The Feasibility of Using Alternative Fuels to Produce Portland Cement

by

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Abstract

The production of cement involves a combination of numerous raw materials, strictly monitored system processes, and temperatures on the order of 1500 °C. Immense quantities of fuel are required for the production of cement. Traditionally, energy from fossil fuels was solely relied upon for the production of cement. Over the past few decades, concerns of sustainability and environmental impact from the utilization of fossil fuels have influenced the research of and implementation of alternative fuel sources.

In this study, construction and demolition waste, woodchips, and soybean seeds were used as alternative fuels at a full-scale cement production facility. These fuels were co-fired with coal and waste plastics. The alternative fuels used in this trial accounted for 5 to 16 % of the total energy consumed during the pyroprocess. The construction and demolition waste and the woodchips possessed roughly half the energy value of the coal. The soybean seeds, however, were within 20 % of the coal's heating value.

Throughout each alternative fuel trial, samples of all process inputs and outputs were collected. Emissions were also monitored using a continuous emission monitoring system (CEMS). The monitored emissions included NO_x, SO_2, VOC, and CO. The alternative fuels used in this study were found to have minimal impact on the overall emission levels. Chemical analyses of all materials in each trial burn were conducted and the performance of each trial burn's cement was thoroughly tested.

Statistical analysis was performed on each trial burn’s clinker to compare the trial mean to the baseline mean. The majority of the trial burn’s clinker parameters had means that were significantly different from the baseline’s mean. These differences could be attributed to changes in the conditions at the cement plant between burns. The statistical differences found, however, did not translate into substantial differences in the cement performance.

The construction and demolition waste trial burn had the greatest similarities to the baseline cement’s physical properties. The other trial burns also produced cement that had comparable mortar strengths compared to baseline results. The concrete produced from the variable feed and soybean seed trial burns’ cement possessed varying strengths compared to the baseline. The concrete strengths, however, were thought to be influenced by the chemical admixtures used in the mixture and therefore did not accurately represent characteristics of the trial cement.

The cement plant successfully utilized the alternative fuels in this study. Production rates and cement quality were not compromised by the use of alternative fuels. Given the local availability of the fuel sources and compatibility with a cement facility’s operations, construction and demolition waste, woodchips, and soybeans are viable alternative fuel options for portland cement production.

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Research Introduction

1.1 Project Background

The production of cement involves a combination of numerous raw materials, complex facilities, and strictly monitored system processes. Portland cement is the primary ingredient in concrete, which is used worldwide, as a construction material in order to form buildings, roads, dams, and virtually any super- or substructure used by mankind. During the manufacture of cement, immense quantities of fuels are used in order to reach temperatures necessary to produce cement that bears the ideal chemical composition. Traditionally, fossil fuels have been solely relied upon for the production of cement. Over the past few decades, concerns of sustainability and environmental impact from fossil fuels have influenced the research of and utilization of alternative fuel sources.

Portland cement is produced from several raw material mined from the earth. When mixed in the proper proportions, and exposed to gas temperatures in excess of 1800 °C, the raw materials fuse together to form a product known as clinker (Uliasz-Bocheńczyk 2003). The clinker is then ground with an addition of sulfate to a specific fineness to produce a product known as portland cement. A full-scale cement manufacturing facility is shown in Figure 1.1.

In order to produce high kiln temperatures, fossil fuels such as coal, petroleum coke, and natural gas are regularly used. It is not uncommon for a modern cement plant to use 1200 tons of coal every day (Manias 2004). With the rising cost of energy, it is ease to see why fuel costs comprise around 40 percent of a manufacturer's budget and the incentive to seek less costly fuels (Jackson 1998).

Figure 1.1: Full-scale portland cement production facility (Folta 2010)

Around the 1970's, alternative fuels began to be used by the cement industry (Karstensen 2004). Modern facilities typically use alternative fuels to partially replace fossil fuels at rates around 20% (PCA 2009). Alternative fuels are typically waste products from other industries that are destined to be land-filled or incinerated. Examples that have successfully been used in cement manufacture include used oils, municipal solid wastes, tires, solvents, plastic, and biomass (Greco et al. 2004). Not only can waste fuels provide significant savings to a manufacturer, if properly utilized alternative fuels can benefit the community and environment (Mokrzycki and Uliasz-Bocheńczyk 2003).

