landfills, and are routinely incinerated to accommodate additional waste. This incineration process usually requires traditional fuels as a source of heat, and the heat generated is not used. Utilizing alternative fuels in cement production decreases the amount of landfill space occupied, and uses the heat generated and ash produced through the combustion process.

Alternative fuels will typically reduce long-term production costs for a facility, but they may present potential concerns that must be addressed. Employing a new fuel source often requires manufacturers to make modifications to their facility in order to shred and feed these materials, which can be extremely costly. Also, new combustion by-products may be introduced into the system, potentially altering the final chemical composition of the cement, the efficiency of the operation, and the plant emissions. This could have adverse effects on concrete performance if not properly monitored. A facility's sales depend on the buyer's confidence in a consistent and high-quality product, so it is pertinent that the alternative fuels do not disrupt the flow or quality of production.

During this study, forest trimmings, railway ties, and liquid glycerin were individually examined as viable alternative fuel options. They were co-fired with conventional fuels, providing a partial replacement. Tire-derived fuels (TDF) and plastic solid wastes (PSW) were also utilized as conventional fuels since they are used during normal operation at the particular plant where this study was conducted.

Forest trimmings are a by-product of the timber industry. Once cut, timber is stripped of bark, limbs, and other unwanted materials, which provide an abundant source of energy. Railway crossties are typically made of creosote-treated hardwood timber. There are currently more than 2.5 billion wooden crossties installed throughout the world, most of which are deteriorating and may need to be replaced. Their use as an alternative fuel source can provide a productive means of disposal. Liquid glycerin was the first *liquid* fuel used during this study. Utilizing glycerin is a sustainable approach, as it is a by-product from biodiesel production. Additional information on each of these fuels was provided in Section 2.3.4, though little literature exists on the use of these fuels affecting portland cement quality.

To properly examine the impact of each alternative fuel, five distinct sampling and testing periods were conducted, referred to as burns. Each burn lasted 3 to 4 days and was conducted at a full-scale cement production facility. Two baseline burns were conducted in which only conventional fuels were used. Three trial burns were conducted, each utilizing one of the aforementioned alternative fuels. Each trial burn also co-fired portions of the conventional fuels used during its corresponding baseline burn. Much effort was made to hold all other aspects of the operation constant to isolate the fueling scenario as the only variable. Results from each trial burn were compared to its corresponding baseline burn to determine the impact of each alternative fuel.

During each burn period, all materials involved in the production process were sampled and tested. Chemical compositions were determined by two testing agencies, and results of the clinker and cement were compared between the trial burn and its baseline burn. Since most of the incombustible materials are incorporated into the clinker, the intentions were to determine if changes in chemical compositions were a direct result of the alternative fuels used. Cement physical properties were then determined by two parties. Two concrete mixtures were also produced by one agency, and several fresh and hardened properties were evaluated. Cement and concrete results were compared between the trial burn and its corresponding baseline burn to determine whether the changes could be attributed to the alternative fuels used. Finally, the NO_x, SO_2, VOC, and CO emissions released during each burn period were monitored by the cement plant. Results were compared to establish a correlation between the alternative fuels and their emission profiles.

5.2 Conclusions

The first objective of this study was to assess the cement plant's ability to maintain productive operations while incorporating alternative fuels into production. The chemical compositions and moisture contents of the forest trimmings and railway ties were extremely variable. This resulted in a fluctuating ASF heating value, making it difficult to establish a consistent stream of materials with constant properties.

Another potential concern regarding the performance of alternative fuel during operation was the energy content of the fuels. The heating values for the alternative fuels were, on average, much less than the traditional fuels used. The as-received heating values for all fuels utilized during this study were as follows:

1. Coal: 10,730 to 11,500, with an average of 11,170 BTU/lb,
2. Petroleum Coke: 11,683 to 13,756, with an average of 13,120 BTU/lb,
3. Waste Tires: 13,710 to 14,540, with an average of 14,130 BTU/lb,
4. Waste Plastics: 6,850 to 9,530, with an average of 8,720 BTU/lb,
5. Forest Trimmings: 3,491 to 4,959, with an average of 4,140 BTU/lb,
6. Railway Ties: 5,641 to 6,774, with an average of 6,140 BTU/lb, and
7. Liquid Glycerin: 4,307 to 16,684, with an average of 7,730 BTU/lb

Despite the low heating value of each alternative fuel, it is necessary to view additional qualities of the fuel to evaluate the feasibility of its use. For instance, if the unit price of a conventional fuel is twice that of an alternative fuel, but so is the unit energy, these two fuels would be of equal cost in terms of energy.

In terms of the energy supplied, the alternative fuels substituted the conventional fuels, on average, by 4%, 8%, and 6%, for the forest trimmings, railway ties, and liquid glycerin, respectively. When combined with the waste tires and plastics, fossil fuel usage was reduced by more than 20%, 25%, and 30% for the FT, RR, and GL burns, respectively.

Despite the minor operational complications mentioned, alternative fuels were used to produce portland cement of considerably high consistency and quality while maintaining targeted production rates. Furthermore, a substantial amount of waste was diverted from landfills, reducing harmful greenhouse gases caused by incineration. Unfortunately, detailed pricing information was not disclosed by the cement plant. Since fuel usage is generally dependent on cost, any knowledge of regarding future use of these fuels remains solely with the cement plant.

The second task of this study was to analyze the chemical compositions of the clinker and cement, and link any changes to the addition of a single alternative fuel. Efforts were made to ensure consistency in production throughout each burn period. However, several changes were made between burn periods such as the source of raw materials and collection of waste plastic materials. Inherent variability was also experienced as expected in a full-scale cement plant due to the numerous materials and complex processes involved. These changes were seen to have a greater impact on the final product than the alternative fuels. Since all materials involved in production were tested, it was possible to determine the likelihood of other materials being the source of these changes in clinker and/or cement chemistry.

Regardless of the cause for these changes in cement chemistry, several important changes from each trial burn are shown in Table 5.1. The arrows indicate whether a parameter was increased or decreased during the trial burn relative to that parameter during the baseline burn. Only the changes that showed a statistical or practical significance are listed. Similar trends that were determined by all available testing agencies may also be listed. Note that statistical significance was only determined for Cement Plant Results (CPR) data. In other words, it was uncertain whether the external and specialty laboratory results were statistically significant. Most trends seen in the clinker were consistent with those of the cement. In the cases where this was not true, results are indicated as such in the table. The resulting effects of these changes on cement and concrete performance will be discussed later in this section.

The important changes in chemistry from the cement produced during the FT trial burn are shown in Table 5.1. The reduced SO_3 content was seen in the cement but not in the clinker, indicating less sulfate was ground with the FT clinker during the grinding. Though not shown in the table, there were also several trends in minor parameters seen in both the cement and clinker from the FT burn. Among all the burns, the FT burn had the lowest As and the highest Mo contents. In addition, Cl and Cr concentrations were considerably higher than the baseline burn. Recall from Section 2.5.2 that excess chlorine may cause corrosion problems in reinforcing steel. Though these effects were not tested, it should be noted that long-term adversities regarding this issue might be encountered.

Several of the parameters listed in Table 5.1 were also tested for the kiln feed. Most kiln feed results showed a consistent trend with the cement results, implying that changes are a result of variability in the raw materials.

Table 5.1: Changes in cement chemistry for trial burns

Parameter	FT Cement Relative to B-CCTP	RR Cement Relative to B-CCP	GL Cement Relative to B-CCP
Al_2O_3	↑	$\uparrow^{1}$	$\uparrow^{1}$
CaO	↓	↓	$\downarrow^{1}$
Fe_2O_3	NSC	$\uparrow^{1}$	$\uparrow^{1}$
K_2O	$\uparrow^{1}$	NSC	$\downarrow^{1}$
MgO	↓	$\uparrow^{1}$	$\uparrow^{1}$
P_2O_5	NSC	NSC	↑
Na_2O_{eq}	$\uparrow^{1}$	↓	↓
SiO_2	$\uparrow^{1, 2}$	$\uparrow^{1, 2}$	$\downarrow^{1}$
SO_3	↓	NSC	$\uparrow^{2}$
LOI	↓	↓	↓
C_3S	$\downarrow^{3}$	$\downarrow^{1}$	↑
C_2S	$\uparrow^{3}$	$\uparrow^{1}$	$\downarrow^{1}$
C_3A	$\uparrow^{3}$	$\uparrow^{1}$	↑
C_4AF	$\uparrow^{2, 3}$	$\uparrow^{1}$	$\uparrow^{1, 3}$
Blaine SSA	$\uparrow^{1}$	NSC	NSC

Notes: [1] Statistically Significant [3] Results not consistent

[2] Not seen in clinker NSC - No Significant Change

Several changes in cement chemistry for the RR burn are also shown in Table 5.1. Note that all of the Bogue compounds showed a significant change relative to B-CCP. The formation of the Bogue compounds is primarily dependent on the four primary oxides. As shown in Table 4.29, the waste plastics are highly variable in the primary oxides, indicating a probable source for the changes in Bogue compounds. Regarding the minor elements determined by the external laboratory, no significant trends could be established.

Many changes in the GL cement relative to its baseline cement are shown in Table 5.1. Note that all four of the primary oxides showed a statistically significant change, and all but CaO were increased. The percentage of MgO increased significantly from the GL burn to the B-CCP burn. This was also seen in the kiln feed, and as discussed in Chapter 4, was primarily due to RM3. C_2S and C_4AF also showed a significant change. According to the specialty laboratory results shown in Table 4.50, C_2S decreased by nearly 40% relative to its baseline burn. Several trends in the minor elements were also noticed in the GL cement and clinker. Cr and Zn contents were the lowest of all burns while Pb was the highest. Effects from these changes will be discussed later in this section.

Notice the increased level of P_2O_5 shown in Table 5.1. Recall from Section 2.5.4, excessive P_2O_5 levels may inhibit the formation of C_3S. During the GL burn, the concentration P_2O_5 was 25% higher than burn B-CCP (0.059 compared to 0.047 percent by weight), yet all results showed increased C_3S percentages. Although sources disagreed as to what percentage of P_2O_5 is considered excessive, reductions in C_3S were not seen in this study. The standard parameters of all fuels from the GL burn were shown in Table

4.40. Compared to the other fuels, the liquid glycerin contains an exorbitant amount of P_2O_5, with a value of 8.58 percent by weight. This is approximately fifteen times the concentration of P_2O_5 in waste plastics, and nearly *fifty* times the amount found in coal and petroleum coke. Therefore, glycerin fuel is the most likely source of the abundant P_2O_5 in the GL cement. However, the increase in P_2O_5 in the GL cement was not statistically significant, and was similar to the other cements. The performance-related effects of P_2O_5 discussed later in this section will indicate the practical significance of this finding.

The third and fourth objectives in this study were to determine the impacts of alternative fuels on both cement and concrete physical properties. Though cement chemistry will collectively determine the performance of cement, it is difficult to relate these effects to one particular chemical parameter. For instance, an increase in one parameter may often be offset by the decrease in another. Regardless, an attempt was made to link the changes in physical properties to a change in the chemical composition of the cement, thus relating the alternative fuels to the performance aspects of cement and concrete. Several significant changes in cement chemistry discussed earlier led to a practical significance in cement and/or concrete performance. However, few could be attributed directly to the addition of a single alternative fuel.

The changes in physical properties for both the cement and concrete from each trial burn are summarized in Tables 5.2 through 5.4. Each arrow indicates either an increase or a decrease as determined from a single test. Therefore, more arrows indicate more consistency among the test results and/or testing agencies. For perspective, the number of tests used to determine each property is also shown. Many results showed slight changes relative to the baseline burn, but only results of practical significance are provided in the tables. This was determined by using the single-laboratory precision requirements from ASTM, as explained in Section 4.4.7. Several results, especially regarding the cement physical properties, were inconsistent. A trend was only reported if the majority of results agreed. Otherwise, no consistent trend was established, and that result is labeled as such.

Effects on concrete properties are based on the results from Mixes A and B as conducted by Auburn University. Effects on cement properties are based on results obtained by Auburn University and the cement plant. Several properties, such as slump and cube flow, were determined for either cement or concrete, but not both. Other properties, such as strength and drying shrinkage, were determined for both materials. Note that trends in strength were determined by evaluating the cube strength of cement mortar, and tensile and air-corrected compressive strengths of concrete.

Table 5.2 shows the notable changes in physical properties from the FT burn. Notice that the early-age strength development was evaluated by six tests, three of which showed a decrease and one showed an increase relative to the baseline results. The two remaining tests showed no significant change and are therefore not shown. A 14.6% increase in the 1-day, air-corrected compressive strength was seen from Mix B and was the only result with this finding. The 28- and 91-day strengths were also seen to increase, as determined by the same test. This behavior in strength development was likely due to the decreased C_3S and increased C_2S, as they govern early-age and long-term strength development, respectively. Several other results indicated an increase in long-term strength development, but none exceeded 10%. However, an overall decrease in strength was expected due to the increased total air content seen in both concrete mixtures.

Table 5.2: Summary of physical properties of cement and concrete from the FT burn

Property	# of Tests	Trend or Effect Relative to B-CCTP	Likely Cause
Air	3	↑↑	Unknown
Slump	2	NCT	Related to air content
Unit Weight	2	NC	
Initial Set (↑ = retarded)	6	NCT	NA
Final Set (↑ = retarded)	6	↓↓↓↓	↑↑ Alkalies, ↓↓ SO_3
Strength	6	↓↓ ↑ Early-age	↓↓ C_3S
	6	↑ Long-term	↑↑ C_2S
Autoclave Exp.	2	NC	NA
Cube Flow	2	NC	NA
Normal Consistency	2	↓	Unknown
Drying Shrinkage	3	NC	NA
Permeability	2	NC	NA
Blaine SSA	1	NC	NA

Notes:
↑ - Increase (per result)
↓ - Decrease (per result)
NA - Not Applicable
NC - No Change
NCT - No Consistent Trend

Final setting times were accelerated in the FT cement and concrete mixtures. This can likely be attributed to the alkali and sulfur trioxide contents of the FT cement as shown in Table 5.1. Recall from Section 2.5.1 that alkalies can be detrimental to the hydration process of cement, thus affecting setting times. However, this depends on the amount of sulfate present. Assuming the increased alkali equivalency was primarily caused by the increased K_2O content, the setting time results found here are consistent with Jackson (1998) and Lawrence's (1998) findings, presented in Section 2.5.1. Although several changes in physical properties of the FT cement/concrete were found to be significant, no change was directly attributed to the addition of forest trimmings.

The changes in physical properties for the RR cement and concrete are summarized in Table 5.3. The total air content of the concrete and setting times were the only properties that showed a significant difference relative to the baseline condition. Several results indicated a decrease in overall strength, but once compressive strengths were normalized in terms of the B-CCP air content, no consistent trend could be established. Several slight changes in physical properties were noticed throughout, but they were all close enough to the baseline condition to consider these results similar.

Table 5.3: Summary of physical properties of cement and concrete from the RR burn

Property	# of Tests	Trend or Effect Relative to B-CCP	Likely Cause
Air	3	↑↑	Unknown
Slump	2	NC	Related to air content
Unit Weight	2	NC	
Initial Set **(↑ = retarded)**	5	↑↑ ↓	↓↓↓ C_3S
Final Set **(↑ = retarded)**	5	↓↓	Unknown
Strength	6	NCT	NA
	6	NCT	NA
Autoclave Exp.	2	NCT	NA
Cube Flow	2	NC	NA
Normal Consistency	2	NC	NA
Drying Shrinkage	3	NC	NA
Permeability	2	NC	NA
Blaine SSA	1	NC	NA

Notes:
↑ - Increase (per result)
↓ - Decrease (per result)
NA - Not Applicable
NC - No Change
NCT - No Consistent Trend

The changes in physical properties for the GL cement and concrete are summarized in Table 5.4. As mentioned previously, the GL cement possessed a high percentage of P_2O_5, which significantly affected both the cement and concrete performance. Initial and final setting times were delayed, and early-age and long-term strengths were reduced as a results of the high P_2O_5 level in the liquid glycerin fuel. Several other parameters contributed to these results as well. As mentioned throughout Chapter 4, many materials involved in the GL burn had a high percentage of MgO. This also contributed to a reduction in strength. However, the high MgO concentration could not be directly attributed to the liquid glycerin.

Table 5.4: Summary of physical properties of cement and concrete from the GL burn

Property	# of Tests	Trend or Effect Relative to B-CCP	Likely Cause
Air	3	↑↑	Unknown
Slump	2	NC	Related to air content
Unit Weight	2	↓↓	
Initial Set **(↑ = retarded)**	5	↑↑↑ ↓	↓ Cr, ↑ Pb, ↑ P_2O_5, ↓ Zn
Final Set **(↑ = retarded)**	5	↑↑ ↓↓	
Strength	6	↓↓↓ ↑ Early-age	↑↑ MgO, ↑ P_2O_5
	6	↓ Long-term	↓↓↓ C_2S, ↑↑ MgO, ↑ P_2O_5
Autoclave Exp.	2	NC	NA
Cube Flow	2	NC	NA
Normal Consistency	2	↓	Unknown
Drying Shrinkage	3	NC	NA
Permeability	1	NC	NA
Blaine SSA	1	NC	NA

Notes: ↑ - Increase (per result) NA - Not Applicable
↓ - Decrease (per result) NC - No Change
NCT - No Consistent Trend

Another set of physical properties determined, but not shown in the tables, was the admixture effects. During this investigation, three cement paste mixtures were prepared for each cement: one containing no admixture (control), one containing an accelerator, and one containing a retarder. The primary goal was to determine if the alternative fuels would alter the effects of the chemical admixtures. As mentioned in Chapter 4, few trends were noticed, and none could be linked to the fueling scenario.

Three tests were conducted on each paste mixture, the first of which was flow. The *Daraset 200* (accelerator) had the greatest affect on the FT paste, which showed a decrease in flow, and the *Daracem 19* (retarder) had the greatest impact on GL, which showed an increase in flow. Overall, the retarder had the greatest impact on flow, increasing the flow of all cements by more than 50%. In comparison to their baseline, each trial cement remained relatively consistent. Again, the greatest difference was seen in the retarding admixture, especially in the RR and GL cement.

The second test conducted on each paste mixture was the determination of final setting time. The retarder showed the greatest effect on the RR paste, increasing the final set by nearly 60% relative to the control paste. The accelerating admixture had the greatest impact on the GL paste, decreasing the final set time by more than 40%. Relative to their baselines, the trial cements performed similarly, with two exceptions. The accelerated FT mixture and the GL control mixture showed an increase in final setting time by more than 20%. All RR mixtures remained within about 6%.

The final property evaluated during the admixture study was the heat of hydration. A hydration curve was generated for each mixture using isothermal calorimetry. The most profound difference was seen in the FT cement. From Figure 4.19, the accelerated and control mixtures were seen to have the lowest peak heat flow as compared to all other burns. Also, the C_3S peak in each mixture was lower than the C_3A peak. This was thought to be primarily due to the low C_3S and high C_3A concentrations in the FT cement. Another likely cause was the high alkali equivalency and low sulfate content of this cement. Recall from Section 2.5.1, if sulfate concentrations are low (relative to the alkalies), excess alkalies may increase hydroxide concentrations during hydration, causing deleterious effects on hydration.

The heat of hydration results for the remaining paste mixtures were seen to perform similarly to their control mixtures. The same was true for the pastes made with alternative fuels relative to their baselines. Few insignificant changes were noticed, but all could be explained by the small differences in principle cement compounds.

The fifth and final objective in this study was to evaluate the primary emission components, and determine their relationship with alternative fuels. A Continuous Emission Monitoring System (CEMS) was used by the cement plant to determine NO_x, SO_2, VOC, and CO quantities emitted during each burn period. As shown in Table 4.63, ADEM limits were calculated based the average amount of clinker produced during all burns. All emissions were within the allowable limit, but much variability was seen throughout.

Figure 5.1 plots the emissions data collected from each burn period. This is identical to Figure 4.34 shown in Chapter 4. Based on the NO_x emissions shown, all burns are very similar to their baseline. The FT and B-CCTP burns released larger quantities of NO_x, but there is no supporting evidence to explain this trend. Though these burns utilized waste tires, this fuel was not seen to attribute to this difference.

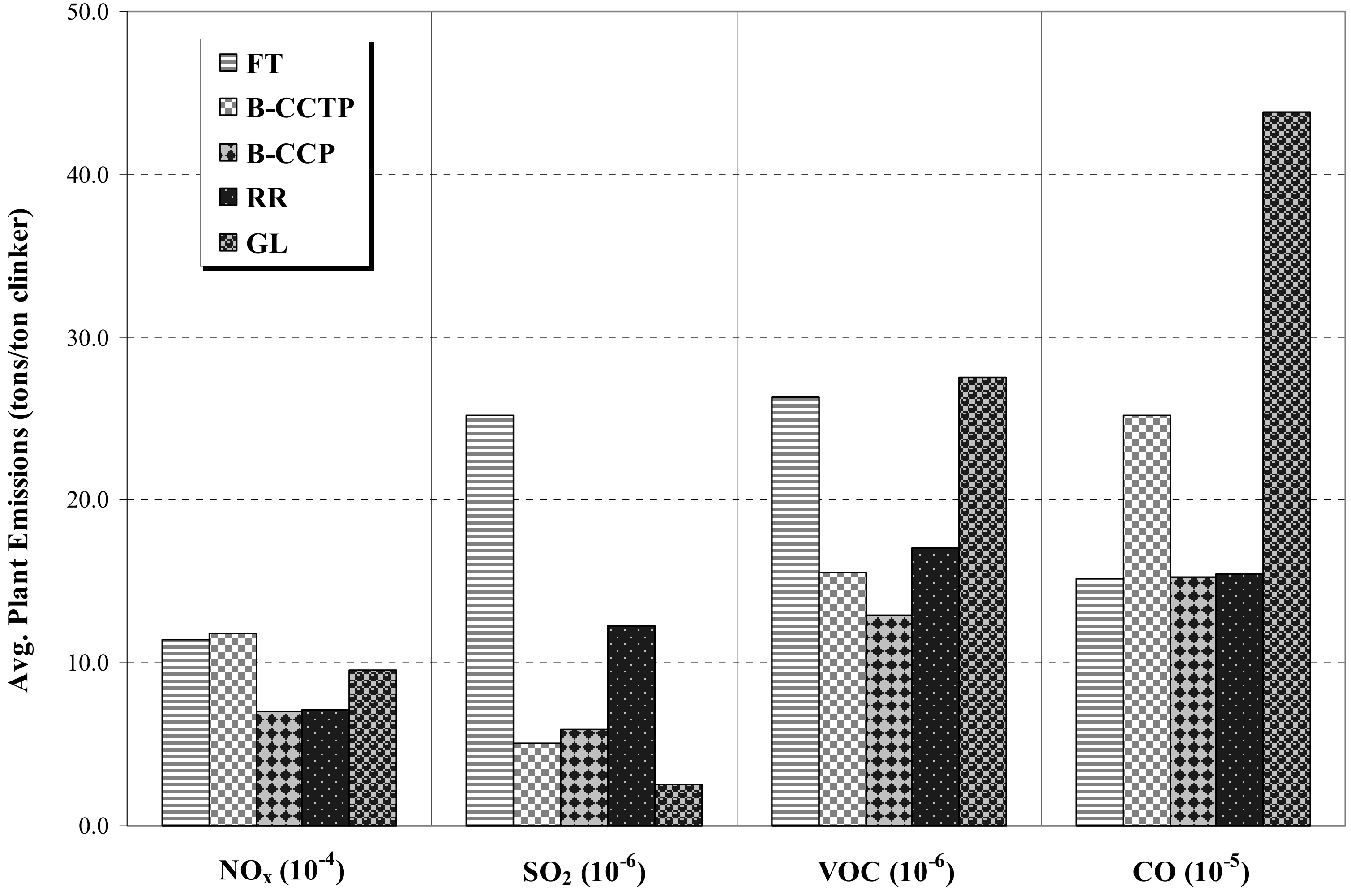


Figure 5.1: CPR – Average of normalized plant emissions for all burns

It can be easily seen that the FT burn emits the largest quantity of SO_2. Relative to B-CCTP all fuels utilized during the FT burn, other than coal, have increased percentages of sulfur. This is likely the reason for the increased emissions. Still, the increase in SO_2 emissions could not be directly attributed to the forest trimmings. RR is also seen to emit large levels of SO_2. However, this is not expected, as most fuels during this burn had lower sulfur quantities as compared to the B-CCP burn.