It is, however, necessary to test and thoroughly understand all the attributes of the alternative fuel and its effects on the final product and manufacturing process.

As a means to reduce congestion in landfills, waste incineration has been used for a number of years. Waste incinerators also use fossil fuels in order to destroy the landfill material, but emit more harmful pollutants than cement plants because of lower temperatures and residence times. There is also no final product, like cement, produced from waste incineration.

Regardless of the whether the fuel is a natural resource or a second life for a waste product, the chemical makeup of the fuel and its interaction with the chemical components of the raw materials determine the final chemical composition of the clinker. Also, the majority of the noncombustible components of the fuel and raw material are incorporated in the clinker. Therefore, the use of alternative fuels could alter the chemical composition of cement and thus negatively affect the properties of the cement and concrete. During this study, the chemical composition of each fuel, raw material, and process output were determined. In addition, an extensive battery of fresh and hardened concrete property tests were performed in an attempt to determine if any change in the cement could be directly linked to the use of alternative fuels. If detrimental effects are found within a particular cement, any advantage gained from the utilization of the alternative fuel is lost.

Emissions such as nitrogen oxides, sulfur dioxide, and volatile organic compounds from the firing of raw material and the combustion of fuel can be a significant health risk. Allowable emissions limits set by environmental agencies were continuously monitored throughout each burn. Preliminary testing of alternative fuels provides information about the chemical properties and expected emissions.

Over the years, the utilization of alternative fuels has proven to be both beneficial to the cement facility and the environment. It is, however, imperative to fully understand the effects of each new fuel. This study considers three fuels, one of which utilized three different replacement rates. The remaining sections of this chapter will introduce each fuel as well as the processes taken to evaluate their use in the industry.

1.2 Statement of Objectives

The three fuels investigated during this study were construction and demolition waste, woodchips, and soybeans. The woodchips trial implemented a progressively increasing substitution rate. Each fuel was evaluated separately to assess its viability as a fuel for the production of portland cement. The following assessments were used in order to measure the viability of an alternative fuel:

1. the ability of the cement plant to maintain productive operations,
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.

Collaborative efforts between three parties were required to fulfill these objectives. The parties involved included a full-scale cement production facility, and external chemical laboratory, and Auburn University.

The first objective was responsibility of the cement plant personnel. Fuels that produce problems in the manufacturing process cannot be considered as viable replacement options.

The performance of the cement is directly related to its chemical composition and therefore, the chemical components of the cement and clinker needed were determined. Using two laboratories satisfied the second objective as well as provided confidence in accuracy of the data received.

The third and fourth objectives of this study were the primary objectives in this study. The cement plant conducted tests on mortar specimens made from the produced cement. Auburn University conducted testing on mortar, paste, and concrete specimens. The results of these tests were compared to results of similar specimens prepared by each entity from cement produced by only traditional fuels.

The final objective was to monitor emissions released by the cement plant during each trial. The emissions data collection was performed by the cement plant using a continuous emission monitoring system (CEMS). Results from each trial were compared to emissions data collected during a burn that utilized traditional fuels.

1.3 Research Plan

Alternative fuels included in this study are construction and demolition waste, woodchips, and soybeans. Each of these fuels was utilized in order to partially replace and therefore lessen the demand for traditional fuels. Each trial fuel was co-fired with traditional fuels. Lafarge North America’s Roberta cement plant, a full-scale cement plant located in Calera, Alabama, produced the cement during each trial. Each trial or burn, as it will be referred from this point forward, was continuous for between 3 and 6 days. A thorough sampling plan was implemented during each of the burns to carry out the objectives listed above. Although each burn utilized a unique fuel, the plant made an effort to maintain consistent conditions in all other aspects of operation.

The first burn conducted, which will be know as the baseline burn, utilized coal and plastics. All the alternative fuel burns are compared to this baseline burn. Although plastics are generally considered alternative fuels, in this study the plastic blend is considered a traditional fuel because it is routinely used by this cement plant. The baseline burn was performed in June of 2010 and lasted 3 days.

The first alternative fuel burn utilized coal, plastics, and construction and demolition waste. The construction and demolition waste consisted of wood paper and plastics. The types of wood utilized include dimensional lumber, plywood, and pallets. The paper included corrugated boxes and miscellaneous paper materials. The plastic consisted of solid and cellular foam and polyethylene film. This burn lasted for 80 hours and also occurred in June of 2010. The first two burns were closely spaced in order to maintain similar plant conditions.

The second alternative fuel burn utilized coal, plastics, and woodchips. This burn was conducted over a 6-day period in July of 2010. This burn was unique to this phase of the project due to the progressively increasing substitution rate of woodchips. This trial burn was broken into three phases. The initial substitution rate of woodchips was 5 percent and every two days thereafter the substitution rate increased by 5 percent. Therefore the average substitution rates for the burn were 5, 10, and 15 percent.

The third and final burn utilized coal, plastics, and soybeans. The soybeans were treated with herbicide. This burn was conducted over a 3-day period in October of 2010.

During each of the burns, samples were collected according to the sampling plan. These samples were transported to Auburn University for further conditioning and testing. The cement plant tested all materials to determine chemical composition except for the fuels used. The cement plant also tested various properties of the final cement to ensure adequate properties were being obtained during production. The final responsibility of the cement plant was to monitor emissions produced during each burn.

Specimens were prepared at Auburn University from each of the samples transported from the cement plant. The specimens were then shipped to the external chemical laboratory for further testing. The external laboratory determined the chemical compositions of each specimen and they conducted proximate, ultimate, and combustion analyses on each fuel.

Auburn University was responsible for the transportation, preparation, and shipment of all specimens. Auburn University also conducted testing on mortar, paste, and concrete to determine the behavior of the cement. Results from each party were collected and analyzed by Auburn University in order to determine the effect of using alternative fuels on portland cement.

1.4 Document Organization

This document is organized into five chapters, followed by a set of appendices. This chapter provides background information on the benefits and possible problems that could arise from the utilization of alternative fuels in the production of portland cement. This chapter also outlines the experimental alternative fuels and presents an outline of project objectives.

The second chapter of this document details previous research and literature that pertain to many facets of this project. Chapter 2 provides a detailed description of the production process for a general cement plant. The potential benefits and concerns for the utilization of portland cement are then discussed. An overview of the alternative fuels used in this study is then provided along with any available previous research. The chemistry revolving around cement manufacture will be discussed along with how it affects the performance of cement. Finally, the hydration process of portland cement will be discussed and how chemical admixtures are used to alter the hydration process.

Chapter three details the experimental plan used throughout this project. The methods used to sample the materials from the cement plant are discussed as well as how these samples were prepared for testing. The testing procedures used by all parties are also discussed in this chapter.

A presentation and summary of all results collected through this study are presented in chapter four. Following the study objectives presented in Chapter one, the data are first presented and then analyzed and discussed. As necessary, results from previous studies presented in Chapter two will be referred as needed. Conclusions are drawn from the presented data, and the performance of each alternative fuel is assessed.

The final chapter of this document contains summaries, conclusions, and recommendations related to this study. A summary of the work done for this study and methods used to satisfy objectives are reviewed. Conclusions are drawn as they pertain to the objectives. Finally, Chapter five concludes with recommendations on a number of aspects of this project. Suggestions for future work as well as possible ways to improve testing to better satisfy study objectives are presented.

Following Chapter 5, Appendices A through F provide the raw data collected during each burn. Appendix G presents the statistical analysis results and provides examples of the sample output obtained for all statistical analysis.