The VOC emissions shown in Figure 5.1 are seen to be highly variable. All burns containing alternative fuels produced more VOC emissions than their corresponding baseline burn. The GL burn produced the highest VOC emissions, 113% more than the B-CCP burn. The variability of all VOC emissions was not expected considering the consistency in the proximate and ultimate analyses of all fuels.

The GL burn was seen to emit the greatest level of CO and was significantly higher than the B-CCP burn. However, this was not a result of the alternative fuel as glycerin possessed the lowest percentage of carbon as relative to the other fuels used during this burn. CO emissions during the FT burn were significantly less than the baseline, which may have partially been due to the forest trimmings. During this burn, the forest trimmings contained the lowest percentage of carbon relative to the other fuels used, as shown in Table 4.31. However, the carbon content of the coal and waste plastics decreased significantly relative to the baseline, which may have also contributed to the reduced CO emissions. The oxygen-to-fuel ratio within the kiln and the rate of cooling are the primary factors of CO emissions. Unfortunately, these data were not collected during the burns, so their contributions cannot be evaluated.

Overall, the cement plant was able to utilize alternative fuels to produce high-quality, relatively consistent cement with little impact on emission levels and cement performance. Therefore, it is concluded from the study that forest trimmings, railway crossties, and liquid glycerin are all viable alternative fuel options for the production of portland cement pending consideration of local availability, associated costs, and compatibility with the local facility's production operations.

5.3 Recommendations

Although much effort was made to ensure consistency between the burns, more care should be taken in this regard. Throughout the burns, raw material and fuel sources were changed, waste plastic contents varied, and fuel utilization was inconsistent. Consequently, this created several difficulties in determining the impact of alternative fuels, hence evaluating the project objectives. It is understandable that the primary concern of a production facility is to maintain a profitable operation, and this requires adjustments in production to remain competitive within the industry. However, considering the extent of this project and the number of people involved, it is pertinent that all parties are aware of any changes so adjustments to the experimental plan may be made accordingly.

Chemical analysis results show that many of the materials involved are variable in their chemical composition. Furthermore, several results were seen to be inconsistent between two testing agencies. Perhaps collecting additional samples or extending the burn period would remedy this issue. Although this would increase project costs, testing more samples to quantify material properties is recommended. This would also allow for a complete statistical analysis of the data, providing evidence that is more conclusive. This is particularly true in the case of alternative fuel testing. Though ASF sample were tested frequently and tested as discrete specimens, the forest trimmings and railway ties were not. This made it difficult to conclude which fuel was responsible for the changes, the plastics or alternative fuel.

Regarding the physical properties of the cement and concrete, several results were inconsistent between and within testing agencies. Additionally, several trends were noticed with no supporting evidence to explain their cause. For instance, the total air content was seen to increase in both concrete mixtures for all cement produced from alternative fuels. To avert from claiming this trend a mere coincidence, concrete should be remixed for confirmation. However, not enough cement was collected during each burn to repeat any concrete testing. Therefore, it is recommended that more cement be collected in the future to remedy this issue.

Another trend that could not be explained was the increase in VOC emissions during each of the burns using alternative fuels. Considering the high variability within the kiln, several unknown factors could have influenced these emissions levels. It is recommended that VOC emissions, in addition to the other primary emission components, be monitored under controlled conditions. Additionally, it was difficult to analyze the CO emissions without any data regarding the oxygen present in the kiln. Therefore, it is recommended that oxygen levels within the kiln be collected from the cement plant.

Finally, it is recommended that the alternative fuels provide a greater contribution to the total energy consumed during production. The alternative fuels did not contribute more than 8% during any of the trial burns, making it difficult to evaluate their impacts. Obviously, this is easier said than done, considering several limitations govern the amounts and types of fuel needed to establish an ideal kiln environment. However, increasing the amount of alternative fuels consumed would increase the changes relative to the baseline condition, making it easier to determine its effects. Perhaps conducting a trial burn with variable feed rates would provide the same benefits. This is expected to take place in future phases of this project and may possibly be the key to determining an alternative fuel's overall impact on portland cement production and performance.

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Appendix A

Raw Data for the Forest Trimmings Trial Burn (FT)

A.1 General Comments

- Raw data from the FT burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, petroleum coke, waste tires, waste plastics, and forest trimmings were the fuels utilized during this trial burn.
- This burn lasted from 6 PM on 1/13/2009 to 1 PM on 1/17/2009, excluding 3 PM on 1/13/2009 through 6 PM on 1/14/2009.

A.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NA – Not Applicable

ND – Not Detected

NR – Not Reported

^{1} As-Received

^{2} Dry Basis

^{3} Calculated by Auburn University

A.3 Chemical Composition of Kiln Feed

Table A.1: CPR – Chemical composition of kiln feed for FT burn

Parameter (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.14	3.06	3.12	3.22	3.02	3.00
CaO	43.3	43.3	43.4	42.8	43.1	43.2
Fe_2O_3	2.02	2.01	2.03	2.00	2.03	2.00
K_2O	0.370	0.360	0.360	0.400	0.390	0.390
MgO	2.13	2.05	2.08	2.10	2.12	2.07
Na_2O	0.040	0.040	0.040	0.040	0.040	0.040
Na_2O_{eq}	0.280	0.280	0.280	0.310	0.300	0.300
SiO_2	13.2	13.3	13.2	13.4	13.5	13.0
SO_3	0.130	0.120	0.100	0.100	0.130	0.130
Moisture	2.82	3.05	3.58	4.00	3.01	3.01
LOI	36.3	36.2	36.3	35.0	36.2	36.3

A.4 Chemical Composition of Cement Kiln Dust (CKD)

Table A.2: CPR – Chemical composition of CKD for FT burn

Parameter (wt. %)	Sample Number						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Al_2O_3	3.89	4.75	3.90	3.74	4.18	3.87	3.82
CaO	45.5	40.4	45.2	45.8	44.1	45.4	45.1
Fe_2O_3	1.82	2.03	1.82	1.80	1.88	1.79	1.82
K_2O	0.520	1.220	0.490	0.470	0.530	0.550	0.530
MgO	1.54	1.44	1.33	1.42	1.44	1.57	1.68
Na_2O	0.050	0.080	0.040	0.050	0.050	0.050	0.050
SiO_2	11.7	12.5	11.7	11.9	12.3	12.0	11.7
SO_3	0.790	1.22	0.220	0.190	0.140	0.910	0.760

Table A.3: ELR – Chemical composition of CKD for FT burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.74	4.38	3.73	3.53	3.95	3.77
CaO	46.1	44.2	45.1	46.0	44.6	47.1
Fe_2O_3	1.76	1.93	1.76	1.77	1.74	1.79
K_2O	0.379	0.817	0.398	0.427	0.475	0.396
MgO	1.59	1.46	1.41	1.52	1.54	1.71
Na_2O	0.091	0.119	0.063	0.052	0.072	0.087
P_2O_5	0.039	0.046	0.038	0.039	0.052	0.027
SiO_2	11.3	12.2	11.2	11.4	12.0	11.8
SO_3	0.646	1.04	0.253	0.201	0.169	0.947
TiO_2	0.144	0.178	0.145	0.136	0.163	0.148
Moisture	0.092	0.002	0.045	0.022	0.055	0.103
LOI	34.0	33.5	35.8	34.8	35.2	32.2
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	21.0	51.0	17.0	19.0	29.0	31.0
Cd	< 3	5.00	< 3	< 3	< 3	4.00
Cl	122	2038	199	106	85.0	187
Co	16.0	18.0	21.0	15.0	17.0	15.0
Cr	63.0	104	98.0	160	92.0	111
Cu	45.0	61.0	42.0	35.0	29.0	26.0
Hg	0.295	1.00	0.578	0.400	0.311	0.508
Mo	12.0	< 1	7.00	ND	2.00	2.00
Ni	16.0	25.0	21.0	18.0	18.0	21.0
Pb	17.0	52.0	29.0	6.0	16.0	16.0
Se	< 2	6.00	< 2	3.00	< 2	< 2
V	63.0	81.0	67.0	73.0	73.0	60.0
Zn	63.0	77.0	57.0	72.0	58.0	42.0

A.5 Chemical Composition of Fuels

Table A.4a: ELR – Proximate, ultimate, and combustion analysis of ASF for FT burn

Test	Parameter (wt.%)	Sample Number								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Proximate Analysis	**Ash**	13.2	7.53	7.89	15.3	6.33	9.62	6.10	11.3	12.7
	Fixed Carbon	8.12	4.77	14.3	18.8	10.8	5.93	8.85	10.3	6.01
	Moisture[1]	12.8	19.0	50.8	46.5	9.58	5.22	6.23	22.2	22.4
	Volatile Matter	78.7	87.7	77.8	65.9	82.9	84.5	85.1	78.4	81.3
Ultimate Analysis	**Carbon**	49.3	67.9	49.4	42.6	57.5	62.2	59.4	61.7	53.8
	Hydrogen	4.37	7.72	4.55	3.87	5.77	3.29	6.23	7.21	5.73
	Nitrogen	0.220	1.16	0.920	0.740	0.920	1.13	1.03	1.19	0.480
	Oxygen	32.4	15.6	36.8	37.4	29.3	23.6	27.0	18.4	27.1
	Sulfur	0.580	0.130	0.440	0.060	0.130	0.200	0.230	0.250	0.230
Heat Value[2] **(BTU/lb)**		8764	11842	8423	7807	11603	15088	10459	10550	9431

Table A.4b: ELR – Proximate, ultimate, and combustion analysis of ASF for FT burn

Test	Parameter (wt.%)	Sample Number									
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Proximate Analysis	**Ash**	11.2	9.68	9.02	9.32	5.96	5.32	5.45	8.37	8.54	12.3
	Fixed Carbon	9.28	9.10	14.4	16.4	12.0	8.66	8.83	4.23	13.8	15.9
	Moisture [1]	2.55	24.4	46.6	44.2	47.1	32.3	41.7	11.4	35.6	44.7
	Volatile Matter	79.5	81.2	76.6	74.3	82.0	86.0	85.7	87.4	77.7	71.8
Ultimate Analysis	**Carbon**	47.6	53.7	45.8	50.2	46.2	49.9	46.0	50.4	55.8	48.9
	Hydrogen	4.91	5.50	4.26	4.65	4.26	5.37	5.25	5.19	4.62	4.52
	Nitrogen	1.45	1.46	0.730	0.990	0.960	0.830	0.660	1.00	0.930	0.710
	Oxygen	34.6	29.4	40.0	34.8	42.6	38.4	42.5	35.0	30.1	33.5
	Sulfur	0.230	0.220	0.120	0.120	0.120	0.230	0.130	0.060	0.030	0.080
Heat Value [2] **(BTU/lb)**		9318	10126	9063	9614	8041	9847	10647	13005	10293	7974

Table A.5a: ELR – Standard parameters of ASF for FT burn

Test	**Parameter (wt.%)**	**Sample Number**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Standard Parameters	Al_2O_3	25.6	3.50	10.3	15.5	24.8	17.2	16.6	17.0	17.6
	CaO	5.70	26.4	11.1	11.5	33.1	20.6	21.5	23.6	22.6
	Fe_2O_3	0.484	12.5	7.57	3.24	0.805	0.935	0.592	0.571	0.638
	K_2O	0.179	0.723	2.92	2.29	0.322	0.254	0.201	0.230	0.385
	MgO	0.641	2.89	1.61	1.42	1.24	2.37	2.48	2.49	2.39
	Na_2O	32.7	0.271	0.735	0.784	7.69	2.56	5.06	1.59	4.25
	P_2O_5	0.200	0.47	0.684	0.625	0.612	0.224	0.261	0.240	0.233
	SiO_2	23.3	14.7	60.4	62.8	27.6	49.7	51.0	52.0	49.0
	SO_3	9.04	0.779	0.858	0.318	1.74	0.732	0.713	0.281	0.800
	TiO_2	1.60	30.9	2.72	1.18	1.89	2.29	1.50	1.20	1.86
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	As	< 10	< 10	119	< 10	< 10	20.0	< 10	< 10	< 10
	Cd	< 5	< 5	< 5	< 5	6.00	7.00	7.00	7.00	< 5
	Cl	62.0	208	21.0	40.0	82.0	61.0	89.0	211	47.0
	Co	38.0	23.0	21.0	11.0	95.0	18.0	12.0	24.0	18.0
	Cr	61.0	5170	369	62.0	174	110	153	48.0	134
	Cu	745	2470	1850	430	428	21300	775	5290	1430
	Hg	0.046	0.013	0.021	0.030	0.031	0.033	0.037	0.062	0.054
	Mo	51.0	467	49.0	40.0	31.0	14.0	8.00	2.00	18.0
	Ni	< 10	76.0	61.0	16.0	15.0	20.0	13.0	9.00	7.00
	Pb	66.0	13900	1352	38.0	70.0	145	21.0	42.0	75.0
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	119	1804	299	185	203	199	138	127	173
	Zn	2950	23500	3760	534	1475	2890	1020	570	681

Table A.5b: ELR – Standard parameters of ASF for FT burn

Test	**Parameter (wt.%)**	**Sample Number**									
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Standard Parameters	**Al_2O_3**	21.2	15.0	7.15	10.0	7.73	12.9	9.76	11.6	8.10	14.0
	CaO	49.2	24.7	32.2	15.6	25.3	20.9	13.3	15.3	12.0	12.3
	Fe_2O_3	0.586	0.767	3.19	3.47	3.39	1.54	3.51	2.79	3.48	3.59
	K_2O	0.218	0.484	1.99	2.54	1.97	0.859	2.40	1.98	2.22	2.63
	MgO	1.77	2.51	1.67	1.55	1.55	2.22	1.43	1.85	1.59	1.40
	Na_2O	4.44	2.47	1.63	3.10	1.66	3.76	1.65	6.21	1.09	1.16
	P_2O_5	0.195	0.315	0.555	0.702	0.528	0.307	0.593	0.624	0.596	0.759
	SiO_2	19.2	51.0	47.4	56.3	48.8	49.2	50.2	48.2	57.7	55.1
	SO_3	0.942	0.536	0.683	0.970	0.863	0.350	0.777	0.770	0.711	0.592
	TiO_2	1.91	1.32	1.34	1.28	0.884	4.02	2.70	6.21	3.15	2.68
	Parameter (ppm)	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
	As	< 10	11.0	14.0	40.0	16.0	< 10	56.0	< 10	< 10	15.0
	Cd	< 5	< 5	6.00	< 5	< 5	7.00	< 5	7.00	6.00	6.00
	Cl	73.0	82.0	36.0	31.0	27.0	94.0	32.0	103	71.0	56.0
	Co	37.0	20.0	25.0	31.0	18.0	16.0	20.0	43.0	15.0	15.0
	Cr	156	102	69.0	114	43.0	88.0	147	119	143	86.0
	Cu	827	5650	13800	31100	51000	27200	102000	25400	66400	40500
	Hg	0.043	0.046	0.031	0.109	0.125	0.081	0.049	0.027	0.099	0.615
	Mo	6.00	7.00	31.0	16.0	43.0	20.0	37.0	96.0	33.0	22.0
	Ni	2.00	8.00	13.0	26.0	18.0	28.0	40.0	41.0	37.0	26.0
	Pb	76.0	58.0	34.0	392	135	85.0	501	134	390	129
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	132	119	115	125	96.0	329	203	393	282	192
	Zn	500	1142	685	1013	677	1330	1730	4810	1850	1280

Table A.6: ELR – Proximate, ultimate, and combustion analysis of plastics for FT burn

Test	**Parameter (wt.%)**	**Sample Number**	
		1	**2**
Proximate Analysis	**Ash**	12.4	10.0
	Fixed Carbon	6.6	8.5
	Moisture [1]	4.62	8.07
	Volatile Matter	81.0	81.5
Ultimate Analysis	**Carbon**	58.0	49.7
	Hydrogen	5.52	5.27
	Nitrogen	0.740	0.890
	Oxygen	22.7	33.9
	Sulfur	0.570	0.240
Heat Value [2] **(BTU/lb)**		9774	9497

Table A.7: ELR – Standard parameters of plastics for FT burn

Test	Parameter (wt.%)	Sample Number	
		1	2
Standard Parameters	**Al_2O_3**	13.7	40.0
	CaO	41.7	17.1
	Fe_2O_3	0.559	0.669
	K_2O	0.186	0.240
	MgO	1.46	1.41
	Na_2O	17.1	9.64
	P_2O_5	0.112	0.250
	SiO_2	17.9	26.7
	SO_3	4.69	1.64
	TiO_2	2.30	2.25
	Parameter (ppm)	**1**	**2**
	As	< 10	11.0
	Cd	7.00	6.00
	Cl	62.0	120
	Co	20.0	44.0
	Cr	71.0	67.0
	Cu	2116	2548
	Hg	0.042	0.045
	Mo	< 5	44.0
	Ni	27.0	106
	Pb	16.0	123
	Se	< 2	< 2
	V	113	188
	Zn	447	232

Table A.8: ELR – Proximate, ultimate, and combustion analysis of forest trimmings for FT burn

Test	Parameter (wt.%)	Sample Number		
		1	2	3
Proximate Analysis	Ash	13.7	14.8	17.0
	Fixed Carbon	14.0	14.8	14.1
	Moisture [1]	50.0	40.4	50.7
	Volatile Matter	72.3	70.4	68.9
Ultimate Analysis	Carbon	46.0	54.7	45.4
	Hydrogen	4.63	2.92	4.13
	Nitrogen	0.800	1.21	0.850
	Oxygen	34.8	26.4	32.6
	Sulfur	0.080	0.020	0.060
Heat Value [2] (BTU/lb)		8052	8316	7087

Table A.9: ELR – Standard parameters of forest trimmings for FT burn

Test	Parameter (wt.%)	Sample Number		
		1	2	3
Standard Parameters	**Al_2O_3**	9.41	11.1	7.44
	CaO	13.3	12.3	20.7
	Fe_2O_3	5.10	4.10	4.57
	K_2O	3.52	3.40	4.07
	MgO	1.80	1.58	2.00
	Na_2O	0.336	0.359	0.205
	P_2O_5	0.744	0.657	1.37
	SiO_2	61.4	61.7	57.6
	SO_3	0.622	0.626	0.606
	TiO_2	1.03	0.975	0.667
	Parameter (ppm)	**1**	**2**	**3**
	As	16.0	27.0	30.0
	Cd	6.00	< 5	6.00
	Cl	29.0	42.0	24.0
	Co	19.0	15.0	15.0
	Cr	105	104	103
	Cu	12200	16200	2790
	Hg	0.126	0.051	0.028
	Mo	53.0	14.0	14.0
	Ni	41.0	21.0	26.0
	Pb	60.0	64.0	234
	Se	< 2	< 2	< 2
	V	262	105	81.0
	Zn	2530	2950	589

A.6 Chemical Composition of Clinker

Table A.10a: CPR – Chemical composition of clinker for FT burn

Parameter (wt.%)	**Sample Number**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Al_2O_3	5.09	5.44	5.22	5.25	5.14	5.13	5.17	5.45	5.51	5.47	5.39	5.17
CaO	65.0	64.3	64.7	64.6	64.8	64.8	64.6	64.3	64.6	64.4	64.8	65.1
Fe_2O_3	3.37	3.43	3.45	3.42	3.51	3.42	3.37	3.54	3.49	3.46	3.55	3.40
K_2O	0.590	0.710	0.620	0.680	0.520	0.580	0.630	0.640	0.570	0.710	0.560	0.550
MgO	3.26	3.15	3.32	3.23	3.34	3.32	3.30	3.26	3.25	3.21	3.19	3.18
Na_2O	0.090	0.100	0.090	0.100	0.080	0.090	0.080	0.080	0.080	0.090	0.080	0.070
Na_2O_{eq}	0.480	0.570	0.500	0.550	0.420	0.470	0.490	0.500	0.450	0.560	0.450	0.440
SiO_2	21.1	21.3	21.4	21.0	21.2	21.3	21.3	21.4	21.1	20.8	21.0	21.0
SO_3	0.770	1.27	0.680	1.16	0.790	0.970	1.19	1.21	1.30	1.85	1.10	1.02
Free CaO	0.660	0.770	0.730	2.810	0.470	0.440	0.400	0.240	0.220	0.730	0.510	1.13
C_3S	65.0	58.9	60.8	63.5	63.2	62.5	61.8	57.7	60.7	61.9	62.7	65.9
C_2S	11.5	16.5	15.5	12.3	13.1	13.9	14.5	17.7	14.7	13.1	13.0	10.4
C_3A	7.79	8.61	7.99	8.13	7.70	7.80	8.01	8.45	8.69	8.64	8.29	7.94
C_4AF	10.2	10.4	10.5	10.4	10.7	10.4	10.3	10.8	10.6	10.5	10.8	10.4

Table A.10b: CPR – Chemical composition of clinker for FT burn

Parameter (wt.%)	Sample Number											
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Al_2O_3	5.30	5.11	5.17	5.18	5.24	5.03	5.34	5.43	5.28	5.31	5.31	5.32
CaO	64.8	64.8	64.8	64.8	64.7	65.0	64.6	64.1	64.6	64.5	64.5	64.5
Fe_2O_3	3.48	3.41	3.40	3.40	3.41	3.30	3.30	3.40	3.40	3.40	3.33	3.41
K_2O	0.560	0.600	0.620	0.620	0.590	0.620	0.630	0.710	0.550	0.620	0.660	0.630
MgO	3.29	3.20	3.20	3.25	3.18	3.12	3.18	3.26	3.21	3.22	3.15	3.22
Na_2O	0.080	0.080	0.080	0.080	0.080	0.080	0.090	0.090	0.080	0.090	0.090	0.090
Na_2O_{eq}	0.450	0.470	0.490	0.490	0.470	0.490	0.500	0.560	0.440	0.490	0.520	0.500
SiO_2	21.1	21.2	21.0	21.1	21.1	21.3	21.0	21.1	21.4	21.3	21.3	21.3
SO_3	1.35	1.17	1.42	1.43	1.32	1.04	1.83	1.72	1.07	1.13	1.16	0.950
Free CaO	0.550	0.550	1.20	0.660	0.950	0.660	0.550	0.730	0.440	0.370	0.550	0.690
C_3S	62.9	63.5	64.5	64.1	62.8	64.2	62.8	59.0	60.4	60.5	60.3	60.1
C_2S	13.0	12.9	11.6	12.0	13.2	12.6	12.8	16.1	15.6	15.3	15.6	15.8
C_3A	8.18	7.77	7.97	7.99	8.12	7.74	8.57	8.64	8.24	8.32	8.45	8.33
C_4AF	10.6	10.4	10.3	10.4	10.4	10.0	10.0	10.4	10.3	10.4	10.1	10.4

Table A.10c: CPR – Chemical composition of clinker for FT burn

Parameter (wt.%)	Sample Number											
	25	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
Al_2O_3	5.41	5.29	5.05	5.12	5.19	5.12	5.21	5.23	5.09	5.12	5.22	5.30
CaO	64.5	64.3	64.8	64.9	64.9	64.8	64.7	64.6	64.8	64.6	64.5	64.5
Fe_2O_3	3.45	3.33	3.32	3.23	3.37	3.34	3.32	3.34	3.37	3.41	3.41	3.50
K_2O	0.640	0.750	0.670	0.620	0.530	0.580	0.580	0.660	0.600	0.670	0.660	0.640
MgO	3.33	3.34	3.23	3.26	3.27	3.18	3.25	3.23	3.24	3.23	3.28	3.29
Na_2O	0.090	0.080	0.080	0.080	0.080	0.070	0.080	0.080	0.080	0.080	0.080	0.080
Na_2O_{eq}	0.510	0.570	0.520	0.490	0.430	0.450	0.460	0.510	0.480	0.520	0.510	0.500
SiO_2	21.2	20.8	21.2	21.1	21.2	21.3	21.1	21.1	21.2	21.1	21.1	21.0
SO_3	1.18	2.18	0.970	0.910	0.810	0.790	1.28	1.38	1.08	1.20	1.42	1.39
Free CaO	0.620	1.28	1.10	2.41	0.290	0.330	0.510	0.550	0.510	0.880	0.580	2.56
C_3S	59.7	63.4	64.0	64.9	63.0	62.6	63.4	63.2	64.0	63.3	62.1	62.4
C_2S	15.9	11.7	12.5	11.4	13.3	13.9	12.7	12.7	12.5	12.8	13.7	13.1
C_3A	8.50	8.38	7.77	8.10	8.05	7.92	8.19	8.21	7.80	7.80	8.06	8.12
C_4AF	10.5	10.1	10.1	9.83	10.3	10.2	10.1	10.2	10.3	10.4	10.4	10.7

Table A.11: ELR – Chemical composition of clinker for FT burn

Parameter (wt.%)	**Sample Number**			
	1	**2**	**3**	**4**
Al_2O_3	4.98	4.99	4.94	4.93
CaO	63.8	64.1	64.1	63.9
Fe_2O_3	3.41	3.46	3.46	3.34
K_2O	0.592	0.566	0.591	0.618
MgO	3.45	3.48	3.47	3.47
Na_2O	0.109	0.088	0.105	0.088
P_2O_5	0.059	0.059	0.053	0.059
SiO_2	21.5	21.2	21.3	21.3
SO_3	1.42	1.36	1.31	1.49
TiO_2	0.197	0.195	0.200	0.196
Moisture	0.025	0.043	0.021	0.021
LOI	0.199	0.194	0.247	0.306
Parameter (ppm)	**1**	**2**	**3**	**4**
As	23.0	25.0	20.0	18.0
Cd	6.00	6.00	6.00	6.00
Cl	592	327	571	528
Co	13.0	16.0	18.0	17.0
Cr	162	198	121	168
Cu	59.0	127	498	242
Hg	0.098	0.091	0.077	0.058
Mo	10.0	14.0	7.0	15.0
Ni	21.0	22.0	27.0	18.0
Pb	14.0	< 4	26.0	45.0
Se	< 2	< 2	< 2	< 2
V	88.0	98.0	88.0	83.0
Zn	84.0	83.0	98.0	79.0

Table A.12: SLR – Rietveld analysis of clinker for FT burn

Parameter (wt.%)	**Sample Number**			
	1	**2**	**3**	**4**
C_3S	55.3	58.3	57.9	58.8
C_2S	26.0	23.0	23.4	22.1
C_3A	3.65	2.76	2.87	2.82
C_4AF	12.4	12.2	11.9	12.0

A.7 Chemical Composition of Cement

Table A.13a: CPR – Chemical composition of cement for FT burn

Parameter (wt.%)	Sample Number									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Al_2O_3	4.77	4.78	4.79	5.02	4.96	4.91	4.94	4.92	4.86	4.98
CaO	63.0	62.2	62.8	62.3	62.6	62.9	62.9	62.6	62.9	62.7
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	3.22	3.22	3.23	3.29	3.28	3.26	3.25	3.24	3.24	3.27
K_2O	0.560	0.560	0.580	0.580	0.570	0.560	0.570	0.570	0.580	0.570
MgO	3.18	3.13	3.04	3.14	3.13	3.17	3.16	3.11	3.2	3.14
Na_2O	0.090	0.090	0.090	0.080	0.080	0.080	0.080	0.080	0.090	0.080
Na_2O_{eq}	0.460	0.460	0.470	0.460	0.460	0.450	0.460	0.460	0.470	0.460
SiO_2	19.3	19.2	19.1	19.4	19.5	19.6	19.6	19.4	19.5	19.6
SO_3	2.75	2.84	3.36	3.04	2.85	2.92	2.88	3.02	2.84	2.85
Free CaO	0.840	NR	1.28	NR	1.06	NR	0.770	NR	1.10	NR
LOI	1.50	1.63	1.44	1.12	1.17	1.26	1.21	1.24	1.30	1.20
C_3S	65.2	62.3	63.8	58.7	60.3	61.4	60.9	61.1	62.7	59.8
C_2S	6.30	7.99	6.66	11.4	10.5	9.74	10.2	9.55	8.55	11.2
C_3A	7.20	7.23	7.23	7.74	7.60	7.50	7.60	7.56	7.40	7.67
C_4AF	9.80	9.80	9.83	10.0	9.98	9.92	9.89	9.86	9.86	9.95
Blaine SSA (m^2/kg)	404	415	415	404	398	400	402	401	398	392

Table A.13b: CPR – Chemical composition of cement for FT burn

Parameter (wt.%)	**Sample Number**									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Al_2O_3	4.99	5.06	4.94	5.04	5.02	5.02	5.04	4.96	4.88	4.92
CaO	62.1	62.1	62.3	62.0	62.1	63.0	63.0	62.5	62.2	62.5
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	3.23	3.26	3.22	3.25	3.26	3.27	3.24	3.23	3.21	3.24
K_2O	0.590	0.580	0.580	0.590	0.600	0.610	0.610	0.600	0.600	0.600
MgO	3.08	3.13	3.12	3.13	3.14	3.21	3.22	3.18	3.09	3.16
Na_2O	0.090	0.080	0.080	0.080	0.080	0.080	0.070	0.080	0.080	0.070
Na_2O_{eq}	0.480	0.460	0.460	0.470	0.470	0.480	0.470	0.470	0.470	0.460
SiO_2	19.4	19.9	19.7	19.7	19.7	19.9	19.9	19.8	19.5	19.7
SO_3	3.16	3.25	3.16	3.29	3.15	2.28	2.07	2.76	3.18	2.89
Free CaO	1.17	1.13	NR	1.10	NR	0.800	0.910	NR	NR	0.910
LOI	1.15	0.900	1.47	0.800	0.700	1.20	1.16	NR	1.39	1.44
C_3S	58.2	53.9	56.9	54.5	55.8	60.3	60.5	58.5	58.8	58.6
C_2S	11.7	16.3	13.6	15.5	14.5	11.6	11.5	12.6	11.5	12.3
C_3A	7.76	7.90	7.65	7.86	7.79	7.78	7.88	7.69	7.51	7.56
C_4AF	9.83	9.92	9.80	9.89	9.92	9.95	9.86	9.83	9.77	9.86
Blaine SSA (m^2/kg)	390	405	388	378	396	381	387	NR	398	410

Table A.13c: CPR – Chemical composition of cement for FT burn

Parameter (wt.%)	**Sample Number**										
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Al_2O_3	4.88	4.87	4.88	4.89	4.84	4.65	4.83	4.88	4.9	4.81	4.92
CaO	63.3	63.2	63.0	62.9	62.9	62.0	63.1	63.5	63.3	62.5	63.5
CO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe_2O_3	3.25	3.28	3.29	3.26	3.26	3.2	3.22	3.23	3.23	3.23	3.25
K_2O	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.600	0.620	0.610
MgO	3.14	3.14	3.15	3.16	3.11	2.99	3.14	3.19	3.17	3.05	3.19
Na_2O	0.080	0.080	0.070	0.070	0.070	0.080	0.070	0.080	0.080	0.080	0.080
Na_2O_{eq}	0.480	0.480	0.470	0.470	0.470	0.480	0.470	0.480	0.470	0.490	0.480
SiO_2	20.3	20.3	20.3	20.2	20.3	19.5	20.3	20.5	20.4	19.8	20.5
SO_3	2.91	2.87	2.86	2.85	2.9	3.46	2.74	2.59	2.71	3.49	2.61
Free CaO	NR	1.13	NR	2.19	NR	3.96	2.30	1.20	NR	1.06	NR
LOI	NR	1.42	1.71	1.37	1.67	1.69	1.57	1.34	1.25	1.40	1.31
C_3S	57.3	57.3	56.1	56.8	56.7	58.3	57.4	58.2	57.5	57.2	58.0
C_2S	15.1	15.0	16.0	15.2	15.3	12.0	15.0	14.8	15.1	13.6	15.0
C_3A	7.44	7.36	7.37	7.45	7.32	6.91	7.36	7.47	7.53	7.29	7.55
C_4AF	9.89	9.98	10.0	9.92	9.92	9.74	9.80	9.83	9.83	9.83	9.89
Blaine SSA (m^2/kg)	NR	407	417	412	420	424	408	396	397	401	391

Table A.14: ELR – Chemical composition of cement for FT burn

Parameter (wt.%)	**Sample Number**		
	1	**2**	**3**
Al_2O_3	4.97	4.92	5.01
CaO	62.5	62.7	62.5
Fe_2O_3	3.21	3.22	3.11
K_2O	0.501	0.489	0.502
MgO	3.32	3.28	3.32
Na_2O	0.098	0.088	0.098
P_2O_5	0.059	0.049	0.059
SiO_2	20.6	20.6	20.7
SO_3	2.92	2.86	2.85
TiO_2	0.206	0.196	0.216
Moisture	0.202	0.154	0.156
LOI	1.37	1.36	1.39
C_3S	51.2	52.9	50.9
C_2S	20.5	19.1	21.0
C_3A	7.73	7.59	8.01
C_4AF	9.77	9.79	9.46
TOC	0.114	0.103	0.244
Parameter (ppm)	**1**	**2**	**3**
As	15.0	17.0	24.0
Cd	5.00	5.00	4.00
Cl	134	148	199
Co	13.0	17.0	16.0
Cr	163	156	95.0
Cu	119	109	91.0
Hg	0.060	0.059	0.053
Mo	7.00	10.0	8.00
Ni	19.0	23.0	22.0
Pb	24.0	16.0	11.0
Se	< 2	< 2	3.00
V	78.0	90.0	79.0
Zn	87.0	88.0	85.0

Table A.15: SLR – Rietveld analysis of cement for FT burn

Parameter (wt.%)	**Sample Number**		
	1	**2**	**3**
C_3S	50.1	51.0	50.7
C_2S	26.2	24.9	25.4
C_3A	3.40	3.06	2.87
C_4AF	11.58	11.6	11.4

A.8 Plant Emissions

Table A.16a: CPR – Normalized plant emissions for FT burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
1/13/2009 6:00	169.2	1.31E-03	2.61E-05	1.84E-05	1.72E-04
1/13/2009 7:00	165.8	1.23E-03	9.56E-05	3.77E-05	3.66E-04
1/13/2009 8:00	167.1	1.15E-03	4.09E-05	3.28E-05	2.94E-04
1/13/2009 9:00	166.2	1.23E-03	4.02E-05	1.92E-05	2.76E-04
1/13/2009 10:00	163.0	1.30E-03	3.08E-05	1.13E-05	1.31E-04
1/13/2009 11:00	168.4	1.42E-03	2.91E-05	1.01E-05	1.20E-04
1/13/2009 12:00	177.8	1.59E-03	7.35E-05	3.20E-05	4.99E-04
1/13/2009 13:00	175.8	1.44E-03	3.04E-05	1.15E-05	1.81E-04
1/13/2009 14:00	180.3	1.07E-03	3.35E-05	1.19E-05	1.31E-04
1/14/2009 18:00	140.3	1.48E-03	4.08E-05	1.59E-05	9.00E-05
1/14/2009 19:00	174.8	1.18E-03	2.86E-05	3.46E-05	1.33E-04
1/14/2009 20:00	189.3	1.17E-03	2.59E-05	2.66E-05	1.66E-04
1/14/2009 21:00	192.2	1.19E-03	2.55E-05	2.74E-05	1.77E-04
1/14/2009 22:00	197.3	1.24E-03	2.83E-05	2.78E-05	2.08E-04
1/14/2009 23:00	201.6	1.22E-03	2.55E-05	2.30E-05	1.69E-04
1/15/2009 0:00	203.1	1.22E-03	2.96E-05	2.56E-05	1.57E-04
1/15/2009 1:00	208.8	1.19E-03	2.78E-05	2.48E-05	1.56E-04
1/15/2009 2:00	210.5	1.22E-03	2.66E-05	2.35E-05	1.54E-04
1/15/2009 3:00	205.9	1.37E-03	3.60E-05	2.59E-05	1.36E-04
1/15/2009 4:00	198.9	1.40E-03	3.59E-05	4.08E-05	2.86E-04
1/15/2009 5:00	206.3	1.34E-03	2.81E-05	1.85E-05	1.16E-04
1/15/2009 6:00	206.5	1.38E-03	5.01E-05	2.58E-05	2.94E-04
1/15/2009 7:00	205.0	1.22E-03	1.79E-05	1.07E-05	1.17E-04
1/15/2009 8:00	199.4	1.11E-03	1.79E-05	1.46E-05	7.82E-05
1/15/2009 9:00	197.6	1.08E-03	1.66E-05	1.53E-05	1.32E-04
1/15/2009 10:00	194.8	1.19E-03	1.91E-05	1.31E-05	1.48E-04
1/15/2009 11:00	190.9	1.31E-03	1.89E-05	1.66E-05	1.87E-04
1/15/2009 12:00	190.7	1.26E-03	1.99E-05	1.64E-05	1.56E-04
1/15/2009 13:00	190.8	1.05E-03	2.06E-05	2.69E-05	3.02E-04
1/15/2009 14:00	190.5	1.31E-03	2.76E-05	2.29E-05	1.84E-04
1/15/2009 15:00	191.1	9.20E-04	2.36E-05	2.26E-05	2.56E-04
1/15/2009 16:00	190.9	1.20E-03	2.27E-05	2.44E-05	1.59E-04
1/15/2009 17:00	190.7	1.20E-03	2.27E-05	2.59E-05	1.64E-04
1/15/2009 18:00	190.9	1.31E-03	2.12E-05	2.53E-05	1.82E-04
1/15/2009 19:00	190.7	1.19E-03	1.87E-05	2.18E-05	1.70E-04
1/15/2009 20:00	190.6	1.36E-03	2.06E-05	1.88E-05	1.56E-04
1/15/2009 21:00	190.8	1.26E-03	1.76E-05	1.60E-05	1.58E-04
1/15/2009 22:00	190.7	1.23E-03	2.03E-05	1.52E-05	1.74E-04
1/15/2009 23:00	190.7	1.33E-03	2.11E-05	0.00E+00	1.96E-04

Table A.16b: CPR – Normalized plant emissions for FT burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
1/16/2009 0:00	190.0	1.16E-03	1.88E-05	1.07E-05	1.85E-04
1/16/2009 1:00	190.4	1.15E-03	1.61E-05	1.27E-05	1.88E-04
1/16/2009 2:00	190.6	1.08E-03	1.54E-05	1.19E-05	1.79E-04
1/16/2009 3:00	191.1	9.64E-04	1.57E-05	8.57E-06	1.74E-04
1/16/2009 4:00	191.0	1.10E-03	1.70E-05	7.40E-06	1.85E-04
1/16/2009 5:00	190.6	1.07E-03	1.63E-05	4.05E-06	1.72E-04
1/16/2009 6:00	190.7	1.06E-03	1.43E-05	4.24E-06	1.68E-04
1/16/2009 7:00	188.3	1.02E-03	1.42E-05	4.04E-06	1.67E-04
1/16/2009 8:00	186.3	1.09E-03	1.72E-05	1.37E-05	1.66E-04
1/16/2009 9:00	180.1	1.16E-03	2.24E-05	1.81E-05	1.80E-04
1/16/2009 10:00	164.6	1.09E-03	2.43E-05	1.24E-05	1.62E-04
1/16/2009 11:00	153.0	1.14E-03	2.98E-05	2.66E-05	2.07E-04
1/16/2009 12:00	167.6	9.36E-04	2.98E-05	2.96E-05	1.87E-04
1/16/2009 13:00	170.2	9.10E-04	2.93E-05	3.05E-05	1.73E-04
1/16/2009 14:00	171.0	7.94E-04	2.64E-05	3.76E-05	1.63E-04
1/16/2009 15:00	172.2	8.49E-04	2.48E-05	4.21E-05	1.53E-04
1/16/2009 16:00	173.4	1.11E-03	2.26E-05	5.04E-05	1.55E-04
1/16/2009 17:00	167.3	9.99E-04	2.48E-05	5.24E-05	1.49E-04
1/16/2009 18:00	137.8	1.28E-03	2.61E-05	5.77E-05	1.23E-04
1/16/2009 19:00	124.4	1.28E-03	2.93E-05	5.89E-05	1.03E-04
1/16/2009 20:00	125.6	1.00E-03	2.75E-05	5.80E-05	9.60E-05
1/16/2009 21:00	134.0	8.72E-04	2.66E-05	5.14E-05	1.13E-04
1/16/2009 22:00	144.5	7.40E-04	2.43E-05	4.06E-05	1.24E-04
1/16/2009 23:00	149.1	7.49E-04	2.78E-05	3.69E-05	1.31E-04
1/17/2009 0:00	158.9	9.75E-04	2.57E-05	4.38E-05	1.22E-04
1/17/2009 1:00	162.6	9.44E-04	2.57E-05	4.34E-05	1.19E-04
1/17/2009 2:00	160.0	9.53E-04	2.97E-05	4.47E-05	1.41E-04
1/17/2009 3:00	150.5	9.50E-04	2.75E-05	4.31E-05	1.42E-04
1/17/2009 4:00	148.6	1.12E-03	2.60E-05	4.38E-05	1.29E-04
1/17/2009 5:00	140.8	9.35E-04	2.95E-05	4.24E-05	1.32E-04
1/17/2009 6:00	137.4	1.13E-03	2.96E-05	4.41E-05	1.46E-04
1/17/2009 7:00	140.1	9.20E-04	2.83E-05	3.13E-05	1.33E-04
1/17/2009 8:00	139.4	9.25E-04	3.56E-05	1.87E-05	1.16E-04

Appendix B

Raw Data for the B-CCTP Baseline Burn

B.1 General Comments

- Raw data from the B-CCTP burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, petroleum coke, waste tires, and waste plastics, were the fuels utilized during this baseline burn.
- This burn lasted from 8 AM on 3/3/2009 to 7 AM on 3/6/2009.
- This baseline burn serves as a reference for the FT trial burn.

B.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NA – Not Applicable

ND – Not Detected

NR – Not Reported

^{1} As-Received

^{2} Dry Basis

^{3} Calculated by Auburn University

B.3 Chemical Composition of Kiln Feed

Table B.1: CPR – Chemical composition of kiln feed for B-CCTP burn

Parameter (wt. %)	Sample Number						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Al_2O_3	2.94	3.01	2.92	2.96	3.03	3.17	3.11
CaO	43.3	42.8	42.9	43.0	42.9	43.1	43.1
Fe_2O_3	2.03	2.08	2.06	2.08	2.06	2.12	2.07
K_2O	0.340	0.340	0.330	0.330	0.340	0.360	0.350
MgO	2.19	2.08	2.17	2.24	2.23	2.25	2.22
Na_2O	0.040	0.040	0.040	0.050	0.040	0.050	0.050
Na_2O_{eq}	0.260	0.260	0.260	0.270	0.260	0.290	0.280
SiO_2	12.9	13.5	13.4	13.0	13.0	13.0	12.8
SO_3	0.150	0.120	0.120	0.140	0.150	0.200	0.120
Moisture	2.27	2.84	2.77	2.46	2.27	1.85	3.02
LOI	36.4	35.6	35.8	36.2	36.1	36.3	36.3

B.4 Chemical Composition of Cement Kiln Dust (CKD)

Table B.2: CPR – Chemical composition of CKD for B-CCTP burn

Parameter (wt. %)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.81	3.85	3.96	4.03	4.14	3.91
CaO	46.1	45.2	45.2	44.7	44.8	44.5
Fe_2O_3	1.78	1.84	1.81	1.90	1.84	1.92
K_2O	0.480	0.460	0.470	0.470	0.510	0.440
MgO	1.63	1.52	1.44	1.49	1.54	1.40
Na_2O	0.060	0.050	0.060	0.060	0.060	0.050
SiO_2	11.5	11.2	11.2	11.4	11.8	11.5
SO_3	0.920	0.860	0.710	0.530	0.720	0.120

Table B.3: ELR – Chemical composition of CKD for B-CCTP burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.50	3.74	3.88	3.94	3.99	3.77
CaO	44.3	45.9	45.5	46.6	46.7	44.6
Fe_2O_3	1.86	1.82	1.75	1.89	1.80	1.85
K_2O	0.328	0.367	0.416	0.475	0.466	0.401
MgO	1.37	1.55	1.53	1.65	1.67	1.47
Na_2O	0.045	0.098	0.047	0.094	0.088	0.057
P_2O_5	0.032	0.039	0.047	0.053	0.047	0.051
SiO_2	11.7	10.7	10.9	10.7	11.1	10.8
SO_3	0.225	0.748	0.590	1.08	1.15	0.286
TiO_2	0.084	0.085	0.040	0.127	0.101	0.115
Moisture	0.00	0.00	0.00	0.00	0.00	0.00
LOI	36.5	35.0	35.2	33.3	32.9	36.5
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	26.0	26.0	22.0	30.0	33.0	27.0
Cd	< 2	< 2	< 2	< 2	< 2	< 2
Cl	122	2038	199	106	85.0	187
Co	11.0	18.0	17.0	19.0	16.0	20.0
Cr	44.0	47.0	18.0	36.0	100	65.0
Cu	65.0	35.0	74.0	65.0	81.0	53.0
Hg	0.265	0.23	0.200	0.137	1.64	0.425
Mo	< 1	< 1	4.00	9.00	< 1	< 1
Ni	19.0	20.0	23.0	21.0	23.0	21.0
Pb	< 4	15.0	30.0	25.0	< 4	37.0
Se	< 2	< 2	< 2	< 2	< 2	< 2
V	61.0	61.0	60.0	74.0	68.0	65.0
Zn	35.0	60.0	51.0	56.0	60.0	63.0

B.5 Chemical Composition of Fuels

Table B.4: ELR – Proximate, ultimate, and combustion analysis of plastics for B-CCTP burn

Test	**Parameter (wt.%)**	**Sample Number**	
		1	**2**
Proximate Analysis	**Ash**	12.4	10.0
	Fixed Carbon	6.6	8.5
	Moisture[1]	4.62	8.07
	Volatile Matter	81.0	81.5
Ultimate Analysis	**Carbon**	58.0	49.7
	Hydrogen	5.52	5.27
	Nitrogen	0.740	0.890
	Oxygen	22.7	33.9
	Sulfur	0.570	0.240
Heat Value[2] **(BTU/lb)**		9774	9497

Table B.5: ELR – Standard parameters of plastics for B-CCTP burn

Test	**Parameter (wt.%)**	**Sample Number**	
		1	**2**
Standard Parameters	Al_2O_3	13.7	40.0
	CaO	41.7	17.1
	Fe_2O_3	0.559	0.669
	K_2O	0.186	0.240
	MgO	1.46	1.41
	Na_2O	17.1	9.64
	P_2O_5	0.112	0.250
	SiO_2	17.9	26.7
	SO_3	4.69	1.64
	TiO_2	2.30	2.25
	Parameter (ppm)	**1**	**2**
	As	< 10	11.0
	Cd	7.00	6.00
	Cl	62.0	120
	Co	20.0	44.0
	Cr	71.0	67.0
	Cu	2116	2548
	Hg	0.042	0.045
	Mo	< 5	44.0
	Ni	27.0	106
	Pb	16.0	123
	Se	< 2	< 2
	V	113	188
	Zn	447	232