Chapter 2
Literature Review

2.1 Introduction

In 2010, over 3 billion tons of portland cement were produced globally making it the most widely used and manufactured material in the world (Aïtcin 2000; Chen and Juenger 2009; ICR 2011). In the United States, 113 cement plants that operate in 36 states produced 65 million tons of cement in 2010. The United States is the third largest cement producer following China and India (PCA 2010; ICR 2011). Various countries' contribution to the total 3.3 billion tons of cement produced in 2010 is shown in Figure 2.1.

Joseph Aspin, an English mason, was credited with the invention of portland cement. In 1824 Aspin was granted a patent for his formulation of artificial stone. Portland cement's name comes from the cement's similar qualities and appearance to a natural Portland stone quarried from the Isle of Portland (Klemm 2004). Aspin's cement was a hydraulic lime due to the low kiln temperatures inhibiting any lime-silica reaction formation. Joseph's son, William, was also involved in the cement trade but burned his raw material at higher temperatures. He was the first to achieve formations of alite and belite (Blezard 1998). Since Aspin's patent, significant improvements have been made to the chemical formulation and manufacture of cement, but the term portland cement has become the spoken reference used for all modern hydraulic cements.

When portland cement is mixed with water, an exothermic chemical reaction occurs forming a hydraulic paste. The paste acts as a binder and when mixed with fine and coarse aggregate, such as sand and gravel, forms a solid mass known as concrete.

Temperatures in excess of 1600 °C are required to properly blend raw materials and form a homogenous product. Traditionally fossil fuels such as coal, natural gas, and petroleum coke have been used to fuel the energy-intensive process of cement production.

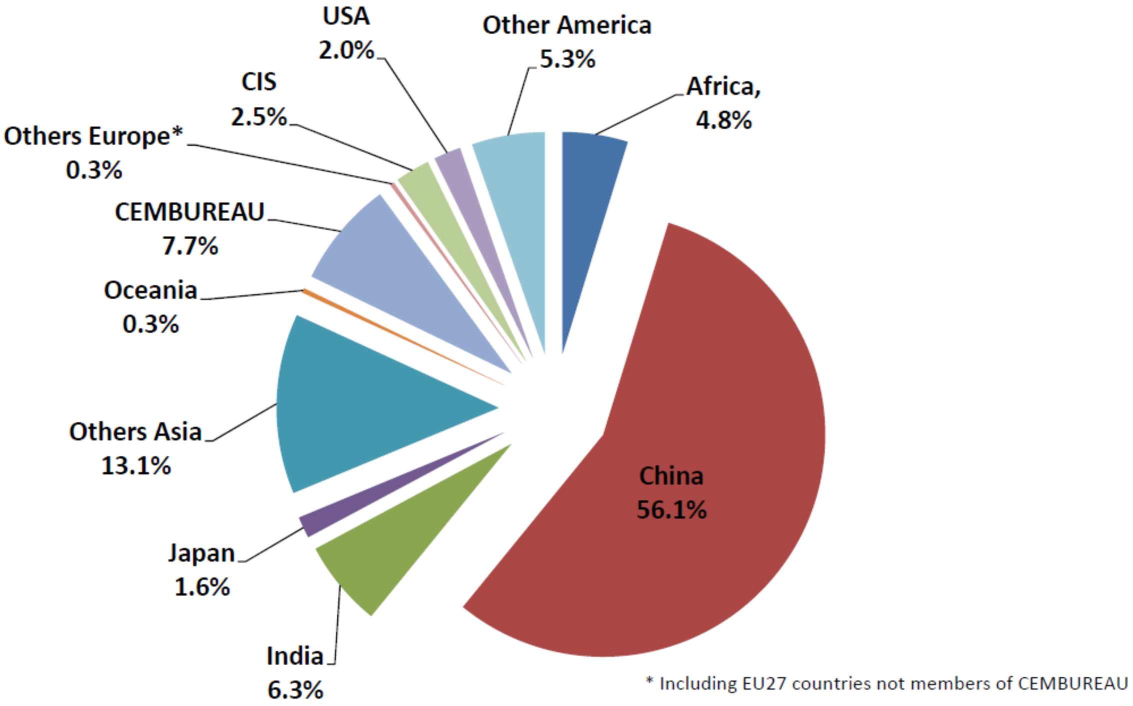

Figure 2.1: World cement production in 2010, by region and main countries (Cembureau 2010)

According to Jackson (1998) and others, fuel costs account for upwards of 40% of production costs (Mokrzycki et al. 2003). The rising fuel costs have forced many cement producers to look towards the use and benefits of alternative fuels in order to offset these costs.