B.6 Chemical Composition of Clinker

Table B.6a: CPR – Chemical composition of clinker for B-CCTP burn

Parameter (wt.%)	**Sample Number**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Al_2O_3	4.91	4.78	4.80	4.82	4.79	4.83	4.91	4.75	4.84	4.78	4.69
CaO	64.9	64.8	65.0	64.5	64.7	64.8	64.4	64.9	64.6	64.7	64.9
Fe_2O_3	3.40	3.42	3.37	3.46	3.56	3.41	3.56	3.42	3.48	3.48	3.52
K_2O	0.580	0.540	0.520	0.510	0.490	0.510	0.550	0.520	0.560	0.580	0.510
MgO	3.12	3.18	3.17	3.23	3.29	3.29	3.32	3.33	3.38	3.39	3.40
Na_2O	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.090	0.080
Na_2O_{eq}	0.470	0.450	0.430	0.420	0.410	0.420	0.450	0.420	0.450	0.470	0.410
SiO_2	21.2	21.5	21.4	21.7	21.6	21.5	21.6	21.5	21.6	21.5	21.7
SO_3	1.17	1.25	1.31	1.34	1.06	1.26	1.31	0.830	1.11	1.18	0.770
Free CaO	3.58	0.900	1.43	0.500	0.850	1.48	2.07	1.83	0.900	1.96	1.17
C_3S	65.3	63.7	65.2	60.7	61.8	63.0	59.7	64.4	61.5	62.5	62.5
C_2S	11.4	13.6	12.1	16.4	15.4	14.1	17.0	13.0	15.5	14.6	15.1
C_3A	7.25	6.88	7.01	6.90	6.69	7.02	6.98	6.78	6.95	6.78	6.47
C_4AF	10.3	10.4	10.3	10.5	10.8	10.4	10.8	10.4	10.6	10.6	10.7

Table B.6b: CPR – Chemical composition of clinker for B-CCTP burn

Parameter (wt.%)	**Sample Number**										
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Al_2O_3	4.66	4.65	4.54	4.68	4.98	4.74	4.78	4.53	4.90	4.77	4.89
CaO	65.1	64.9	65.1	65.0	65.0	65.4	65.1	65.3	65.1	65.2	65.1
Fe_2O_3	3.45	3.43	3.35	3.37	3.39	3.45	3.35	3.08	3.32	3.34	3.51
K_2O	0.470	0.530	0.510	0.560	0.580	0.500	0.560	0.550	0.530	0.540	0.560
MgO	3.40	3.44	3.41	3.36	3.36	3.43	3.39	3.32	3.44	3.42	3.53
Na_2O	0.090	0.090	0.090	0.100	0.090	0.090	0.090	0.100	0.090	0.090	0.100
Na_2O_{eq}	0.400	0.440	0.430	0.460	0.470	0.410	0.460	0.460	0.440	0.450	0.460
SiO_2	21.5	21.4	21.4	21.3	21.1	21.4	21.3	21.3	21.0	21.4	21.4
SO_3	0.98	1.14	1.17	1.25	1.68	0.940	1.36	1.70	1.72	1.02	0.910
Free CaO	0.850	1.70	1.03	2.41	2.15	1.56	0.950	0.660	1.03	0.930	1.33
C_3S	65.2	65.8	66.7	66.7	65.8	66.6	66.7	69.1	67.5	66.2	64.4
C_2S	12.4	11.6	11.2	10.6	10.9	11.1	10.6	8.8	9.40	11.3	12.7
C_3A	6.51	6.51	6.37	6.70	7.46	6.72	6.99	6.79	7.37	7.00	7.01
C_4AF	10.5	10.4	10.2	10.3	10.3	10.5	10.2	9.4	10.1	10.2	10.7

Table B.6c: CPR – Chemical composition of clinker for B-CCTP burn

Parameter (wt.%)	**Sample Number**								
	23	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Al_2O_3	4.84	5.01	4.84	4.95	4.99	4.91	5.13	5.05	5.10
CaO	65.2	65.1	65.2	65.3	65.3	65.0	65.2	65.2	65.3
Fe_2O_3	3.44	3.49	3.42	3.33	3.40	3.24	3.32	3.27	3.38
K_2O	0.510	0.580	0.560	0.530	0.560	0.650	0.560	0.590	0.540
MgO	3.46	3.48	3.48	3.39	3.43	3.38	3.43	3.45	3.48
Na_2O	0.100	0.100	0.100	0.100	0.100	0.110	0.100	0.100	0.090
Na_2O_{eq}	0.440	0.480	0.470	0.450	0.470	0.540	0.470	0.490	0.450
SiO_2	21.4	21.1	21.1	21.2	21.1	21.2	21.0	21.0	21.1
SO_3	0.940	1.27	1.20	1.22	0.970	1.33	1.05	1.18	0.790
Free CaO	0.85	2.70	1.27	0.61	1.33	0.500	1.56	1.46	1.59
C_3S	65.3	66.2	67.5	67.0	67.2	65.8	66.5	66.8	66.4
C_2S	12.2	10.5	9.70	10.2	9.71	11.1	10.1	9.90	10.5
C_3A	7.00	7.36	7.04	7.48	7.48	7.53	7.98	7.85	7.79
C_4AF	10.5	10.6	10.4	10.1	10.4	9.9	10.1	9.9	10.3

Table B.7: ELR – Chemical composition of clinker for B-CCTP burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	4.73	4.61	4.76	5.01	4.91	4.90
CaO	65.5	66.0	65.3	65.6	65.5	65.0
Fe_2O_3	3.30	3.19	3.21	3.35	3.19	3.17
K_2O	0.301	0.470	0.488	0.464	0.508	0.488
MgO	3.45	3.66	3.62	3.67	3.87	4.15
Na_2O	0.062	0.084	0.080	0.060	0.073	0.061
P_2O_5	0.041	0.063	0.060	0.060	0.062	0.061
SiO_2	20.9	20.1	20.7	20.4	20.2	20.6
SO_3	1.25	1.46	1.22	0.92	1.33	1.15
TiO_2	0.073	0.063	0.179	0.181	0.073	0.112
Moisture	0.000	0.000	0.000	0.000	0.000	0.005
LOI	0.233	0.080	0.145	0.077	0.005	0.045
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	31.0	22.0	21.0	22.0	26.0	28.0
Cd	6.00	7.00	5.00	5.00	5.00	4.00
Cl	62.0	208.0	21.0	40.0	82.0	61.0
Co	20.0	20.0	20.0	23.0	13.0	15.0
Cr	47.0	42.0	102	116	77.0	101
Cu	50.0	144	170	69.0	62.0	58.0
Hg	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
Mo	8.00	7.00	< 1	2.00	5.00	< 1
Ni	53.0	43.0	92.0	198	49.0	64.0
Pb	< 4	17.0	15.0	29.0	14.0	< 4
Se	< 2	< 2	< 2	< 2	< 2	< 2
V	78.0	88.0	93.0	102	80.0	100
Zn	66.0	95.0	216	102	71.0	80.0

Table B.8: SLR – Rietveld analysis of clinker for B-CCTP burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
C_3S	55	58	63	62	57	60
C_2S	26	23	18	18	23	21
C_3A	3.41	3.27	3.58	3.71	3.11	3.32
C_4AF	11	11	11	11	11	11

B.7 Chemical Composition of Cement

Table B.9: CPR – Chemical composition of cement for B-CCTP burn

Parameter (wt.%)	Sample Number				
	1	2	3	4	5
Al_2O_3	4.70	4.87	4.90	4.83	5.02
CaO	62.8	63.4	63.2	62.9	62.8
CO	0.980	0.970	1.060	1.240	0.900
Fe_2O_3	3.27	3.29	3.29	3.29	3.38
K_2O	0.470	0.490	0.500	0.510	0.540
MgO	3.16	3.35	3.41	3.6	3.61
Na_2O	0.090	0.100	0.090	0.090	0.100
Na_2O_{eq}	0.400	0.430	0.420	0.420	0.450
SiO_2	19.7	19.6	19.7	19.8	20.1
SO_3	3.18	3.2	3.28	3.07	3.09
Free CaO	1.48	1.7	1.43	1.54	1.43
LOI	1.74	1.5	1.48	1.6	1.45
C_3S	56.3	57.6	55.4	53.7	50.8
C_2S	13.9	12.8	14.6	16.2	19.3
C_3A	7.27	7.34	7.41	7.25	7.59
C_4AF	10.0	10.0	10.0	10.0	10.3
Blaine SSA (m^2/kg)	395	401	397	395	382

Table B.10: ELR – Chemical composition of cement for B-CCTP burn

Parameter (wt.%)	Sample Number		
	1	2	3
Al_2O_3	4.60	4.76	4.57
CaO	63.3	62.8	63.7
Fe_2O_3	3.05	3.12	3.15
K_2O	0.387	0.445	0.480
MgO	3.36	3.35	3.32
Na_2O	0.089	0.069	0.060
P_2O_5	0.060	0.059	0.050
SiO_2	19.4	19.6	19.3
SO_3	3.59	3.26	2.83
TiO_2	0.109	0.128	0.160
Moisture	ND	ND	ND
LOI	1.85	2.18	2.14
C_3S	59.8	55.5	64.2
C_2S	10.4	14.4	6.8
C_3A	7.02	7.34	6.79
C_4AF	9.27	9.50	9.59
TOC	0.040	< 0.01	0.070
Parameter (ppm)	**1**	**2**	**3**
As	29.0	19.0	19.0
Cd	4.00	7.00	6.00
Cl	89.0	211	47.0
Co	13.0	16.0	16.0
Cr	82.0	49.0	112
Cu	115	67.0	99.0
Hg	< 0.01	< 0.01	< 0.01
Mo	5.00	10.0	< 1
Ni	22.0	20.0	20.0
Pb	< 4	< 4	16.0
Se	< 2	< 2	< 2
V	81.0	89.0	71.0
Zn	92.0	85.0	96.0

Table B.11: SLR – Rietveld analysis of cement for B-CCTP burn

Parameter (wt.%)	Sample Number		
	1	2	3
C_3S	55.5	53.9	55.2
C_2S	19.5	20.9	20.0
C_3A	3.46	3.43	3.69
C_4AF	10.8	11.3	11.0

B.8 Plant Emissions

Table B.12a: CPR – Normalized plant emissions for B-CCTP burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
3/3/2009 8:00	260.1	1.00E-03	4.34E-06	8.44E-06	1.35E-04
3/3/2009 9:00	269.4	9.29E-04	7.42E-06	1.33E-05	1.78E-04
3/3/2009 10:00	219.2	1.10E-03	9.17E-06	1.90E-05	2.02E-04
3/3/2009 11:00	232.4	1.08E-03	8.78E-06	1.90E-05	1.89E-04
3/3/2009 12:00	244.7	1.13E-03	7.42E-06	1.95E-05	2.28E-04
3/3/2009 13:00	241.6	9.62E-04	7.96E-06	2.17E-05	2.21E-04
3/3/2009 14:00	252.6	1.00E-03	7.34E-06	2.39E-05	2.00E-04
3/3/2009 15:00	246.6	9.89E-04	8.16E-06	3.12E-05	1.89E-04
3/3/2009 16:00	252.2	9.55E-04	6.83E-06	2.64E-05	1.90E-04
3/3/2009 17:00	237.1	1.23E-03	8.71E-06	2.81E-05	1.94E-04
3/3/2009 18:00	268.0	1.08E-03	6.75E-06	2.33E-05	1.61E-04
3/3/2009 19:00	262.1	1.12E-03	7.28E-06	2.15E-05	1.50E-04
3/3/2009 20:00	266.4	1.04E-03	7.98E-06	2.22E-05	1.97E-04
3/3/2009 21:00	234.4	1.20E-03	8.44E-06	2.55E-05	2.29E-04
3/3/2009 22:00	250.6	1.03E-03	9.51E-06	2.37E-05	2.09E-04
3/3/2009 23:00	261.6	9.89E-04	6.78E-06	2.41E-05	1.85E-04
3/4/2009 0:00	277.2	1.01E-03	7.13E-06	2.16E-05	1.60E-04
3/4/2009 1:00	191.1	1.07E-03	6.85E-06	2.62E-05	2.13E-04
3/4/2009 2:00	248.1	9.46E-04	6.50E-06	1.90E-05	1.80E-04
3/4/2009 3:00	240.0	8.52E-04	5.99E-06	1.99E-05	2.00E-04
3/4/2009 4:00	241.2	1.11E-03	8.18E-06	2.32E-05	2.48E-04
3/4/2009 5:00	246.9	1.10E-03	7.63E-06	2.22E-05	2.82E-04
3/4/2009 6:00	244.9	1.01E-03	8.75E-06	2.04E-05	2.82E-04
3/4/2009 7:00	253.8	9.44E-04	7.78E-06	2.13E-05	2.66E-04
3/4/2009 8:00	258.5	1.05E-03	6.79E-06	9.54E-06	2.78E-04
3/4/2009 9:00	211.4	1.60E-03	4.10E-06	1.37E-05	3.41E-04
3/4/2009 10:00	232.0	1.52E-03	4.90E-06	1.43E-05	3.56E-04
3/4/2009 11:00	249.5	1.30E-03	8.47E-06	1.48E-05	3.59E-04
3/4/2009 12:00	257.7	1.36E-03	8.20E-06	1.41E-05	3.78E-04
3/4/2009 13:00	239.9	1.50E-03	7.50E-06	1.81E-05	4.34E-04
3/4/2009 14:00	262.4	1.32E-03	8.52E-06	1.73E-05	3.47E-04

Table B.12b: CPR – Normalized plant emissions for B-CCTP burn

Date/Time	Clinker Produced (tons/hr)	NO$_x$ (tons/ton clinker)	SO$_2$ (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
3/4/2009 15:00	254.8	9.30E-04	7.74E-06	1.62E-05	3.62E-04
3/4/2009 16:00	261.0	9.03E-04	8.00E-06	1.57E-05	3.04E-04
3/4/2009 17:00	242.4	1.11E-03	6.99E-06	1.73E-05	3.10E-04
3/4/2009 18:00	256.5	1.23E-03	8.13E-06	1.51E-05	2.90E-04
3/4/2009 19:00	264.6	1.09E-03	6.75E-06	1.46E-05	2.67E-04
3/4/2009 20:00	232.0	1.53E-03	7.97E-06	1.54E-05	2.96E-04
3/4/2009 21:00	240.3	1.67E-03	7.50E-06	1.39E-05	2.84E-04
3/4/2009 22:00	283.1	1.47E-03	5.41E-06	1.19E-05	2.71E-04
3/4/2009 23:00	277.3	1.52E-03	5.84E-06	1.22E-05	2.81E-04
3/5/2009 0:00	282.2	1.35E-03	6.66E-06	1.18E-05	2.59E-04
3/5/2009 1:00	269.2	1.18E-03	6.38E-06	1.21E-05	2.46E-04
3/5/2009 2:00	262.9	1.33E-03	6.31E-06	1.24E-05	2.63E-04
3/5/2009 3:00	261.0	1.36E-03	6.04E-06	1.24E-05	2.68E-04
3/5/2009 4:00	271.2	1.22E-03	6.05E-06	1.10E-05	2.52E-04
3/5/2009 5:00	269.5	1.32E-03	4.19E-06	9.17E-06	2.72E-04
3/5/2009 6:00	292.8	1.07E-03	2.21E-06	8.28E-06	2.17E-04
3/5/2009 7:00	282.2	1.06E-03	2.29E-06	8.10E-06	2.48E-04
3/5/2009 8:00	251.0	1.10E-03	4.86E-07	7.45E-06	2.52E-04
3/5/2009 9:00	261.9	1.26E-03	5.42E-07	9.75E-06	2.57E-04
3/5/2009 10:00	272.5	1.18E-03	3.16E-07	8.98E-06	2.82E-04
3/5/2009 11:00	290.7	1.01E-03	1.79E-07	9.23E-06	2.91E-04
3/5/2009 12:00	264.5	1.13E-03	2.00E-07	1.04E-05	3.22E-04
3/5/2009 13:00	267.0	1.21E-03	5.77E-07	9.93E-06	2.91E-04
3/5/2009 14:00	270.5	1.18E-03	4.81E-07	1.15E-05	2.80E-04
3/5/2009 15:00	265.2	1.24E-03	4.41E-07	1.20E-05	2.90E-04
3/5/2009 16:00	283.5	1.10E-03	4.73E-07	1.10E-05	2.60E-04
3/5/2009 17:00	282.8	1.06E-03	9.87E-07	1.29E-05	2.66E-04
3/5/2009 18:00	231.3	1.52E-03	2.87E-06	1.46E-05	3.08E-04
3/5/2009 19:00	249.1	1.34E-03	2.00E-06	1.28E-05	2.70E-04
3/5/2009 20:00	251.7	1.43E-03	2.26E-06	1.20E-05	2.42E-04
3/5/2009 21:00	252.4	1.50E-03	1.42E-06	1.21E-05	2.40E-04
3/5/2009 22:00	269.6	1.12E-03	1.44E-06	1.09E-05	2.19E-04
3/5/2009 23:00	262.2	1.32E-03	1.36E-06	1.11E-05	2.52E-04
3/6/2009 0:00	275.5	1.26E-03	1.74E-06	1.02E-05	2.41E-04
3/6/2009 1:00	262.2	1.12E-03	2.24E-06	1.03E-05	2.39E-04
3/6/2009 2:00	278.4	1.08E-03	1.84E-06	1.20E-05	2.26E-04
3/6/2009 3:00	282.1	1.03E-03	1.48E-06	1.20E-05	2.26E-04
3/6/2009 4:00	273.2	1.08E-03	1.87E-06	1.27E-05	2.34E-04
3/6/2009 5:00	288.1	1.01E-03	1.57E-06	1.23E-05	2.35E-04
3/6/2009 6:00	268.0	1.21E-03	2.00E-06	1.37E-05	2.55E-04
3/6/2009 7:00	267.1	1.47E-03	1.74E-06	1.30E-05	2.94E-04

Appendix C

Raw Data for the B-CCP baseline Burn

C.1 General Comments

- Raw data from the B-CCP baseline burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, petroleum coke, and waste plastics were the fuels utilized during this baseline burn.
- This burn lasted from 9 AM on 7/2/2009 to 9 AM on 7/5/2009.
- This baseline burn serves as a reference for the FT trial burn.

C.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NA – Not Applicable

ND – Not Detected

NR – Not Reported

^{1} As-Received

^{2} Dry Basis

^{3} Calculated by Auburn University

C.3 Chemical Composition of Kiln Feed

Table C.1: CPR – Chemical composition of kiln feed for B-CCP burn

Parameter (wt. %)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.06	3.15	3.17	3.18	3.13	3.00
CaO	43.3	43.4	43.4	43.2	43.2	42.9
Fe_2O_3	2.14	2.15	2.12	2.17	2.16	2.12
K_2O	0.360	0.360	0.360	0.370	0.360	0.350
MgO	1.86	1.83	1.83	1.86	1.86	1.89
Na_2O	0.060	0.070	0.060	0.060	0.060	0.060
Na_2O_{eq}	0.297	0.307	NR	0.303	0.297	0.290
SiO_2	13.3	13.4	13.4	13.6	13.5	13.6
SO_3	0.150	0.170	0.110	0.170	0.170	0.160
Moisture	2.56	2.33	NR	2.31	2.26	2.34
LOI	NR	NR	NR	NR	NR	NR

C.4 Chemical Composition of Cement Kiln Dust (CKD)

Table C.2: CPR – Chemical composition of CKD for B-CCP burn

Parameter (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.99	3.61	4.14	3.63	3.70	3.95
CaO	44.0	49.3	44.6	45.5	45.7	44.5
Fe_2O_3	1.92	1.49	1.90	1.83	1.80	1.87
K_2O	0.450	0.460	0.450	0.440	0.430	0.440
MgO	1.25	1.69	1.27	1.40	1.39	1.33
Na_2O	0.070	0.080	0.070	0.070	0.080	0.060
SiO_2	12.2	11.1	12.2	11.6	11.6	12.1
SO_3	0.100	0.990	0.170	0.420	0.340	0.210

Table C.3: ELR – Chemical composition of CKD for B-CCP burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.82	3.65	3.70	3.51	3.66	3.44
CaO	48.1	52.4	48.6	51.6	55.7	50.7
Fe_2O_3	1.86	1.76	1.91	1.81	1.85	1.62
K_2O	0.384	0.384	0.380	0.356	0.388	0.222
MgO	1.51	1.85	1.56	1.81	2.05	1.79
Na_2O	0.075	0.064	0.061	0.071	0.067	0.069
P_2O_5	0.045	0.040	0.046	0.040	0.034	0.042
SiO_2	11.1	10.4	11.1	10.2	10.3	9.77
SO_3	0.324	0.816	0.357	0.672	1.04	0.950
TiO_2	0.151	0.136	0.144	0.150	0.152	0.132
Moisture	0.135	0.102	0.237	0.162	0.142	0.057
LOI	32.5	28.4	32.0	29.6	24.7	31.1
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	37.9	42.5	27.9	19.1	38.0	34.2
Cd	< 6	< 6	< 6	< 6	< 6	< 6
Cl	79.0	161	72.0	115	189	331
Co	21.2	20.1	16.8	23.6	19.0	13.1
Cr	165	115	192	138	134	176
Cu	81.4	110	81.6	155	92.9	66.4
Hg	< 0.01	0.117	0.224	0.220	0.150	0.604
Mo	4.46	<1	7.82	<1	4.48	5.03
Ni	24.5	19.0	17.9	23.6	19.0	20.1
Pb	26.7	<4	8.94	51.7	13.4	5.03
Se	<2	<2	5.00	<2	<2	<2
V	62.4	52.5	62.6	59.5	50.3	52.3
Zn	114	89.4	131	89.8	82.8	85.5

C.5 Chemical Composition of Fuels

Table C.4: ELR – Proximate, ultimate, and combustion analysis of plastics for B-CCP burn

Test	Parameter (wt.%)	Sample Number						
		1	2	3	4	5	6	7
Proximate Analysis	**Ash**	10.8	7.77	9.34	15.8	7.12	8.82	14.3
	Fixed Carbon	4.54	7.51	6.24	1.58	11.3	7.47	3.66
	Moisture [1]	7.55	3.01	7.62	11.2	6.63	8.26	9.25
	Volatile Matter	84.7	84.7	84.4	82.6	81.6	83.7	82.1
Ultimate Analysis	**Carbon**	52.2	53.4	53.9	61.2	51.1	55.4	55.5
	Hydrogen	6.03	5.45	5.93	7.03	5.21	5.23	5.21
	Nitrogen	0.740	0.830	1.65	1.84	1.46	1.95	2.02
	Oxygen	30.1	32.3	29.1	14.0	35.0	28.5	23.0
	Sulfur	0.080	0.180	0.160	0.140	0.120	0.120	0.090
Heat Value [2] **(BTU/lb)**		9500	10092	11468	11283	8766	9117	9181

Table C.5: ELR – Standard parameters of plastics for B-CCP burn

Test	Parameter (wt.%)	Sample Number						
		1	2	3	4	5	6	7
Standard Parameters	Al_2O_3	15.6	23.1	14.1	4.11	39.0	17.7	15.1
	CaO	32.4	20.2	49.4	19.3	18.3	13.4	26.9
	Fe_2O_3	7.58	0.856	1.46	33.9	0.620	13.2	3.38
	K_2O	1.45	0.328	0.365	0.259	0.246	0.456	0.251
	MgO	3.69	11.77	4.13	4.43	2.59	2.52	2.80
	Na_2O	1.96	1.01	1.61	0.923	13.9	4.41	4.50
	P_2O_5	0.618	0.296	0.257	0.363	0.305	0.721	0.346
	SiO_2	24.9	30.4	23.6	9.50	20.3	26.4	17.3
	SO_3	2.98	3.65	2.36	4.67	2.30	14.4	20.6
	TiO_2	6.71	3.75	1.63	6.83	1.82	1.95	2.03
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
	As	363	NR	50.0	64.0	7	67.0	4.00
	Cd	8.00	8.00	8.00	8.00	8.00	8.00	8.00
	Cl	528	134	148	199	129	107	1415
	Co	1680	58.0	253	81.0	30.0	81.0	38.0
	Cr	NR	97.0	89.0	608	64.0	60.0	35.0
	Cu	317	152	114	13200	319	4150	2220
	Hg	0.033	0.085	0.041	0.007	0.044	0.023	< 0.01
	Mo	297	134	118	116	764	601	126
	Ni	3780	51.0	286	120	42.0	3010	44.0
	Pb	142	353	391	2330	16.0	682	473
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	3790	297	222	407	124	522	198
	Zn	2650	815	740	50900	898	5260	12300