The use of industrial waste products as alternative fuels started in the early 1970’s. Tires, waste oils, solvents, and other hazardous wastes are examples of fuels used to partially replace natural fossil fuels because of their high energy content (Karstensen 2008). Cement plants today typically use alternative fuels at replacement rates between 20-70%, which studies have proven to be both economical and ecological (Mokrzycki and Uliasz-Bochenczyk 2003; PCA 2009). The most significant benefits are the preservation of fossil fuels, reduction of waste materials incinerated or landfilled, and the reduction of greenhouse gasses (Greco et al. 2004). It is, however, necessary to study the effects of alternative fuels on the manufacture and performance of portland cement before its implementation.

This chapter provides a review of literature and former research results of studies conducted in previous phases regarding the effects of alternative fuels as they apply to the cement and concrete industries.

2.2 Portland Cement Production

Portland cement is manufactured by combining raw materials containing calcium, silica, alumina, and iron. After the raw materials are crushed to a specific fineness and blended together, the mixture, or kiln feed, is transported to the kiln where it is heated to temperatures in excess of 1600 °C. This fuses the homogeneous mixture together into a uniform product known as clinker. The clinker is immediately cooled as it exits the kiln and is stored in silos until it is ready to be ground with a predetermined quantity of sulfates. The final product is known as portand cement. Since the quantity of raw materials used is dependent on the material’s chemical composition, a facility’s geographical location and local industrial conditions determines its use of the raw materials.

Cement is manufactured through a wet or dry process. Dry process manufacturing is the most modern approach and is more fuel efficient and widely used than the wet process. The cement produced from either process is packaged, stored, and sold to consumers.

Figure 2.2 shows a schematic of a typical dry process cement manufacturing facility. Predetermined quantities of raw materials are first fed into grinders that simultaneously crush the raw materials to a certain fineness and create a homogeneous mixture. Next, the raw material is sent through a series of preheaters where the mixture is partially calcined. The calcination process is discussed in more detail in later sections. The mixture in then fed from the preheating tower into the kiln where high temperatures causes the materials to chemically fuse together. Rapid cooling of the fused material forms clinker. The clinker is ground with an addition of gypsum to a specified fineness to form portland cement. Dust, commonly known as cement kiln dust (CKD), is collected through the entire process and is recycled back into the raw feed.