C.6 Chemical Composition of Clinker

C.6a: CPR – Chemical composition of clinker for B-CCP burn

Parameter (wt.%)	**Sample Number**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Al_2O_3	4.64	4.87	4.68	4.82	4.93	5.22	5.24	5.05	5.23	5.12	5.30	5.22
CaO	66.1	65.7	66.3	65.0	65.9	65.2	65.5	65.9	65.2	65.2	65.0	64.9
Fe_2O_3	3.35	3.31	3.30	3.23	3.28	3.39	3.41	3.30	3.37	3.35	3.37	3.40
K_2O	0.410	0.550	0.410	0.530	0.510	0.589	0.524	0.510	0.610	0.590	0.610	0.547
MgO	2.76	2.84	2.80	2.79	2.81	2.84	2.89	2.75	2.81	2.83	2.88	2.84
Na_2O	0.110	0.110	0.110	0.120	0.140	0.136	0.153	0.150	0.150	0.170	0.140	0.130
Na_2O_{eq}	0.380	0.472	0.380	0.469	0.476	0.524	0.498	0.486	0.551	0.558	0.541	0.490
SiO_2	21.3	21.2	21.4	21.1	21.3	21.5	21.4	21.2	21.3	21.4	21.1	21.2
SO_3	0.610	1.360	0.810	1.19	1.12	0.960	0.740	1.08	1.29	1.09	1.51	1.33
Free CaO	0.900	1.24	0.710	NR	1.09	1.67	1.18	1.43	1.36	NR	1.33	1.12
C_3S	71.6	69.0	70.6	67.2	68.7	61.9	63.6	68.9	63.5	63.9	63.4	63.2
C_2S	7.00	8.67	8.21	9.87	9.13	15.0	13.5	8.72	13.2	13.1	12.8	13.0
C_3A	6.63	7.30	6.82	7.31	7.51	8.10	8.12	7.80	8.16	7.90	8.34	8.08
C_4AF	10.2	10.1	10.0	9.83	10.0	10.3	10.4	10.0	10.3	10.2	10.3	10.4

Table C.6b: CPR – Chemical composition of clinker for B-CCP burn

Parameter (wt.%)	**Sample Number**											
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Al_2O_3	5.13	5.20	5.14	5.11	5.05	4.97	4.89	4.85	4.71	5.01	5.07	5.09
CaO	65.3	65.1	65.4	65.6	65.4	65.6	65.8	65.8	66.0	65.4	64.9	64.9
Fe_2O_3	3.37	3.40	3.45	3.40	3.35	3.29	3.23	3.20	3.14	3.26	3.29	3.30
K_2O	0.514	0.551	0.510	0.510	0.570	0.550	0.520	0.520	0.500	0.545	0.590	0.620
MgO	2.80	2.85	2.84	2.83	2.81	2.79	2.78	2.78	2.75	2.84	2.87	2.90
Na_2O	0.127	0.137	0.128	0.120	0.150	0.130	0.140	0.150	0.140	0.129	0.140	0.120
Na_2O_{eq}	0.465	0.500	0.464	0.456	0.525	0.492	0.482	0.492	0.469	0.488	0.528	0.528
SiO_2	21.3	21.4	21.4	21.1	21.2	21.0	21.1	21.2	21.4	21.5	21.1	21.5
SO_3	1.10	1.30	0.880	1.12	1.16	1.46	1.23	1.37	1.21	1.22	1.63	1.44
Free CaO	1.86	0.930	1.21	NR	1.18	1.58	1.86	1.58	0.870	1.05	1.33	1.36
C_3S	64.4	62.7	64.0	67.8	66.4	69.3	70.0	69.5	69.6	64.8	65.1	62.0
C_2S	12.6	13.9	13.2	9.30	10.7	7.94	7.69	8.29	8.95	12.7	11.3	14.8
C_3A	7.89	8.02	7.77	7.79	7.71	7.60	7.49	7.44	7.17	7.75	7.87	7.90
C_4AF	10.3	10.3	10.5	10.3	10.2	10.0	9.83	9.74	9.56	9.91	10.0	10.0

Table C.7: ELR – Chemical composition of clinker for B-CCP burn

Parameter (wt.%)	Sample Number			
	1	2	3	4
Al_2O_3	4.95	5.09	4.88	4.94
CaO	65.3	65.2	65.7	65.0
Fe_2O_3	3.64	3.41	3.41	3.38
K_2O	0.504	0.468	0.392	0.475
MgO	3.20	3.14	3.14	3.17
Na_2O	0.172	0.100	0.100	0.109
P_2O_5	0.054	0.060	0.050	0.059
SiO_2	20.1	20.9	20.8	20.9
SO_3	1.36	1.03	1.01	1.33
TiO_2	0.182	0.199	0.191	0.198
Moisture	0.007	0.042	0.012	0.050
LOI	0.247	0.072	0.062	0.202
Parameter (ppm)	**1**	**2**	**3**	**4**
As	19.4	26.9	24.1	21.8
Cd	8.00	< 6	< 6	< 6
Cl	488	68	78	233
Co	11.8	18.9	18.1	17.9
Cr	603	484	556	532
Cu	778	201	750	366
Hg	0.72	0.05	0.53	0.26
Mo	9.68	<1	4.02	8.93
Ni	37.6	43.8	33.2	43.7
Pb	<4	10.0	22.1	26.8
Se	<2	<2	<2	<2
V	101	92.6	88.5	100
Zn	181	197	213	201

Table C.8: SLR – Rietveld analysis of clinker for B-CCP burn

Parameter (wt.%)	Sample Number			
	1	2	3	4
C_3S	69.6	65.4	64.6	62.0
C_2S	13.9	17.6	17.9	20.4
C_3A	2.84	3.34	3.27	2.75
C_4AF	10.5	10.4	10.8	11.1

C.7 Chemical Composition of Cement

Table C.9: CPR – Chemical composition of cement for B-CCP burn

Parameter (wt.%)	**Sample Number**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Al_2O_3	4.70	4.67	4.69	4.64	4.63	4.54	4.62	4.74	4.70
CaO	63.4	63.5	63.3	63.6	63.4	63.4	63.6	63.5	63.5
CO	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
Fe_2O_3	3.16	3.16	3.16	3.16	3.15	3.11	3.15	3.17	3.17
K_2O	0.540	0.550	0.540	0.480	0.500	0.520	0.530	0.540	0.560
MgO	2.69	2.68	2.65	2.58	2.58	2.54	2.56	2.58	2.60
Na_2O	0.120	0.100	0.110	0.120	0.120	0.120	0.120	0.140	0.130
Na_2O_{eq}	0.475	0.462	0.465	0.436	0.449	0.462	0.469	0.495	0.498
SiO_2	20.1	20.1	19.9	20.0	19.9	19.7	19.8	19.9	19.9
SO_3	3.06	3.21	3.14	3.13	3.42	3.43	3.35	2.85	3.21
Free CaO	1.15	1.05	NR	0.99	NR	NR	NR	1.55	NR
LOI	2.15	2.13	2.33	2.2	2.44	NR	2.35	2.4	2.31
C_3S	53.79	54.17	54.82	55.57	54.66	57.09	NR	56.35	55.29
C_2S	16.96	16.62	15.61	15.36	15.82	13.33	14.54	14.40	15.34
C_3A	7.11	7.04	7.09	6.96	6.95	6.78	6.92	7.20	7.10
C_4AF	9.62	9.62	9.62	9.62	9.59	9.46	9.59	9.65	9.65
Blaine SSA (m^2/kg)	397	403	405	376	385	NR	386	375	376

Table C.10: ELR – Chemical composition of cement for B-CCP burn

Parameter (wt.%)	Sample Number		
	1	2	3
Al_2O_3	4.62	4.57	4.63
CaO	64.1	63.9	64.2
Fe_2O_3	3.18	3.22	3.20
K_2O	0.492	0.471	0.484
MgO	2.93	2.95	2.95
Na_2O	0.102	0.251	0.081
P_2O_5	0.041	0.050	0.050
SiO_2	19.3	19.2	19.3
SO_3	2.94	3.04	2.74
TiO_2	0.164	0.201	0.171
Moisture	0.172	0.205	0.250
LOI	1.87	1.79	1.82
C_3S	63.5	63.4	64.4
C_2S	7.43	7.36	6.87
C_3A	6.87	6.67	6.86
C_4AF	9.67	9.80	9.72
TOC	0.923	1.56	1.42
Parameter (ppm)	**1**	**2**	**3**
As	26.1	22.5	17.5
Cd	< 6	< 6	< 6
Cl	198	187	182
Co	19.8	19.4	15.4
Cr	430	504	494
Cu	729	221	507
Hg	0.006	0.006	0.010
Mo	3.13	9.19	3.08
Ni	32.4	32.7	29.8
Pb	20.9	12.3	4.00
Se	<2	<2	<2
V	96.1	99.1	92.4
Zn	217	229	190

Table C.11: SLR – Rietveld analysis of cement for B-CCP burn

Parameter (wt.%)	Sample Number		
	1	2	3
C_3S	54.3	54.7	53.8
C_2S	21.3	21.2	22.3
C_3A	2.89	3.02	3.23
C_4AF	10.5	10.6	10.2

C.8 Plant Emissions

Table C.12a: CPR – Normalized plant emissions for B-CCP burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/2/2009 9:00	307.5	9.28E-04	1.17E-05	1.04E-05	1.70E-04
7/2/2009 10:00	347.1	7.73E-04	1.13E-05	1.04E-05	1.37E-04
7/2/2009 11:00	327.2	8.71E-04	9.95E-06	1.04E-05	1.47E-04
7/2/2009 12:00	337.9	7.67E-04	5.47E-06	7.70E-06	1.48E-04
7/2/2009 13:00	326.7	8.65E-04	6.28E-06	1.08E-05	1.69E-04
7/2/2009 14:00	286.3	9.51E-04	7.14E-06	9.47E-06	2.33E-04
7/2/2009 15:00	295.8	1.03E-03	6.90E-06	1.02E-05	2.14E-04
7/2/2009 16:00	336.4	8.03E-04	1.69E-05	1.55E-05	2.37E-04
7/2/2009 17:00	337.3	6.31E-04	4.31E-06	9.31E-06	2.12E-04
7/2/2009 18:00	297.7	9.07E-04	6.27E-06	8.57E-06	2.02E-04
7/2/2009 19:00	307.6	8.41E-04	6.62E-06	8.85E-06	1.87E-04
7/2/2009 20:00	338.1	6.96E-04	4.92E-06	1.09E-05	1.25E-04
7/2/2009 21:00	329.8	9.27E-04	5.50E-06	1.30E-05	1.28E-04
7/2/2009 22:00	330.2	8.66E-04	5.34E-06	8.99E-06	1.41E-04
7/2/2009 23:00	306.6	1.02E-03	5.78E-06	1.07E-05	1.50E-04
7/3/2009 0:00	329.3	1.02E-03	9.31E-06	1.20E-05	1.38E-04
7/3/2009 1:00	347.7	9.12E-04	1.03E-05	1.28E-05	1.36E-04
7/3/2009 2:00	324.3	1.07E-03	1.03E-05	1.81E-05	1.28E-04
7/3/2009 3:00	350.2	8.53E-04	1.05E-05	1.59E-05	1.30E-04
7/3/2009 4:00	330.5	9.23E-04	1.11E-05	1.72E-05	1.55E-04
7/3/2009 5:00	344.5	9.01E-04	1.24E-05	1.45E-05	1.57E-04
7/3/2009 6:00	339.8	8.03E-04	1.13E-05	1.37E-05	1.62E-04
7/3/2009 7:00	332.9	9.75E-04	9.90E-06	1.42E-05	1.56E-04
7/3/2009 8:00	373.4	7.99E-04	4.51E-06	1.18E-05	1.59E-04
7/3/2009 9:00	284.1	9.78E-04	7.65E-06	1.46E-05	1.82E-04
7/3/2009 10:00	335.3	8.57E-04	4.95E-06	1.18E-05	1.55E-04
7/3/2009 11:00	330.5	9.73E-04	5.68E-06	1.52E-05	1.62E-04
7/3/2009 12:00	330.9	8.79E-04	5.92E-06	1.46E-05	1.78E-04
7/3/2009 13:00	335.0	7.24E-04	5.43E-06	1.34E-05	1.74E-04
7/3/2009 14:00	335.5	5.85E-04	5.36E-06	1.21E-05	1.92E-04
7/3/2009 15:00	350.2	7.76E-04	4.41E-06	1.32E-05	1.72E-04

Table C.12b: CPR – Normalized plant emissions for B-CCP burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/3/2009 16:00	330.0	8.20E-04	6.55E-06	1.18E-05	1.89E-04
7/3/2009 17:00	344.1	7.86E-04	6.12E-06	1.24E-05	1.83E-04
7/3/2009 18:00	326.9	8.22E-04	6.17E-06	1.38E-05	1.87E-04
7/3/2009 19:00	336.2	6.91E-04	5.64E-06	1.23E-05	1.58E-04
7/3/2009 20:00	343.0	5.80E-04	5.09E-06	1.80E-05	1.47E-04
7/3/2009 21:00	337.0	6.25E-04	5.39E-06	1.23E-05	1.52E-04
7/3/2009 22:00	344.7	5.19E-04	5.43E-06	1.26E-05	1.59E-04
7/3/2009 23:00	344.6	5.47E-04	5.14E-06	1.42E-05	1.63E-04
7/4/2009 0:00	341.3	5.86E-04	5.86E-06	1.38E-05	1.51E-04
7/4/2009 1:00	336.4	6.41E-04	5.06E-06	1.62E-05	1.58E-04
7/4/2009 2:00	343.3	6.92E-04	4.83E-06	1.53E-05	1.55E-04
7/4/2009 3:00	344.1	5.40E-04	4.16E-06	1.70E-05	1.51E-04
7/4/2009 4:00	351.0	5.94E-04	4.35E-06	1.61E-05	1.42E-04
7/4/2009 5:00	363.3	5.99E-04	3.65E-06	1.91E-05	1.29E-04
7/4/2009 6:00	350.2	5.15E-04	4.89E-06	1.73E-05	1.35E-04
7/4/2009 7:00	305.3	6.56E-04	5.38E-06	1.90E-05	1.43E-04
7/4/2009 8:00	350.0	6.03E-04	5.89E-06	1.45E-05	1.40E-04
7/4/2009 9:00	341.8	5.31E-04	5.92E-06	1.48E-05	1.56E-04
7/4/2009 10:00	362.6	6.21E-04	5.31E-06	1.22E-05	1.77E-04
7/4/2009 11:00	347.8	7.66E-04	5.62E-06	1.20E-05	2.13E-04
7/4/2009 12:00	359.4	6.11E-04	4.79E-06	1.14E-05	2.15E-04
7/4/2009 13:00	347.2	6.20E-04	4.98E-06	1.07E-05	2.05E-04
7/4/2009 14:00	350.6	4.40E-04	4.25E-06	1.14E-05	2.04E-04
7/4/2009 15:00	344.6	4.38E-04	4.29E-06	9.76E-06	1.79E-04
7/4/2009 16:00	351.8	4.88E-04	5.03E-06	8.64E-06	1.06E-04
7/4/2009 17:00	353.9	4.69E-04	5.32E-06	1.19E-05	8.64E-05
7/4/2009 18:00	359.2	5.92E-04	5.83E-06	8.98E-06	9.83E-05
7/4/2009 19:00	323.2	4.38E-04	4.68E-06	1.01E-05	8.71E-05
7/4/2009 20:00	330.7	3.72E-04	5.12E-06	1.26E-05	5.36E-05
7/4/2009 21:00	321.2	3.32E-04	5.27E-06	9.30E-06	6.41E-05
7/4/2009 22:00	333.1	2.64E-04	4.06E-06	9.38E-06	9.67E-05
7/4/2009 23:00	331.3	4.48E-04	6.46E-06	1.23E-05	1.04E-04
7/5/2009 0:00	333.9	4.83E-04	6.71E-06	1.37E-05	9.29E-05
7/5/2009 1:00	332.9	5.76E-04	7.27E-06	1.40E-05	9.21E-05
7/5/2009 2:00	333.5	7.17E-04	5.29E-06	1.50E-05	1.18E-04
7/5/2009 3:00	360.0	6.05E-04	1.02E-06	1.40E-05	1.24E-04
7/5/2009 4:00	343.1	6.09E-04	1.07E-06	1.35E-05	1.67E-04
7/5/2009 5:00	345.7	6.21E-04	6.02E-07	1.38E-05	1.53E-04
7/5/2009 6:00	353.4	5.86E-04	9.48E-07	1.37E-05	1.36E-04
7/5/2009 7:00	345.3	6.49E-04	1.19E-06	1.53E-05	1.40E-04
7/5/2009 8:00	346.4	6.33E-04	7.79E-08	1.59E-05	1.39E-04
7/5/2009 9:00	351.4	4.72E-04	1.64E-06	1.49E-05	1.68E-04

Appendix D

Raw Data for Railway Ties Trial Burn (RR)

D.1 General Comments

- Raw data from the RR burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, petroleum coke, waste plastics, and railway were the fuels utilized during this trial burn.
- This burn lasted from 8 AM on 7/8/2009 to 8 AM on 7/12/2009.

D.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NA – Not Applicable

ND – Not Detected

NR – Not Reported

^{1} As-Received

^{2} Dry Basis

^{3} Calculated by Auburn

D.3 Chemical Composition of Kiln Feed

Table D.1: CPR – Chemical composition of kiln feed for RR burn

Parameter (wt. %)	**Sample Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Al_2O_3	3.14	3.17	3.22	3.2	3.23	3.22	3.22	3.23	3.22	3.20
CaO	43.1	43.1	43.4	43.1	42.7	43.1	43.0	42.7	43.5	42.7
Fe_2O_3	2.16	2.15	2.17	2.19	2.20	2.14	2.19	2.27	2.22	2.24
K_2O	0.360	0.370	0.360	0.370	0.370	0.360	0.370	0.370	0.400	0.370
MgO	1.93	1.96	1.96	2.00	2.01	2.00	2.00	2.05	2.08	2.04
Na_2O	0.050	0.060	0.060	0.060	0.060	0.060	0.070	0.060	0.070	0.060
Na_2O_{eq}	0.287	0.303	NR	0.303	0.303	NR	0.313	0.303	0.333	0.303
SiO_2	13.5	13.4	13.6	13.6	13.6	13.6	13.5	13.9	13.5	13.7
SO_3	0.170	0.170	0.160	0.180	0.190	0.140	0.200	0.150	0.220	0.160
Moisture	2.18	2.31	NR	2.18	2.06	NR	2.02	2.61	1.96	2.45
LOI	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR

D.4 Chemical Composition of Cement Kiln Dust (CKD)

Table D.2: CPR – Chemical composition of CKD for RR burn

Parameter (wt. %)	**Sample Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Al_2O_3	3.16	2.99	3.85	3.62	4.25	4.09	3.43	3.76	3.55	3.68
CaO	52.8	43.2	46.1	49.4	43.9	43.9	49.7	46.0	47.0	46.0
Fe_2O_3	1.38	2.13	1.82	1.66	1.91	1.96	1.70	1.87	1.71	1.73
K_2O	0.400	0.350	0.450	0.500	0.470	0.460	0.420	0.440	0.450	0.450
MgO	2.04	2.10	1.54	2.09	1.29	1.31	1.99	1.48	1.74	1.85
Na_2O	0.090	0.050	0.070	0.080	0.060	0.070	0.070	0.070	0.070	0.070
SiO_2	9.56	13.0	11.6	10.5	12.5	12.2	10.4	11.4	11.5	12.1
SO_3	1.36	0.140	0.500	1.87	0.100	0.110	1.07	0.400	0.820	0.490

Table D.3: ELR – Chemical composition of CKD for RR burn

Parameter (wt.%)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.96	3.43	3.61	3.33	4.01	3.52
CaO	44.8	45.7	52.9	49.6	44.5	51.1
Fe_2O_3	1.89	1.73	1.82	1.69	1.84	1.84
K_2O	0.401	0.295	0.482	0.423	0.442	0.408
MgO	1.38	1.49	2.11	1.83	1.37	2.04
Na_2O	0.102	0.075	0.061	0.057	0.094	0.080
P_2O_5	0.054	0.034	0.046	0.036	0.054	0.044
SiO_2	11.3	10.9	10.0	10.0	11.6	9.94
SO_3	0.143	0.144	1.461	0.925	0.167	0.888
TiO_2	0.163	0.110	0.145	0.129	0.174	0.146
Moisture	0.125	0.030	ND	0.347	0.536	0.015
LOI	35.7	35.9	27.3	31.8	35.7	29.9
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	35.0	21.0	45.0	47.0	34.0	34.0
Cd	< 5	< 5	< 5	< 5	< 5	< 5
Cl	52.0	148	536	130	50.0	144
Co	17.0	17.0	15.0	19.0	18.0	13.0
Cr	396	416	403	465	405	442
Cu	198	169	191	371	1250	355
Hg	0.070	0.10	0.210	0.100	0.060	0.070
Mo	4.00	2.00	3.00	4.00	3.00	3.00
Ni	21.0	20.0	20.0	20.0	28.0	24.0
Pb	21.0	4.00	8.00	< 4	56.0	15.0
Se	< 2	< 2	4.00	< 2	< 2	< 2
V	67.0	54.0	55.0	54.0	68.0	52.0
Zn	116	126	78.0	91.0	242	110

D.5 Chemical Composition of Fuels

Table D.4a: ELR – Proximate, ultimate, and combustion analysis of ASF for RR burn

Test	**Parameter (wt.%)**	**Sample Number**									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Proximate Analysis	**Ash**	14.9	18.1	13.4	8.7	7.53	6.80	9.18	14.2	8.5	10.1
	Fixed Carbon	10.8	9.82	10.2	12.3	14.2	6.72	10.7	14.2	13.2	10.7
	Moisture [1]	25.1	1.9	21.3	15.1	26.4	0.630	13.5	25.6	26.4	19.4
	Volatile Matter	74.3	72.1	76.4	79.0	78.3	86.5	80.2	71.6	78.3	79.2
Ultimate Analysis	**Carbon**	6.09	5.85	5.47	5.79	5.38	7.59	6.25	5.09	4.99	5.82
	Hydrogen	54.0	50.2	49.6	52.7	55.1	59.1	52.8	50.4	55.9	51.9
	Nitrogen	1.22	1.22	1.30	1.04	0.940	1.79	1.09	0.950	0.840	1.29
	Oxygen	23.5	23.9	29.8	31.5	30.9	24.5	30.5	29.2	29.6	30.7
	Sulfur	0.360	0.640	0.420	0.210	0.140	0.270	0.180	0.140	0.160	0.200
Heat Value [2] **(BTU/lb)**		9643	9851	9501	9958	10067	12151	9951	9318	9579	10796

Table D.4b: ELR – Proximate, ultimate, and combustion analysis of ASF for RR burn

Test	Parameter (wt.%)	Sample Number									
		11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Proximate Analysis	**Ash**	6.08	8.75	5.02	8.54	8.76	8.25	6.74	6.83	5.9	3.8
	Fixed Carbon	16.6	8.3	18.1	7.6	12.6	15.3	15.3	15.2	12.7	14.8
	Moisture [1]	34.2	0.730	29.1	27.0	25.1	22.6	29.5	28.6	29.4	30.8
	Volatile Matter	77.3	83.0	76.9	83.9	78.6	76.4	78.0	78.0	81.4	81.3
Ultimate Analysis	**Carbon**	4.97	6.03	5.04	7.13	5.07	5.51	5.15	4.92	5.54	5.45
	Hydrogen	50.5	59.4	50.7	60.1	47.8	52.8	51.5	50.6	50.4	56.3
	Nitrogen	0.770	1.41	0.760	2.630	0.830	1.10	0.720	1.10	0.820	0.730
	Oxygen	37.6	24.1	38.4	21.4	37.3	32.2	35.8	36.4	37.2	33.6
	Sulfur	0.120	0.250	0.060	0.210	0.190	0.130	0.110	0.170	0.120	0.110
Heat Value [2] **(BTU/lb)**		8376	10525	9994	10979	8407	8877	8704	8833	9498	10332

Table D.5a: ELR – Standard parameters of ASF for RR burn

Test	Parameter (wt.%)	Sample Number									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Standard Parameters	**Al_2O_3**	9.11	13.7	11.0	10.8	7.73	12.8	58.1	7.41	12.0	8.65
	CaO	26.0	23.4	22.1	34.6	37.8	52.2	19.7	29.0	33.2	30.9
	Fe_2O_3	9.64	6.01	8.14	9.63	13.5	4.74	4.69	8.06	10.7	12.0
	K_2O	0.991	1.09	0.949	0.900	0.699	0.646	0.324	0.959	0.896	0.863
	MgO	2.88	3.41	2.87	2.37	5.36	1.96	1.82	2.72	2.99	3.50
	Na_2O	1.24	2.83	2.22	1.44	0.975	1.72	0.677	1.16	2.20	1.09
	P_2O_5	0.553	0.432	0.463	0.300	0.634	0.242	0.574	0.256	0.787	0.508
	SiO_2	40.9	39.8	42.6	35.3	25.9	17.4	11.6	45.5	29.4	34.9
	SO_3	3.42	3.74	3.47	2.34	2.78	0.989	0.765	2.16	3.72	2.51
	TiO_2	1.27	2.20	2.47	1.71	1.69	6.84	1.41	0.937	1.25	1.78
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	As	18.4	32.4	22.0	-9.00	< 4	-616	< 4	32.0	< 4	< 4
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	671	2088	1060	580	8775	249	508	230	463	652
	Co	266	233	319	225	182	200	97.1	124	212	246
	Cr	1868	859	660	1920	832	4327	3021	859	1259	850
	Cu	1340	727	900	2798	4611	1608	475	1103	4760	3431
	Hg	0.743	0.419	0.436	0.418	0.420	0.375	0.727	0.430	0.389	0.390
	Mo	187	124	113	120	807	274	157	68.2	190	201
	Ni	682	276	218	321	340	1707	1017	246	678	236
	Pb	126	87.5	117	141	253	1189	210	219	450	518
	Se	< 2	< 2	< 2	< 2	4.00	< 2	< 2	< 2	< 2	< 2
	V	138	200	179	108	119	343	121	96.9	103	142
	Zn	24683	22526	25376	11713	13718	2299	4642	10502	13729	14254

Table D.5b: ELR – Standard parameters of ASF for RR burn

Test	Parameter (wt.%)	Sample Number									
		11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Standard Parameters	**Al_2O_3**	7.33	26.2	5.91	5.55	17.7	7.93	10.3	11.6	24.7	5.41
	CaO	39.7	16.3	42.5	53.5	34.8	38.2	43.8	29.3	32.1	24.1
	Fe_2O_3	10.4	18.2	9.94	7.71	5.68	12.8	8.16	19.5	8.57	30.1
	K_2O	0.945	0.309	0.719	0.539	0.817	1.00	0.787	0.764	0.940	0.582
	MgO	2.60	7.37	5.60	3.49	1.67	3.64	2.60	2.37	2.35	3.08
	Na_2O	2.47	3.57	0.933	1.21	5.99	2.18	0.892	1.17	2.35	0.770
	P_2O_5	0.158	0.118	0.311	1.11	0.170	0.214	0.131	0.153	0.104	0.187
	SiO_2	28.3	20.1	26.4	20.3	26.3	29.0	25.7	27.9	23.2	18.6
	SO_3	4.04	1.58	3.54	2.95	4.80	2.50	3.99	3.41	3.03	3.68
	TiO_2	0.762	1.41	0.856	2.73	1.46	1.75	0.866	0.586	1.78	0.936
	Parameter (ppm)	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	As	< 4	13.3	< 4	< 4	< 4	< 4	< 4	< 4	< 4	27.0
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	130	171	492	253	371	245	92.0	212	336	86.0
	Co	255	140	210	193	191	297	260	288	1338	424
	Cr	1269	17009	2275	1250	1314	647	286	420	721	27252
	Cu	6408	342	860	2055	3907	3158	742	942	987	1599
	Hg	0.510	0.326	0.340	0.340	0.340	0.350	0.328	0.310	0.350	0.330
	Mo	91.9	822	457	187	54.5	67.9	60.3	78.9	47.0	189
	Ni	491	3477	2246	1760	286	164	247	176	2544	3380
	Pb	843	76.6	169	606	517	1661	207	252	831	25.0
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	179	175	83.6	184	126	139	126	112	104	185
	Zn	17082	1400	15176	11009	10092	11543	20309	19956	26714	19233

Table D.6a: ELR – Proximate, ultimate, and combustion analysis of plastics for RR burn

Test	**Parameter (wt.%)**	**Sample Number**								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Proximate Analysis	**Ash**	8.24	15.7	7.56	5.89	11.9	10.6	9.09	5.89	7.01
	Fixed Carbon	9.28	6.12	8.14	8.11	6.87	9.08	10.1	10.4	9.16
	Moisture [1]	1.22	1.09	0.60	1.55	2.01	3.56	2.73	1.36	1.78
	Volatile Matter	82.5	78.2	84.3	86.0	81.2	80.3	80.8	83.8	83.8
Ultimate Analysis	**Carbon**	53.3	48.1	61.0	55.7	44.4	45.7	49.5	56.8	54.6
	Hydrogen	6.27	5.44	7.26	6.65	5.40	5.05	5.80	5.38	6.40
	Nitrogen	0.860	0.950	1.19	1.74	1.03	1.10	1.11	1.48	1.45
	Oxygen	31.0	29.7	22.8	29.8	37.1	37.3	34.3	30.1	30.4
	Sulfur	0.290	0.21	0.160	0.200	0.190	0.230	0.250	0.320	0.180
Heat Value [2] **(BTU/lb)**		9633	9252	11647	9705	8538	8252	9354	9427	8833

Table D.6b: ELR – Proximate, ultimate, and combustion analysis of plastics for RR burn

Test	Parameter (wt.%)	Sample Number									
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Proximate Analysis	**Ash**	3.81	7.47	6.20	9.43	5.33	10.5	9.28	13.0	6.25	9.60
	Fixed Carbon	10.4	9.97	10.8	9.00	3.22	0.880	2.24	8.81	5.24	7.15
	Moisture [1]	1.71	2.01	2.14	2.43	1.41	0.890	1.90	2.40	1.33	1.01
	Volatile Matter	85.8	82.6	83.0	81.6	91.5	88.6	88.5	78.2	88.5	83.3
Ultimate Analysis	**Carbon**	54.8	52.0	52.0	48.0	58.3	60.1	46.9	47.9	52.5	58.4
	Hydrogen	6.21	5.61	5.96	5.46	7.19	5.63	5.25	5.76	0.87	6.97
	Nitrogen	1.44	1.30	1.34	1.130	0.870	1.54	1.15	1.00	1.02	1.23
	Oxygen	33.59	33.4	34.3	35.9	28.2	22.1	37.2	32.01	39.1	23.5
	Sulfur	0.190	0.170	0.190	0.170	0.170	0.100	0.160	0.310	0.260	0.300
Heat Value [2] **(BTU/lb)**		10882	9590	9465	9270	11325	10696	8582	8634	10411	11277

Table D.7a: ELR – Standard parameters of plastics for RR burn

Test	Parameter (wt.%)	Sample Number								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Standard Parameters	**Al_2O_3**	19.5	5.88	34.6	20.2	12.2	22.5	23.1	36.9	41.3
	CaO	30.0	72.8	40.9	30.3	66.9	26.4	33.3	28.2	26.0
	Fe_2O_3	6.22	5.83	9.56	11.44	1.92	1.30	1.24	2.02	1.76
	K_2O	0.500	0.231	0.146	0.582	0.197	0.324	0.359	0.266	0.235
	MgO	2.74	1.98	1.42	1.45	1.66	1.73	1.66	5.07	2.17
	Na_2O	4.74	1.92	1.07	2.20	0.787	6.10	4.13	3.03	2.53
	P_2O_5	0.240	0.121	0.146	0.211	0.131	0.210	0.213	0.266	0.199
	SiO_2	30.1	8.58	5.48	23.8	14.1	36.4	24.1	20.3	21.3
	SO_3	1.90	1.13	0.816	1.48	1.07	3.09	3.53	1.64	1.38
	TiO_2	2.40	1.25	2.86	4.35	0.853	1.68	2.97	1.99	2.51
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	As	< 4	< 4	< 4	113	< 4	< 4	< 4	< 4	10.9
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	204	448	243	425	210	230	222	882	147
	Co	93.9	48.4	205	127	56.8	55.3	123	224	90.5
	Cr	3589	5044	6090	10398	195	303	229	1083	715
	Cu	779	391	1127	923	385	715	215	613	403
	Hg	0.320	0.280	0.290	0.360	0.280	0.300	0.267	0.310	0.395
	Mo	216	236	395	680	< 4	70.5	16.8	59.8	23.5
	Ni	1809	2637	4659	5617	131	194	61.6	301	210
	Pb	767	118	389	< 4	13.1	252	76.2	143.9	38.0
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	148	95.7	167	270	63.4	112	269	126	159
	Zn	1293	380	707	589	641	1256	400	3769	499

Table D.7b: ELR – Standard parameters of plastics for RR burn

Test	Parameter (wt.%)	Sample Number									
		10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Standard Parameters	**Al_2O_3**	38.3	44.8	43.1	31.4	5.69	5.55	26.7	20.2	13.5	9.64
	CaO	29.7	19.3	26.6	45.2	83.9	63.3	23.5	34.0	34.7	26.8
	Fe_2O_3	3.81	2.20	2.50	1.60	0.477	7.11	4.24	2.50	7.84	9.70
	K_2O	0.400	0.238	0.472	0.340	0.093	0.207	0.259	0.210	0.349	0.761
	MgO	1.23	3.55	1.08	1.80	1.66	1.77	1.67	2.81	2.20	4.43
	Na_2O	2.21	1.43	2.39	1.46	0.361	0.738	1.18	2.47	2.07	1.11
	P_2O_5	0.492	0.256	0.250	0.176	0.081	0.251	0.210	0.362	0.453	0.637
	SiO_2	16.0	25.2	18.1	14.5	6.03	11.7	35.4	32.5	24.8	31.4
	SO_3	0.553	0.878	1.17	1.21	0.535	3.1	3.34	2.17	4.65	4.51
	TiO_2	6.21	1.94	3.66	2.09	0.838	1.25	1.59	1.92	2.25	2.04
	Parameter (ppm)	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
	As	< 4	18.3	< 4	< 4	< 4	43	< 4	< 4	26	19
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	128	216	217	77.0	207	967	340	259	288	630
	Co	166	65.9	144	42.8	32.6	168	66.4	28.0	113	173
	Cr	3099	1054	711	703	67.5	6375	2647	1283	6816	6035
	Cu	888	247	691	230	232	763	426	711	751	11068
	Hg	0.280	0.315	0.270	0.250	0.240	0.196	0.267	0.160	0.150	0.230
	Mo	188	62.2	38.9	372.5	3.49	663	950	2009	1197	543
	Ni	1303	443	178	277	74.5	3486	1213	734	3613	3001
	Pb	624	< 4	336	51.6	106	< 4	120	74.6	19.2	47.3
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	231	132	164	131	86.1	114	151	215	183	227
	Zn	2810	767	1057	643	262	381	457	380	256	6783

Table D.8: ELR – Proximate, ultimate, and combustion analysis of railway ties for RR burn

Test	Parameter (wt.%)	Sample Number									
		1	2	3	4	5	6	7	8	9	10
Proximate Analysis	**Ash**	2.43	5.44	14.6	6.96	3.54	13.0	3.64	9.12	8.88	7.28
	Fixed Carbon	14.0	12.4	4.48	16.2	19.2	12.8	16.6	15.8	14.8	15.7
	Moisture [1]	25.4	25.2	26.2	29.1	32.6	24.5	35.1	22.0	32.3	31.8
	Volatile Matter	83.6	82.2	80.9	76.9	77.3	74.2	79.8	75.1	76.3	77.0
Ultimate Analysis	**Carbon**	51.6	50.2	48.9	50.1	50.1	49.4	52.3	51.6	49.2	49.2
	Hydrogen	5.16	4.93	5.01	4.79	5.24	5.01	5.03	5.36	4.61	4.72
	Nitrogen	0.920	0.910	1.01	0.960	0.930	1.17	0.740	0.710	0.760	0.690
	Oxygen	39.8	38.4	30.3	36.8	40.1	31.3	38.2	32.9	36.5	38.1
	Sulfur	0.090	0.080	0.160	0.480	0.070	0.150	0.090	0.360	0.050	0.050
Heat Value [2] **(BTU/lb)**		8925	8575	8209	8511	8586	8917	8695	8684	8242	8371

Table D.9: ELR – Standard parameters of railway ties for RR burn

Test	Parameter (wt.%)	Sample Number									
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Standard Parameters	**Al_2O_3**	6.83	4.43	4.45	5.67	7.43	5.77	5.06	12.4	4.54	4.69
	CaO	39.8	54.5	52.8	45.4	26.9	45.1	42.1	18.2	54.3	52.0
	Fe_2O_3	10.8	6.24	4.61	7.90	11.3	6.52	8.97	8.04	6.61	6.44
	K_2O	1.00	0.558	0.537	0.881	1.15	0.705	0.692	1.22	0.659	0.613
	MgO	4.27	3.78	8.98	4.56	2.95	9.40	9.21	2.29	4.66	5.08
	Na_2O	0.365	0.268	0.548	0.776	0.583	0.560	0.494	0.958	0.270	0.365
	P_2O_5	0.228	0.172	0.215	0.168	0.252	0.291	0.212	0.252	0.238	0.204
	SiO_2	24.6	23.1	22.3	29.8	39.3	24.7	26.4	43.6	24.3	25.5
	SO_3	7.90	4.08	3.33	3.08	5.66	3.82	4.35	5.97	2.77	2.89
	TiO_2	0.457	0.290	0.387	0.367	0.552	1.13	0.438	0.816	0.454	0.516
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
	As	22.8	16.1	30.1	56.6	7.88	21.3	31.1	22.2	45.4	34.4
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	93.0	59.0	586	86.0	78.0	1668	69.0	121	95.0	356
	Co	356	113	134	88.1	367	219	185	486	95.1	112
	Cr	363	352	841	291	342	440	533	292	196	233
	Cu	836	2190	413	2558	1007	1249	1913	1875	625	1077
	Hg	0.178	0.560	0.182	0.169	0.176	0.141	0.126	0.110	0.092	0.086
	Mo	1590	218	339	152	769	459	521	281	4343	220
	Ni	496	275	492	187	270	207	297	165	145	131
	Pb	132	96.5	40.8	86.0	205	102	65.0	171	< 4	46.2
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	73.1	49.3	77.4	61.9	139	126.5	60.7	106	500	72.0
	Zn	21045	15246	11051	5382	24632	12180	9543	42474	5201	9729

D.6 Chemical Composition of Clinker

Table D.10a: CPR – Chemical composition of clinker for RR burn

Parameter (wt.%)	**Sample Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Al_2O_3	4.98	4.80	5.08	5.02	4.30	4.47	4.22	4.77	4.55	4.98
CaO	62.0	61.7	63.6	64.3	54.0	59.5	54.4	61.6	58.5	64.2
Fe_2O_3	3.38	3.32	3.38	3.29	2.92	3.03	2.90	3.23	3.09	3.29
K_2O	0.590	0.560	0.590	0.640	0.500	0.530	0.490	0.550	0.620	0.610
MgO	2.83	3.25	2.83	2.87	2.42	2.59	2.49	2.68	2.53	2.94
Na_2O	0.120	0.140	0.130	0.140	0.080	0.110	0.090	0.120	0.050	0.140
Na_2O_{eq}	0.508	0.508	0.518	0.561	0.409	0.459	0.412	0.482	0.458	0.541
SiO_2	20.1	20.5	21.0	20.8	18.0	19.2	18.2	19.7	19.1	20.7
SO_3	1.60	1.50	1.16	1.49	0.950	1.07	1.23	1.33	1.53	1.36
Free CaO	0.900	0.930	2.29	1.40	2.39	1.98	1.64	ND	ND	1.40
C_3S	61.1	58.4	60.5	65.0	49.7	62.2	50.5	64.4	57.9	65.8
C_2S	11.5	14.8	14.4	10.7	14.2	8.03	14.2	7.86	11.1	9.69
C_3A	7.48	7.10	7.74	7.74	6.45	6.72	6.28	7.18	6.83	7.63
C_4AF	10.3	10.1	10.3	10.0	8.89	9.22	8.82	9.83	9.40	10.0

Table D.10b: CPR – Chemical composition of clinker for RR burn

Parameter (wt.%)	**Sample Number**									
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Al_2O_3	5.07	5.08	5.12	5.23	5.17	5.15	5.21	5.40	5.27	5.36
CaO	63.9	63.1	64.8	64.5	64.5	64.7	64.6	64.3	64.7	64.6
Fe_2O_3	3.37	3.28	3.41	3.46	3.40	3.37	3.42	3.46	3.35	3.47
K_2O	0.590	0.760	0.525	0.510	0.595	0.580	0.570	0.680	0.630	0.591
MgO	2.96	2.94	3.16	3.12	3.09	3.08	3.09	3.06	3.08	3.07
Na_2O	0.130	0.150	0.109	0.111	0.103	0.109	0.113	0.130	0.130	0.118
Na_2O_{eq}	0.518	0.650	0.454	0.447	0.495	0.491	0.488	0.577	0.545	0.507
SiO_2	20.8	20.0	21.5	21.3	21.2	21.4	21.4	21.2	21.1	21.3
SO_3	1.45	3.09	1.15	1.18	1.47	1.24	1.15	1.54	1.41	1.12
Free CaO	0.810	1.77	0.710	0.930	0.430	0.810	0.740	1.77	1.43	1.58
C_3S	63.4	66.4	61.4	60.4	61.8	61.4	60.5	59.2	62.6	60.0
C_2S	11.8	7.16	15.3	15.6	14.1	15.0	15.7	16.1	13.4	15.9
C_3A	7.73	7.91	7.79	8.00	7.95	7.94	8.02	8.46	8.30	8.34
C_4AF	10.3	10.0	10.4	10.5	10.3	10.3	10.4	10.5	10.2	10.6

Table D.10c: CPR – Chemical composition of clinker for RR burn

Parameter (wt.%)	**Sample Number**								
	21	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Al_2O_3	5.32	5.55	5.28	5.32	5.44	5.23	5.25	5.34	5.43
CaO	64.3	63.6	65.2	64.6	64.6	64.9	64.5	64.4	64.3
Fe_2O_3	3.44	3.55	3.46	3.45	3.54	3.44	3.40	3.46	3.50
K_2O	0.650	0.650	0.557	0.608	0.546	0.569	0.640	0.537	0.570
MgO	3.06	2.96	3.29	3.17	3.14	3.11	3.19	3.15	3.14
Na_2O	0.120	0.110	0.111	0.121	0.105	0.114	0.120	0.113	0.120
Na_2O_{eq}	0.548	0.538	0.478	0.521	0.464	0.488	0.541	0.466	0.495
SiO_2	21.3	22.0	21.1	21.4	21.4	21.6	21.4	21.4	21.6
SO_3	1.39	0.940	0.960	1.22	0.640	0.890	1.35	1.16	0.820
Free CaO	1.80	4.65	2.17	0.840	2.02	0.810	1.55	0.560	0.620
C_3S	59.6	49.5	64.6	59.6	59.2	59.9	60.1	59.1	56.1
C_2S	16.0	25.6	11.8	16.5	16.5	16.8	15.8	16.6	19.6
C_3A	8.28	8.70	8.14	8.26	8.43	8.04	8.16	8.30	8.47
C_4AF	10.5	10.8	10.5	10.5	10.8	10.5	10.3	10.5	10.7

Table D.11: ELR – Chemical composition of clinker for RR burn

Parameter (wt.%)	**Sample Number**			
	1	**2**	**3**	**4**
Al_2O_3	5.24	4.46	4.94	5.16
CaO	64.2	64.9	64.3	64.6
Fe_2O_3	3.40	3.03	3.41	3.53
K_2O	0.399	0.575	0.480	0.460
MgO	3.22	3.23	3.34	3.38
Na_2O	0.080	0.091	0.100	0.100
P_2O_5	0.060	0.071	0.060	0.060
SiO_2	21.1	21.4	21.3	20.9
SO_3	1.30	1.62	1.21	1.08
TiO_2	0.199	0.151	0.200	0.200
Moisture	0.030	0.047	0.058	0.057
LOI	0.434	0.262	0.458	0.349
Parameter (ppm)	**1**	**2**	**3**	**4**
As	28.0	29.0	31.0	27.0
Cd	< 5	< 5	< 5	7.00
Cl	163	95.0	215	89.0
Co	16.0	15.0	15.0	20.0
Cr	486	495	523	557
Cu	238	506	548	205
Hg	0.02	0.01	0.01	0.01
Mo	18.0	7.00	10.0	6.00
Ni	42.0	46.0	32.0	31.0
Pb	17.0	23.0	30.0	< 4
Se	< 2	< 2	< 2	< 2
V	113	148	96.0	95.0
Zn	165	171	182	123

Table D.12: SLR – Rietveld analysis of clinker for RR burn

Parameter (wt.%)	**Sample Number**				
	1	**2**	**3**	**4**	**5**
C_3S	55.9	62.0	55.9	56.2	52.5
C_2S	25.7	20.6	24.7	25.4	27.2
C_3A	3.03	3.23	2.96	3.99	3.61
C_4AF	11.4	10.9	11.6	11.3	11.2

D.7 Chemical Composition of Cement

Table D.13: CPR – Chemical composition of cement for RR burn

Parameter (wt.%)	**Sample Number**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Al_2O_3	4.60	4.95	4.90	4.87	4.80	4.71	4.79
CaO	63.8	62.9	63.2	62.9	63.0	63.1	62.9
CO	1.30	1.30	1.30	1.30	1.30	1.30	1.30
Fe_2O_3	3.14	3.32	3.28	3.22	3.24	3.19	3.23
K_2O	0.510	0.540	0.530	0.560	0.520	0.510	0.570
MgO	2.65	2.87	2.84	2.80	2.81	2.72	2.74
Na_2O	0.110	0.100	0.100	0.110	0.100	0.110	0.110
Na_2O_{eq}	0.446	0.455	0.449	0.478	0.442	0.446	0.485
SiO_2	20.0	20.4	20.3	20.1	20.2	20.1	20.1
SO_3	3.10	2.95	2.82	3.29	3.30	3.41	3.50
Free CaO	ND	0.810	ND	1.55	ND	0.870	ND
LOI	2.32	1.99	2.12	2.18	2.06	2.43	2.12
C_3S	56.7	48.1	50.4	50.2	50.1	51.9	49.6
C_2S	14.6	22.1	20.2	19.7	20.1	18.4	20.3
C_3A	6.88	7.51	7.44	7.46	7.24	7.09	7.23
C_4AF	9.56	10.1	9.98	9.80	9.86	9.71	9.83
Blaine SSA (m^2/kg)	374	380	372	384	408	392	390

Table D.14: ELR – Chemical composition of cement for RR burn

Parameter (wt.%)	Sample Number		
	1	2	3
Al_2O_3	4.84	4.77	4.86
CaO	64.0	64.6	63.6
Fe_2O_3	3.40	3.29	3.21
K_2O	0.438	0.446	0.485
MgO	3.22	3.18	3.11
Na_2O	0.092	0.073	0.121
P_2O_5	0.051	0.052	0.050
SiO_2	20.0	19.7	20.3
SO_3	2.78	3.00	3.25
TiO_2	0.193	0.166	0.162
Moisture	ND	ND	ND
LOI	0.742	0.480	0.586
C_3S	56.3	60.8	51.6
C_2S	14.9	10.7	19.3
C_3A	7.09	7.08	7.44
C_4AF	10.3	10.0	9.77
TOC	0.384	0.373	0.303
Parameter (ppm)	**1**	**2**	**3**
As	26.0	21.0	18.0
Cd	< 5	< 5	< 5
Cl	118	135	160
Co	17.0	14.0	18.0
Cr	538	438	479
Cu	502	138	72.0
Hg	1.26	1.23	1.32
Mo	11.0	3.0	4.0
Ni	32.0	29.0	31.0
Pb	10.0	14.0	22.0
Se	< 2	< 2	< 2
V	88.0	94.0	100
Zn	159	127	158

Table D.15: SLR – Rietveld analysis of cement for RR burn

Parameter (wt.%)	Sample Number		
	1	2	3
C_3S	52.0	52.5	54.3
C_2S	24.5	23.7	22.3
C_3A	3.30	3.54	3.17
C_4AF	11.2	10.7	10.6

D.8 Plant Emissions

Table D.16a: CPR – Normalized plant emissions for RR burn

Date/Time	**Clinker Produced (tons/hr)**	**NO_x (tons/ton clinker)**	**SO_2 (tons/ton clinker)**	**VOC (tons/ton clinker)**	**CO (tons/ton clinker)**
7/8/2009 8:00	333.0	7.08E-04	1.50E-05	1.16E-05	1.70E-04
7/8/2009 9:00	363.1	7.39E-04	1.30E-05	1.32E-05	1.40E-04
7/8/2009 10:00	340.0	7.98E-04	1.60E-05	1.95E-05	1.44E-04
7/8/2009 11:00	345.8	7.39E-04	1.62E-05	1.25E-05	1.41E-04
7/8/2009 12:00	337.7	7.93E-04	1.61E-05	1.30E-05	1.39E-04
7/8/2009 13:00	355.3	8.03E-04	1.03E-05	3.92E-05	1.39E-04
7/8/2009 14:00	320.7	8.07E-04	1.45E-05	1.70E-05	1.69E-04
7/8/2009 15:00	355.5	7.51E-04	1.34E-05	1.18E-05	1.58E-04
7/8/2009 16:00	317.2	8.46E-04	1.54E-05	1.04E-05	1.71E-04
7/8/2009 17:00	331.4	7.58E-04	1.59E-05	1.01E-05	1.60E-04
7/8/2009 18:00	350.6	5.94E-04	1.51E-05	1.13E-05	1.48E-04
7/8/2009 19:00	340.6	6.71E-04	1.44E-05	4.13E-05	1.58E-04
7/8/2009 20:00	338.9	7.36E-04	1.44E-05	1.12E-05	1.67E-04
7/8/2009 21:00	345.0	7.67E-04	1.41E-05	1.27E-05	1.50E-04
7/8/2009 22:00	335.7	8.56E-04	1.51E-05	1.23E-05	1.37E-04
7/8/2009 23:00	334.6	8.70E-04	1.53E-05	1.36E-05	1.08E-04
7/9/2009 0:00	344.1	8.06E-04	1.52E-05	1.64E-05	7.15E-05
7/9/2009 1:00	336.1	8.93E-04	1.56E-05	1.87E-05	7.14E-05
7/9/2009 2:00	347.2	8.03E-04	1.56E-05	1.44E-05	7.72E-05
7/9/2009 3:00	346.8	7.54E-04	1.53E-05	4.19E-05	9.81E-05
7/9/2009 4:00	349.6	8.80E-04	1.12E-05	4.49E-05	1.31E-04
7/9/2009 5:00	344.7	8.05E-04	9.75E-06	1.11E-05	1.34E-04
7/9/2009 6:00	345.5	6.48E-04	6.80E-06	1.00E-05	1.79E-04
7/9/2009 7:00	345.4	5.83E-04	6.96E-06	1.01E-05	1.72E-04
7/9/2009 8:00	345.0	6.49E-04	1.93E-06	1.32E-05	1.36E-04
7/9/2009 9:00	345.9	6.39E-04	1.51E-06	1.57E-05	1.48E-04
7/9/2009 10:00	339.4	6.21E-04	9.84E-07	2.02E-05	1.41E-04
7/9/2009 11:00	348.4	5.01E-04	1.10E-06	1.08E-05	1.44E-04
7/9/2009 12:00	343.0	6.42E-04	1.16E-06	1.13E-05	1.54E-04
7/9/2009 13:00	348.2	6.39E-04	1.46E-06	1.05E-05	1.52E-04
7/9/2009 14:00	338.5	6.08E-04	7.98E-07	1.06E-05	1.31E-04

Table D.16b: CPR – Normalized plant emissions for RR burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/9/2009 15:00	346.4	6.12E-04	1.24E-06	1.62E-05	1.07E-04
7/9/2009 16:00	338.3	5.00E-04	2.55E-06	2.01E-05	1.10E-04
7/9/2009 17:00	343.0	5.03E-04	5.15E-06	1.17E-05	1.41E-04
7/9/2009 18:00	339.5	6.07E-04	6.19E-06	1.23E-05	1.52E-04
7/9/2009 19:00	340.9	5.46E-04	7.24E-06	1.45E-05	1.40E-04
7/9/2009 20:00	339.4	6.19E-04	9.20E-06	1.71E-05	1.45E-04
7/9/2009 21:00	340.0	6.97E-04	8.33E-06	2.13E-05	1.42E-04
7/9/2009 22:00	333.7	6.39E-04	7.85E-06	1.70E-05	1.37E-04
7/9/2009 23:00	347.0	6.06E-04	9.27E-06	1.80E-05	1.27E-04
7/10/2009 0:00	345.4	6.46E-04	8.78E-06	1.69E-05	1.24E-04
7/10/2009 1:00	352.6	7.52E-04	8.84E-06	1.71E-05	1.16E-04
7/10/2009 2:00	345.7	6.23E-04	7.23E-06	1.79E-05	1.16E-04
7/10/2009 3:00	361.9	5.81E-04	7.29E-06	1.64E-05	1.28E-04
7/10/2009 4:00	336.9	7.40E-04	8.50E-06	1.80E-05	1.40E-04
7/10/2009 5:00	343.1	6.78E-04	7.62E-06	1.99E-05	1.27E-04
7/10/2009 6:00	358.3	7.35E-04	6.55E-06	1.85E-05	1.16E-04
7/10/2009 7:00	342.7	7.40E-04	6.40E-06	1.74E-05	1.61E-04
7/10/2009 8:00	344.3	8.04E-04	1.21E-05	3.16E-05	1.76E-04
7/10/2009 9:00	350.5	7.82E-04	1.09E-05	1.55E-05	1.74E-04
7/10/2009 10:00	338.8	8.35E-04	4.26E-06	1.68E-05	1.92E-04
7/10/2009 11:00	349.0	6.26E-04	8.73E-06	1.45E-05	2.02E-04
7/10/2009 12:00	348.2	7.19E-04	9.30E-06	1.29E-05	2.09E-04
7/10/2009 13:00	349.8	7.25E-04	1.08E-05	1.29E-05	1.69E-04
7/10/2009 14:00	364.9	7.31E-04	9.32E-06	1.41E-05	1.42E-04
7/10/2009 15:00	298.1	8.75E-04	1.21E-05	1.56E-05	1.59E-04
7/10/2009 16:00	289.2	9.75E-04	9.76E-06	1.62E-05	1.53E-04
7/10/2009 17:00	363.5	6.58E-04	7.93E-06	2.41E-05	1.46E-04
7/10/2009 18:00	324.0	6.43E-04	9.16E-06	3.17E-05	1.70E-04
7/10/2009 19:00	331.7	5.47E-04	8.95E-06	3.96E-05	1.71E-04
7/10/2009 20:00	340.3	5.64E-04	1.02E-05	3.55E-05	1.67E-04
7/10/2009 21:00	347.2	5.75E-04	1.01E-05	1.93E-05	1.57E-04
7/10/2009 22:00	350.8	5.20E-04	9.57E-06	1.84E-05	1.46E-04
7/10/2009 23:00	346.3	6.64E-04	1.11E-05	1.77E-05	1.55E-04
7/11/2009 0:00	355.0	7.40E-04	2.10E-05	1.81E-05	1.64E-04
7/11/2009 1:00	351.5	7.97E-04	2.31E-05	2.00E-05	1.51E-04
7/11/2009 2:00	355.1	7.40E-04	2.19E-05	1.94E-05	1.45E-04
7/11/2009 3:00	346.6	7.57E-04	2.31E-05	1.92E-05	1.52E-04
7/11/2009 4:00	344.3	7.17E-04	2.26E-05	1.92E-05	1.59E-04
7/11/2009 5:00	345.1	0.00E+00	0.00E+00	1.86E-05	1.72E-04
7/11/2009 6:00	345.9	7.18E-04	2.34E-05	2.87E-05	1.61E-04
7/11/2009 7:00	331.6	8.13E-04	2.32E-05	3.11E-05	1.69E-04
7/11/2009 8:00:00	348.1	8.15E-04	1.72E-05	2.07E-05	1.61E-04

Table D.16c: CPR – Normalized plant emissions for RR burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/11/2009 9:00:00	335.8	7.95E-04	1.78E-05	1.88E-05	1.69E-04
7/11/2009 10:00:00	351.9	0.00E+00	0.00E+00	1.53E-05	1.70E-04
7/11/2009 11:00:00	353.8	6.87E-04	1.54E-05	2.22E-05	1.67E-04
7/11/2009 12:00:00	364.8	6.62E-04	1.59E-05	2.43E-05	1.71E-04
7/11/2009 13:00:00	360.1	6.80E-04	1.46E-05	2.81E-05	1.83E-04
7/11/2009 14:00:00	349.7	7.92E-04	1.55E-05	1.86E-05	1.83E-04
7/11/2009 15:00:00	351.5	8.00E-04	1.33E-05	1.67E-05	1.91E-04
7/11/2009 16:00:00	342.5	7.75E-04	1.47E-05	1.63E-05	1.87E-04
7/11/2009 17:00:00	350.7	0.00E+00	0.00E+00	1.37E-05	1.99E-04
7/11/2009 18:00:00	342.4	0.00E+00	0.00E+00	1.41E-05	1.62E-04
7/11/2009 19:00:00	346.3	7.17E-04	1.67E-05	4.98E-05	1.51E-04
7/11/2009 20:00:00	339.2	7.83E-04	1.82E-05	4.90E-05	1.44E-04
7/11/2009 21:00:00	330.5	7.97E-04	1.79E-05	2.01E-05	1.34E-04
7/11/2009 22:00:00	350.3	6.59E-04	1.78E-05	1.86E-05	1.33E-04
7/11/2009 23:00:00	342.1	7.26E-04	1.72E-05	1.92E-05	1.44E-04
7/12/2009 0:00:00	355.3	7.33E-04	1.46E-05	1.73E-05	1.56E-04
7/12/2009 1:00:00	350.9	6.95E-04	1.75E-05	1.73E-05	1.54E-04
7/12/2009 2:00:00	360.9	7.11E-04	1.68E-05	4.20E-05	1.60E-04
7/12/2009 3:00:00	351.0	7.47E-04	1.65E-05	2.97E-05	1.63E-04
7/12/2009 4:00:00	351.6	7.68E-04	1.67E-05	1.73E-05	1.70E-04
7/12/2009 5:00:00	355.5	6.58E-04	1.80E-05	1.75E-05	1.80E-04
7/12/2009 6:00:00	350.2	0.00E+00	0.00E+00	1.71E-05	1.87E-04
7/12/2009 7:00:00	362.8	6.81E-04	1.65E-05	4.70E-05	1.84E-04
7/12/2009 8:00:00	344.1	7.95E-04	2.56E-05	3.49E-05	1.89E-04

Appendix E

Raw Data for Liquid Glycerin Trial Burn (GL)

E.1 General Comments

- Raw data from the GL burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, petroleum coke, waste plastics, and liquid glycerin were the fuels utilized during this trial burn.
- This burn lasted from 8 AM on 11/4/2009 to 8 AM on 11/7/2009.

E.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NA – Not Applicable

ND – Not Detected

NR – Not Reported

^{1} As-Received

^{2} Dry Basis

^{3} Calculated by Auburn University

E.3 Chemical Composition of Kiln Feed

Table E.1: CPR – Chemical composition of kiln feed for GL burn

Parameter (wt. %)	**Sample Number**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Al_2O_3	3.21	3.32	3.34	3.09	3.19	3.23	3.15	3.15
CaO	42.7	43.0	42.5	42.4	42.5	42.3	42.8	42.8
Fe_2O_3	2.22	2.18	2.20	2.16	2.16	2.17	2.20	2.19
K_2O	0.310	0.330	0.310	0.290	0.300	0.294	0.280	0.280
MgO	2.74	2.70	2.64	2.81	2.60	2.51	2.41	2.39
Na_2O	0.050	0.050	0.070	0.050	0.050	0.073	0.050	0.050
Na_2O_{eq}	0.254	0.267	NR	0.241	0.247	NR	0.234	0.234
SiO_2	12.6	12.7	12.7	12.9	13.1	13.2	13.1	12.9
SO_3	0.150	0.210	0.140	0.170	0.180	0.129	0.150	0.150
Moisture	2.19	1.64	NR	1.83	1.78	NR	2.02	2.02
LOI	36.5	36.7	NR	36.4	36.2	NR	36.2	36.2

E.4 Chemical Composition of Cement Kiln Dust (CKD)

Table E.2: CPR – Chemical composition of CKD for GL burn

Parameter (wt. %)	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Al_2O_3	3.70	3.77	3.71	3.92	3.56	3.76	3.78
CaO	47.6	47.1	46.2	44.0	47.5	44.7	45.7
Fe_2O_3	1.86	1.88	1.96	2.16	1.85	2.10	1.98
K_2O	0.420	0.440	0.380	0.350	0.400	0.340	0.370
MgO	2.26	2.28	1.98	1.44	2.21	1.37	1.69
Na_2O	0.110	0.110	0.090	0.080	0.100	0.080	0.100
SiO_2	10.5	10.7	10.7	11.5	10.5	11.4	11.0
SO_3	0.950	0.980	0.610	0.080	1.03	0.080	0.470

Table E.3: ELR – Chemical composition of CKD for GL burn

Parameter (wt.%)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.72	3.75	3.70	3.77	3.63	3.57
CaO	49.8	50.3	46.8	43.3	45.6	43.7
Fe_2O_3	1.93	1.97	2.04	2.18	2.08	2.12
K_2O	0.421	0.564	0.412	0.332	0.354	0.328
MgO	2.42	2.51	2.09	1.44	1.75	1.34
Na_2O	0.047	0.346	0.107	0.046	0.056	0.039
P_2O_5	0.047	0.105	0.124	0.054	0.056	0.047
SiO_2	9.56	9.50	9.82	10.5	9.93	10.0
SO_3	0.943	1.38	0.643	0.108	0.402	0.086
TiO_2	0.195	0.226	0.214	0.224	0.217	0.218
Moisture	0.048	0.042	0.098	0.132	0.101	0.118
LOI	30.8	29.2	33.9	37.9	35.8	38.4
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	31.2	25.0	22.3	13.9	39.4	41.4
Cd	< 5	< 5	< 5	< 5	< 5	< 5
Cl	467	504	149	120	119	69.0
Co	12.5	15.3	13.2	13.1	15.3	15.6
Cr	30.4	< 5	< 5	31.6	35.4	29.6
Cu	49.1	152	234	98.8	122	47.6
Hg	0.103	0.10	0.314	0.146	0.114	0.104
Mo	3.90	5.64	1.65	< 1	< 1	< 1
Ni	14.8	18.5	14.8	16.2	12.9	9.36
Pb	7.01	50.8	42.9	54.0	< 4	< 4
Se	< 2	< 2	< 2	< 2	< 2	< 2
V	38.2	58.0	43.7	47.1	39.4	41.4
Zn	50.6	124	61.8	47.9	45.9	77.2

E.5 Chemical Composition of Fuels

Table E.4a: ELR – Proximate, ultimate, and combustion analysis of plastics for GL burn

Test	Parameter (wt.%)	Sample Number										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Proximate Analysis	**Ash**	8.11	2.19	4.69	6.94	8.04	6.13	19.7	9.88	6.70	5.12	6.50
	Fixed Carbon	9.20	7.42	13.6	10.5	12.2	10.3	12.5	11.3	9.30	11.1	11.2
	Moisture [1]	5.51	13.0	16.1	11.2	14.6	10.8	41.9	30.7	4.61	6.02	7.64
	Volatile Matter	82.7	90.4	81.7	82.6	79.8	83.6	67.8	78.8	84.0	83.8	82.3
Ultimate Analysis	**Carbon**	63.3	45.4	54.4	51.9	46.6	55.3	44.0	47.8	50.4	50.2	48.0
	Hydrogen	6.89	4.83	5.35	5.01	4.92	5.59	3.94	4.52	4.56	6.04	5.93
	Nitrogen	2.51	0.670	1.46	1.48	0.740	1.24	1.02	0.910	1.13	0.520	0.480
	Oxygen	19.0	46.7	34.0	34.5	39.6	31.5	31.3	36.7	37.0	37.84	38.9
	Sulfur	0.250	0.250	0.140	0.220	0.160	0.200	0.090	0.170	0.200	0.240	0.250
Heat Value [2] **(BTU/lb)**		8044	12262	9794	9178	9079	10042	7133	8957	10273	8677	8124

Table E.4b: ELR – Proximate, ultimate, and combustion analysis of plastics for GL burn

Test	Parameter (wt.%)	Sample Number											
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Proximate Analysis	**Ash**	7.12	8.48	8.57	7.58	29.2	23.48	4.24	8.50	18.5	7.75	7.75	5.36
	Fixed Carbon	12.9	9.64	15.6	9.72	10.6	12.0	11.4	12.8	11.0	11.8	11.8	10.8
	Moisture [1]	11.3	9.34	41.5	4.37	39.9	42.2	4.80	28.1	37.4	14.8	14.8	23.7
	Volatile Matter	80.0	81.9	75.9	82.7	60.1	64.5	84.4	78.7	70.5	80.4	80.4	83.8
Ultimate Analysis	**Carbon**	52.9	51.4	50.6	50.1	33.8	42.1	51.6	50.9	47.2	51.3	51.3	49.7
	Hydrogen	6.36	6.88	5.66	6.35	3.56	4.49	7.25	6.21	5.12	6.47	6.47	5.91
	Nitrogen	2.340	0.460	0.750	0.700	0.680	0.64	0.560	0.76	0.680	0.77	0.77	0.67
	Oxygen	31.2	32.6	34.4	35.1	32.7	29.20	35.9	33.5	28.4	33.2	33.2	38.0
	Sulfur	0.180	0.200	0.090	0.250	0.100	0.090	0.370	0.150	0.130	0.560	0.560	0.390
Heat Value [2] **(BTU/lb)**		9091	7439	8137	8587	5897	6551	7451	8553	7920	7665	7665	7785

Table E.5a: ELR – Standard parameters of plastics for GL burn

Test	**Parameter (wt.%)**	**Sample Number**							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Standard Parameters	**Al_2O_3**	16.4	15.0	27.3	20.3	51.3	27.3	10.8	20.2
	CaO	13.6	8.83	25.5	49.4	21.3	24.7	17.6	20.3
	Fe_2O_3	2.23	2.49	5.81	0.743	0.486	3.60	18.6	8.73
	K_2O	2.47	3.67	0.895	0.307	0.271	1.06	1.17	1.212
	MgO	1.87	1.96	5.30	2.09	1.82	3.06	3.56	3.35
	Na_2O	6.04	5.84	1.48	6.40	3.42	2.06	0.637	1.20
	P_2O_5	0.490	0.627	0.462	0.327	0.243	0.411	0.288	0.427
	SiO_2	35.4	37.1	28.2	18.1	18.5	33.3	44.3	39.4
	SO_3	1.19	1.34	1.07	0.773	0.486	1.40	1.28	2.09
	TiO_2	17.8	19.3	1.98	1.22	1.48	1.93	0.617	1.38
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
	As	< 4	< 4	17.9	7.93	9.35	29.8	15.4	26.8
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	324	202	315	223	130	142	318	268
	Co	332	677	243	71.4	16.8	111	77.1	120
	Cr	1018	2265	6415	146	65.4	479	960	1141
	Cu	1424	2384	350	1391	26.2	157	1701	1141
	Hg	0.694	0.756	0.699	0.740	0.734	0.676	0.010	0.008
	Mo	15.3	36.6	231	< 4	7.48	48.3	90.4	60.6
	Ni	168	253	2470	60.5	24.3	151	532	312
	Pb	280	411	12	21.8	10	121	220.94	171.8
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	328	1056	166	83.3	158	180	404	263
	Zn	356	4489	2873	493	1811	5671	1910	8486

Table E.5b: ELR – Standard parameters of plastics for GL burn

Test	**Parameter (wt.%)**	**Sample Number**							
		9	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Standard Parameters	**Al_2O_3**	24.1	19.7	20.8	29.3	27.3	6.09	17.7	7.50
	CaO	34.1	29.8	14.7	31.1	34.2	25.3	30.9	25.8
	Fe_2O_3	1.22	0.689	0.89	2.5	0.981	10.4	1.09	7.79
	K_2O	0.332	0.345	0.516	0.563	0.416	2.34	0.291	1.21
	MgO	2.52	6.29	5.61	4.02	1.88	5.40	5.28	2.65
	Na_2O	1.90	2.54	14.5	5.88	7.45	0.702	10.7	0.585
	P_2O_5	0.466	0.750	0.263	0.507	0.268	0.524	0.201	0.195
	SiO_2	31.4	35.6	34.8	22.3	23.7	46.8	28.5	52.1
	SO_3	0.954	1.20	3.00	1.20	1.79	0.722	2.22	0.896
	TiO_2	2.55	2.66	3.76	1.99	1.67	0.613	2.39	0.526
	Parameter (ppm)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
	As	< 4	< 4	< 4	< 4	10.9	29.7	< 4	40.9
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	241	129	143	281	119	200	250	689
	Co	72.6	27.4	68.8	65.7	29.7	160	46.2	50.7
	Cr	550	164	456	814	105	2300	163	1016
	Cu	362	752	1270	655	111	1174	610	725
	Hg	0.006	0.007	0.006	0.006	0.008	0.006	0.005	0.006
	Mo	29.0	4.05	9.10	44.1	11.9	58.3	19.1	31.2
	Ni	451	56.8	59.7	259	50.5	466	110	280
	Pb	126.5	439	102	165	64.4	120	57	107.2
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	188	174	229	164	126	180	154	147
	Zn	802	1247	5391	1406	1301	866	1895	1603

Table E.5c: ELR – Standard parameters of plastics for GL burn

Test	Parameter (wt.%)	Sample Number						
		17	**18**	**19**	**20**	**21**	**22**	**23**
Standard Parameters	**Al_2O_3**	7.31	14.0	9.93	18.9	10.0	10.5	14.2
	CaO	19.0	18.2	25.8	31.5	23.9	26.4	21.1
	Fe_2O_3	6.70	0.991	9.76	1.09	6.28	10.7	5.79
	K_2O	1.74	0.901	1.82	0.390	3.70	2.41	3.95
	MgO	5.07	11.8	6.13	6.41	7.39	5.45	7.99
	Na_2O	0.34	8.14	1.49	2.15	2.31	1.64	4.13
	P_2O_5	0.279	0.851	0.704	0.418	0.872	0.698	0.877
	SiO_2	56.3	40.3	38.5	35.4	40.6	38.2	35.9
	SO_3	0.444	2.99	2.27	1.09	1.94	1.18	2.57
	TiO_2	0.805	1.15	1.16	2.05	1.61	1.58	2.07
	Parameter (ppm)	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	As	16.5	< 4	27.3	< 4	23.1	< 4	310
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	197	264	281	286	621	1180	947
	Co	48.5	47.0	136	37.6	209	152	122
	Cr	1504	199	1884	266	3964	1848	902
	Cu	654	876	5308	1018	1005	878	1033
	Hg	0.003	0.005	0.006	0.004	0.004	0.005	0.004
	Mo	31.0	20.0	79.9	< 4	28.1	18.0	< 4
	Ni	208	69.0	291	53.0	313	192	138
	Pb	124	816.5	199	321	85.2	315.2	< 4
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	106	85.1	199	127	129	136	188
	Zn	11393	2559	7478	1846	3865	3276	4898

Table E.6a: ELR – Proximate, ultimate, and combustion analysis of liquid glycerin for GL burn

Test	Parameter (wt.%)	Sample Number										
		12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Proximate Analysis	**Ash**	0.430	6.01	7.70	7.31	8.20	5.17	6.53	0.030	0.250	1.31	10.6
	Fixed Carbon	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Moisture[1]	ND	12.5	13.0	14.5	10.5	15.5	14.5	ND	< 0.1	23.2	40.5
	Volatile Matter	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ultimate Analysis	**Carbon**	54.1	40.1	31.7	32.2	35.7	39.9	33.2	43.6	56.0	57.5	40.7
	Hydrogen	6.32	5.33	5.33	5.14	5.14	4.91	5.66	5.32	6.90	7.64	6.10
	Nitrogen	0.200	0.080	0.170	0.100	0.180	0.180	0.150	0.120	0.130	0.150	0.150
	Oxygen	39.0	47.9	53.9	53.9	49.6	49.4	54.0	50.0	36.1	32.9	41.5
	Sulfur	0.030	0.64	1.16	1.34	1.17	0.380	0.420	0.940	0.620	0.540	1.03
Heat Value[2] **(BTU/lb)**		16684	9606	9059	9675	9595	10500	9561	16257	16635	10870	6066

Table E.6b: ELR – Proximate, ultimate, and combustion analysis of liquid glycerin for GL burn

Test	Parameter (wt.%)	Sample Number										
		12	13	14	15	16	17	18	19	20	21	22
Proximate Analysis	**Ash**	0.430	6.01	7.70	7.31	8.20	5.17	6.53	0.030	0.250	1.31	10.6
	Fixed Carbon	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Moisture [1]	ND	12.5	13.0	14.5	10.5	15.5	14.5	ND	< 0.1	23.2	40.5
	Volatile Matter	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ultimate Analysis	**Carbon**	54.1	40.1	31.7	32.2	35.7	39.9	33.2	43.6	56.0	57.5	40.7
	Hydrogen	6.32	5.33	5.33	5.14	5.14	4.91	5.66	5.32	6.90	7.64	6.10
	Nitrogen	0.200	0.080	0.170	0.100	0.180	0.180	0.150	0.120	0.130	0.150	0.150
	Oxygen	39.0	47.9	53.9	53.9	49.6	49.4	54.0	50.0	36.1	32.9	41.5
	Sulfur	0.030	0.64	1.16	1.34	1.17	0.380	0.420	0.940	0.620	0.540	1.03
Heat Value [2] **(BTU/lb)**		16684	9606	9059	9675	9595	10500	9561	16257	16635	10870	6066

Table E.7a: ELR – Standard parameters of forest trimmings for GL burn

Parameter (wt.%)	**Sample Number**										
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Al_2O_3	ND	ND	ND	ND	0.686	0.113	0.084	ND	0.233	0.182	ND
CaO	0.077	0.233	0.092	0.235	0.604	0.473	0.591	0.185	0.385	0.344	0.375
Fe_2O_3	2.61	2.53	2.44	1.81	1.72	1.55	1.58	1.31	1.32	1.53	1.26
K_2O	0.571	0.599	0.595	0.439	1.00	0.648	0.855	0.732	0.639	0.738	0.628
MgO	0.223	0.244	0.236	0.214	0.236	0.216	0.201	0.247	0.274	0.233	0.223
Na_2O	39.0	41.7	41.9	42.2	41.2	42.0	43.9	42.8	41.8	41.7	42.1
P_2O_5	2.52	2.43	2.38	1.92	3.47	2.99	3.06	4.34	3.61	3.97	3.58
SiO_2	ND	ND	ND	0.010	1.49	0.309	0.275	0.093	0.811	0.698	0.091
SO_3	54.9	52.1	52.2	53.0	49.5	51.5	49.3	50.2	50.8	50.5	51.6
TiO_2	ND	ND	ND	ND	0.020	0.010	0.011	0.010	0.020	0.020	0.010
Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
As	8.71	< 4	12.3	15.3	< 4	< 4	< 4	78.3	< 4	6.07	56.7
Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
Cl	20.0	20.0	20.0	880	4160	3830	3860	840	1870	2240	2380
Co	22.3	24.4	32.8	23.5	25.6	22.6	19.0	24.7	22.3	19.2	23.3
Cr	48.4	76.1	51.3	119	109	120	87.6	40.2	91.2	162	194
Cu	97.7	154	122	129	129	138	71.8	115	288	202	162
Hg	0.008	0.002	0.003	0.005	0.009	0.011	< 0.01	0.009	0.012	0.013	0.011
Mo	178	199	209	142	153	121	133	112	96.3	137	131
Ni	216	214	216	143	144	142	116	78.3	73.0	99.1	87.1
Pb	6.77	155	6.15	< 4	27.6	24.7	124	< 4	197	< 4	< 4
Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
V	< 4	< 4	< 4	< 4	< 4	6.17	6.33	< 4	7.09	5.05	< 4
Zn	110	113	83.0	92.9	100	111	97.1	133	119	136	114

Table E.7b: ELR – Standard parameters of forest trimmings for GL burn

Parameter (wt.%)	**Sample Number**										
	12	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Al_2O_3	0.857	0.086	ND	ND	ND	ND	0.226	0.969	1.092	0.118	ND
CaO	0.983	1.22	0.510	0.409	0.328	1.78	1.31	1.25	0.556	0.922	0.929
Fe_2O_3	3.61	0.665	1.32	1.19	0.932	0.534	0.939	10.37	11.34	1.80	0.802
K_2O	0.584	1.12	0.704	0.664	0.451	0.982	0.985	8.18	1.88	0.567	0.633
MgO	0.351	0.204	0.225	0.215	0.174	0.158	0.192	1.20	0.644	0.225	0.211
Na_2O	42.6	45.3	42.1	42.4	42.7	51.2	46.2	14.2	16.2	42.1	43.6
P_2O_5	7.66	4.77	3.77	3.87	2.74	7.21	5.17	51.5	60.8	3.82	3.08
SiO_2	4.31	0.590	ND	ND	ND	0.146	4.63	1.51	0.732	2.60	0.074
SO_3	34.0	45.9	51.3	51.2	52.4	37.8	39.8	0.480	0.195	47.6	50.5
TiO_2	0.088	0.054	0.020	0.010	ND	0.012	0.034	ND	ND	0.024	0.011
Parameter (ppm)	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
As	55.5	36.5	< 4	< 4	40.0	< 4	72.4	108	< 4	< 4	< 4
Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
Cl	20.0	5840	1930	2340	2010	7320	5860	3240	3640	2250	5430
Co	< 4	22.5	23.5	22.5	20.5	18.2	24.9	705	< 4	26.0	19.0
Cr	1407	105	161	148	184	143	144	21634	15534	630	171
Cu	261	272	171	149	1069	300	2540	712	404	290	272
Hg	0.029	0.014	0.004	0.001	0.011	0.009	0.003	0.007	0.007	0.170	0.006
Mo	< 4	96.5	147	140	113	108	96.2	624	444	208	74.9
Ni	217	52.6	86.7	83.8	57.4	50.9	66.8	348	260	40.2	36.9
Pb	416	< 4	186	186	< 4	133	< 4	597	< 4	914	42.2
Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
V	134	10.73	10.21	5.11	7.17	7.28	9.05	342	441	23.64	< 4
Zn	153	120	154	129	110	138	115	1110	203	147	195

E.6 Chemical Composition of Clinker

Table E.8a: CPR – Chemical composition of clinker for GL burn

Parameter (wt.%)	**Sample Number**								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Al_2O_3	5.09	5.17	5.23	5.27	5.21	5.18	5.09	5.13	5.33
CaO	63.8	64.7	64.8	64.2	64.5	64.8	65.0	65.0	64.9
Fe_2O_3	3.46	3.50	3.51	3.52	3.52	3.47	3.42	3.44	3.42
K_2O	0.500	0.530	0.550	0.590	0.530	0.500	0.490	0.500	0.570
MgO	4.17	4.18	4.26	4.11	4.16	4.20	4.18	4.11	3.99
Na_2O	0.150	0.150	0.160	0.180	0.190	0.170	0.140	0.150	0.160
Na_2O_{eq}	0.479	0.499	0.522	0.568	0.539	0.499	0.462	0.479	0.535
SiO_2	20.5	20.7	20.6	20.5	20.6	20.6	20.6	20.5	20.2
SO_3	0.860	0.870	0.830	1.02	1.03	0.970	0.800	0.890	1.22
Free CaO	0.980	NR	1.59	1.50	0.720	0.880	0.980	0.750	1.14
C_3S	65.0	66.6	67.0	64.7	66.0	67.3	69.2	69.5	70.0
C_2S	9.66	9.00	8.54	10.1	9.31	8.44	6.85	6.33	5.14
C_3A	7.63	7.78	7.92	8.01	7.85	7.86	7.70	7.77	8.34
C_4AF	10.5	10.7	10.7	10.7	10.7	10.6	10.4	10.5	10.4

Table E.8b: CPR – Chemical composition of clinker for GL burn

Parameter (wt.%)	**Sample Number**								
	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
Al_2O_3	5.18	5.20	5.20	5.11	5.01	5.09	5.29	5.18	5.08
CaO	65.2	64.5	64.5	64.8	64.7	64.9	64.2	64.7	64.7
Fe_2O_3	3.37	3.49	3.46	3.44	3.39	3.45	3.46	3.42	3.37
K_2O	0.550	0.530	0.540	0.560	0.520	0.482	0.570	0.492	0.550
MgO	4.07	4.12	4.25	4.17	4.19	4.09	3.98	3.95	3.86
Na_2O	0.180	0.160	0.170	0.160	0.140	0.141	0.130	0.170	0.150
Na_2O_{eq}	0.542	0.509	0.525	0.528	0.482	0.458	0.505	0.494	0.512
SiO_2	20.4	20.4	20.5	20.6	20.6	21.0	20.8	21.0	20.9
SO_3	1.06	1.04	1.17	1.16	1.47	0.860	1.10	0.930	0.910
Free CaO	1.07	1.07	1.37	1.46	1.24	0.850	1.63	0.390	0.980
C_3S	71.0	67.2	66.5	68.5	68.3	65.6	62.7	64.0	65.7
C_2S	4.89	7.89	8.72	7.24	7.49	10.5	12.3	12.0	10.3
C_3A	8.02	7.87	7.93	7.72	7.54	7.65	8.16	7.94	7.76
C_4AF	10.3	10.6	10.5	10.5	10.3	10.5	10.5	10.4	10.3

Table E.8c: CPR – Chemical composition of clinker for GL burn

Parameter (wt.%)	Sample Number								
	19	20	21	22	23	24	25	26	27
Al_2O_3	5.12	5.13	4.96	5.21	5.10	5.07	4.99	5.20	5.28
CaO	64.8	65.3	64.9	64.7	64.9	64.8	65.0	64.7	64.7
Fe_2O_3	3.43	3.51	3.40	3.42	3.45	3.38	3.34	3.51	3.55
K_2O	0.620	0.384	0.492	0.610	0.489	0.493	0.480	0.493	0.452
MgO	3.71	3.89	3.80	3.73	3.77	3.78	3.65	3.71	3.73
Na_2O	0.150	0.155	0.167	0.140	0.109	0.107	0.100	0.100	0.092
Na_2O_{eq}	0.558	0.408	0.491	0.541	0.431	0.431	0.416	0.424	0.389
SiO_2	20.8	21.0	21.0	20.8	20.9	21.1	21.1	21.1	21.1
SO_3	1.13	0.470	0.770	1.47	0.870	0.960	0.890	0.770	0.480
Free CaO	1.95	0.420	0.590	1.46	1.07	0.680	0.850	0.810	1.37
C_3S	66.2	66.3	66.5	65.6	66.2	64.8	65.6	63.0	62.9
C_2S	9.68	10.3	10.1	10.1	9.96	11.5	11.1	13.1	13.0
C_3A	7.76	7.67	7.38	8.02	7.68	7.72	7.57	7.85	8.00
C_4AF	10.4	10.7	10.3	10.4	10.5	10.3	10.2	10.7	10.8

Table E.9: ELR – Chemical composition of clinker for GL burn

Parameter (wt.%)	Sample Number			
	1	2	3	4
Al_2O_3	5.14	5.13	5.17	5.15
CaO	64.5	64.7	64.2	64.8
Fe_2O_3	3.38	3.33	3.37	3.39
K_2O	0.498	0.478	0.548	0.451
MgO	4.59	4.50	4.13	3.90
Na_2O	0.117	0.088	0.098	0.088
P_2O_5	0.068	0.068	0.078	0.069
SiO_2	20.2	20.3	20.7	20.8
SO_3	1.00	0.975	1.10	0.902
TiO_2	0.263	0.254	0.274	0.274
Moisture	0.000	0.006	0.000	0.000
LOI	0.073	0.052	0.152	0.088
Parameter (ppm)	**1**	**2**	**3**	**4**
As	26.3	30.2	27.4	12.7
Cd	< 5	< 5	< 5	< 5
Cl	109	66.0	298	129
Co	19.5	13.7	18.6	19.6
Cr	45.9	21.5	34.3	47.1
Cu	43.9	97.5	72.4	41.2
Hg	0.02	0.03	0.06	0.02
Mo	4.88	8.78	< 1	2.94
Ni	22.4	27.3	26.4	17.6
Pb	26.3	15.6	56.8	78.4
Se	< 2	< 2	< 2	< 2
V	89.8	92.7	92.0	95.1
Zn	66.3	47.8	53.8	50.0

Table E.10: SLR – Rietveld analysis of clinker for GL burn

Parameter (wt.%)	Sample Number			
	1	2	3	4
C_3S	66.5	67.9	64.5	63.9
C_2S	13.5	12.3	16.8	17.1
C_3A	4.07	3.87	3.64	3.73
C_4AF	10.4	10.3	10.2	10.8

E.7 Chemical Composition of Cement

Table E.11: CPR – Chemical composition of cement for GL burn

Parameter (wt.%)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	4.76	4.83	4.83	4.69	4.65	4.68
CaO	63.2	63.2	63.0	62.8	62.9	62.9
CO	1.30	1.30	1.30	1.30	1.30	1.30
Fe_2O_3	3.18	3.23	3.36	3.28	3.27	3.27
K_2O	0.480	0.480	0.428	0.467	0.480	0.430
MgO	3.65	3.695	3.638	3.687	3.71	3.56
Na_2O	0.130	0.123	0.138	0.130	0.140	0.110
Na_2O_{eq}	0.446	0.439	0.420	0.437	0.456	0.393
SiO_2	19.0	19.1	19.9	19.2	19.1	19.3
SO_3	3.41	3.14	3.01	3.08	3.34	3.41
Free CaO	1.46	NR	0.780	0.980	NR	0.910
LOI	1.97	1.87	0.94	2.24	2.46	1.98
C_3S	59.8	58.9	52.6	57.7	58.5	56.7
C_2S	9.41	10.5	17.4	11.6	10.7	12.6
C_3A	7.24	7.34	7.11	6.89	6.80	6.88
C_4AF	9.68	9.84	10.22	9.98	9.95	9.95
Blaine SSA (m^2/kg)	379	381	385	388	389	385

Table E.12: ELR – Chemical composition of cement for GL burn

Parameter (wt.%)	Sample Number		
	1	2	3
Al_2O_3	4.96	4.87	4.64
CaO	63.8	63.2	63.7
Fe_2O_3	3.21	3.25	3.18
K_2O	0.423	0.450	0.469
MgO	4.27	4.28	4.28
Na_2O	0.098	0.077	0.110
P_2O_5	0.059	0.057	0.060
SiO_2	18.4	18.9	17.9
SO_3	2.84	3.08	3.05
TiO_2	0.236	0.258	0.230
Moisture	0.356	0.303	0.411
LOI	1.61	1.43	2.29
C_3S	67.0	61.0	72.1
C_2S	2.17	8.12	-3.15
C_3A	7.71	7.42	6.91
C_4AF	9.76	9.88	9.69
TOC	0.080	0.040	0.020
Parameter (ppm)	**1**	**2**	**3**
As	27.5	23.0	23.0
Cd	< 5	< 5	< 5
Cl	84.0	120.0	169.0
Co	10.8	16.3	18.0
Cr	58.0	44.0	54.9
Cu	117	171	49.9
Hg	ND	< 0.001	< 0.001
Mo	1.97	8.62	3.99
Ni	21.6	23.9	21.0
Pb	14.8	24.9	12.0
Se	< 2	< 2	< 2
V	85.6	79.5	79.8
Zn	54.1	50.7	50.9

Table E.13: SLR – Rietveld analysis of cement for GL burn

Parameter (wt.%)	Sample Number		
	1	2	3
C_3S	63.0	61.4	58.1
C_2S	11.1	13.5	15.5
C_3A	4.40	4.05	4.33
C_4AF	10.4	10.4	10.1

E.8 Plant Emissions

Table E.14a: CPR – Normalized plant emissions for GL burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
11/4/2009 8:00	189.9	1.08E-03	2.28E-06	2.83E-05	4.88E-04
11/4/2009 9:00	199.0	9.86E-04	1.01E-06	2.24E-05	5.28E-04
11/4/2009 10:00	200.5	1.03E-03	1.87E-06	2.55E-05	5.39E-04
11/4/2009 11:00	203.0	9.31E-04	1.27E-06	1.75E-05	4.85E-04
11/4/2009 12:00	194.1	9.54E-04	7.78E-07	1.57E-05	4.55E-04
11/4/2009 13:00	194.8	1.05E-03	1.31E-06	1.96E-05	4.18E-04
11/4/2009 14:00	204.7	9.90E-04	2.01E-06	2.03E-05	4.13E-04
11/4/2009 15:00	179.5	1.71E-03	2.09E-06	1.86E-05	4.04E-04
11/4/2009 16:00	199.6	1.32E-03	1.32E-06	1.75E-05	3.55E-04
11/4/2009 17:00	197.8	1.25E-03	9.76E-07	1.79E-05	3.67E-04
11/4/2009 18:00	195.6	8.66E-04	1.34E-06	1.66E-05	3.84E-04
11/4/2009 19:00	207.6	9.48E-04	9.54E-07	1.84E-05	3.28E-04
11/4/2009 20:00	196.1	1.04E-03	2.94E-06	2.19E-05	3.87E-04
11/4/2009 21:00	207.7	8.29E-04	6.34E-06	2.50E-05	3.81E-04
11/4/2009 22:00	215.8	8.74E-04	6.95E-06	2.47E-05	4.12E-04
11/4/2009 23:00	187.6	1.18E-03	4.15E-06	2.63E-05	4.26E-04
11/5/2009 0:00	210.5	9.13E-04	2.76E-06	2.68E-05	3.56E-04
11/5/2009 1:00	191.8	1.07E-03	3.02E-06	3.35E-05	3.96E-04
11/5/2009 2:00	206.0	1.13E-03	3.00E-06	3.08E-05	3.94E-04
11/5/2009 3:00	202.9	1.06E-03	2.28E-06	3.06E-05	4.41E-04
11/5/2009 4:00	198.3	1.08E-03	2.82E-06	3.18E-05	4.93E-04
11/5/2009 5:00	195.6	1.24E-03	3.21E-06	3.39E-05	4.39E-04
11/5/2009 6:00	196.5	1.00E-03	2.80E-06	3.40E-05	4.58E-04
11/5/2009 7:00	205.3	9.56E-04	4.34E-06	2.67E-05	4.37E-04
11/5/2009 8:00	199.7	8.48E-04	2.95E-06	3.15E-05	4.25E-04
11/5/2009 9:00	195.4	9.43E-04	2.91E-06	3.21E-05	4.54E-04
11/5/2009 10:00	198.8	1.02E-03	3.49E-06	2.91E-05	4.43E-04
11/5/2009 11:00	201.4	9.61E-04	2.90E-06	3.04E-05	4.38E-04
11/5/2009 12:00	187.7	1.16E-03	4.39E-06	3.27E-05	4.21E-04
11/5/2009 13:00	194.9	1.12E-03	2.36E-06	3.04E-05	4.06E-04
11/5/2009 14:00	201.2	1.58E-03	4.48E-06	2.64E-05	4.23E-04

Table E.14b: CPR – Normalized plant emissions for GL burn

Date/Time	Clinker Produced (tons/hr)	NO_x (tons/ton clinker)	SO_2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
11/5/2009 15:00	204.6	1.29E-03	3.15E-06	2.53E-05	4.16E-04
11/5/2009 16:00	207.4	9.94E-04	4.17E-06	2.41E-05	4.56E-04
11/5/2009 17:00	190.3	9.98E-04	4.24E-06	2.76E-05	4.89E-04
11/5/2009 18:00	192.8	1.23E-03	3.75E-06	2.70E-05	4.63E-04
11/5/2009 19:00	202.8	1.27E-03	4.03E-06	2.87E-05	3.87E-04
11/5/2009 20:00	201.7	1.10E-03	2.73E-06	2.82E-05	3.91E-04
11/5/2009 21:00	197.0	8.64E-04	2.41E-06	3.06E-05	4.10E-04
11/5/2009 22:00	198.0	1.01E-03	2.88E-06	3.07E-05	4.37E-04
11/5/2009 23:00	200.3	1.24E-03	4.49E-06	3.05E-05	4.51E-04
11/6/2009 0:00	194.8	1.42E-03	3.67E-06	2.84E-05	4.96E-04
11/6/2009 1:00	202.0	1.31E-03	3.31E-06	3.02E-05	5.09E-04
11/6/2009 2:00	199.5	1.03E-03	1.55E-06	3.11E-05	4.57E-04
11/6/2009 3:00	199.6	9.81E-04	2.54E-06	3.64E-05	4.05E-04
11/6/2009 4:00	189.0	1.19E-03	1.94E-06	3.59E-05	4.38E-04
11/6/2009 5:00	194.2	7.82E-04	1.70E-06	3.53E-05	4.31E-04
11/6/2009 6:00	198.2	9.12E-04	1.73E-06	3.50E-05	4.10E-04
11/6/2009 7:00	194.8	6.03E-04	7.29E-07	3.71E-05	4.02E-04
11/6/2009 8:00	202.5	6.27E-04	6.32E-07	3.40E-05	4.65E-04
11/6/2009 9:00	195.3	5.36E-04	1.61E-06	3.77E-05	5.77E-04
11/6/2009 10:00	185.8	6.48E-04	1.43E-06	3.21E-05	4.94E-04
11/6/2009 11:00	184.5	5.70E-04	2.04E-06	3.29E-05	6.42E-04
11/6/2009 12:00	193.8	6.72E-04	3.33E-06	2.60E-05	4.93E-04
11/6/2009 13:00	202.5	7.18E-04	4.40E-06	2.15E-05	4.72E-04
11/6/2009 14:00	176.0	8.06E-04	4.65E-06	2.43E-05	5.82E-04
11/6/2009 15:00	214.0	5.41E-04	3.63E-06	2.15E-05	4.16E-04
11/6/2009 16:00	205.9	5.45E-04	4.72E-06	2.22E-05	4.51E-04
11/6/2009 17:00	198.4	6.93E-04	6.10E-06	2.37E-05	4.52E-04
11/6/2009 18:00	201.1	7.49E-04	3.25E-06	2.55E-05	4.03E-04
11/6/2009 19:00	197.4	7.67E-04	1.46E-06	2.43E-05	4.08E-04
11/6/2009 20:00	188.3	8.24E-04	1.27E-06	2.83E-05	4.36E-04
11/6/2009 21:00	189.4	7.37E-04	1.33E-06	2.50E-05	4.31E-04
11/6/2009 22:00	190.6	7.87E-04	1.25E-06	2.62E-05	3.94E-04
11/6/2009 23:00	198.3	8.22E-04	1.63E-06	2.61E-05	3.89E-04
11/7/2009 0:00	201.6	9.45E-04	1.32E-06	2.83E-05	4.11E-04
11/7/2009 1:00	206.3	8.32E-04	1.37E-06	2.82E-05	4.07E-04
11/7/2009 2:00	197.6	7.92E-04	7.04E-07	2.93E-05	4.39E-04
11/7/2009 3:00	204.7	6.94E-04	1.22E-06	2.97E-05	4.28E-04
11/7/2009 4:00	195.8	9.25E-04	1.10E-06	2.65E-05	5.20E-04
11/7/2009 5:00	193.4	1.07E-03	1.09E-06	2.62E-05	4.59E-04
11/7/2009 6:00	200.8	9.67E-04	1.89E-06	2.90E-05	4.15E-04
11/7/2009 7:00	198.6	8.87E-04	1.19E-06	3.01E-05	4.73E-04
11/7/2009 8:00	186.6	1.28E-03	2.73E-07	3.17E-05	5.18E-04