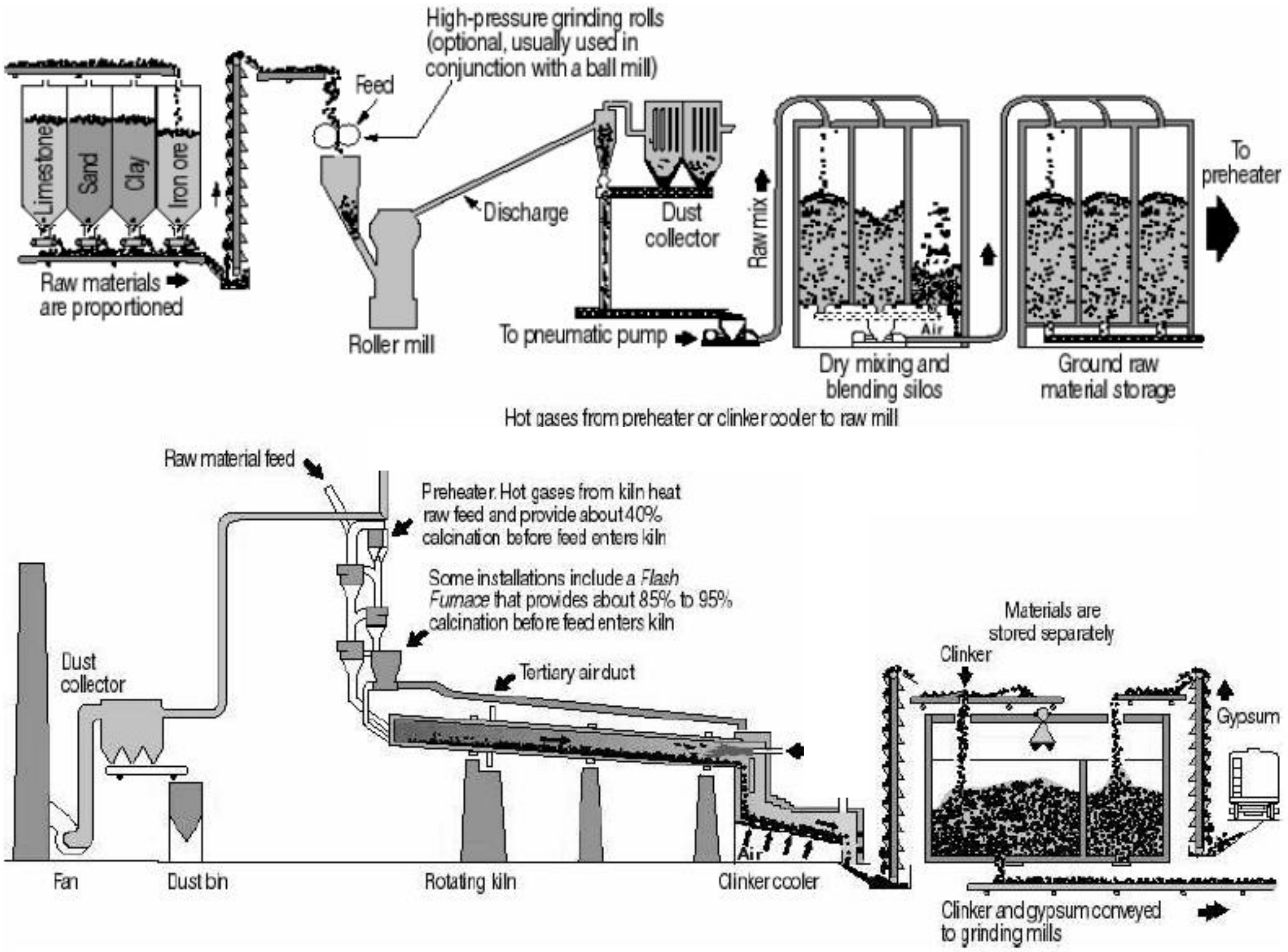

Figure 2.2: Layout of a typical dry-process portland cement production facility (Kosmatka et al. 2002)

Manufacturing portland cement is highly energy intensive. According to Hendrik and Padovani (2003), an average of 3.2 to 6.3 GJ of energy is required to produce one ton of cement. Since there are multiple methods to achieve each step in production, energy consumption is variable between producers. In Table 2.1, energy consumption at various stages of the manufacturing process and between manufacturing types are shown. It should be noted the fuel is only used in the kiln and preheater systems. Also, the fuel used in the wet process far exceeds fuel used in the dry process. Additional fuel in the wet process is required to dry incoming material before clinkering can take place in the kiln. Grinding the raw meal and clinker requires the most electricity during the manufacturing process. Over the years, technology has enabled new production methods to be developed that have increased energy efficiency by more that 37% since 1972 (PCA 2010).

2.2.1 Raw Materials

The selection and combination of raw materials is essential to produce clinker with proper hydraulic properties. Typically, 1.7 tons of raw materials are needed to produce 1 ton of cement (Hendrik and Padovani 2003). The primary raw materials used in the production of clinker are calcareous materials (containing calcium carbonates), siliceous material (containing silica), and argillaceous material (containing both silica and alumina) (Miller 2004). These materials are combined to provide the clinker with the appropriate quantities of the following oxides: calcium oxide or lime ($CaO = 65\% \pm 3$), silica oxide ($SiO = 21\% \pm 2$), alumina oxide ($Al_2O_3 = 5\% \pm 1.5$), and iron oxide ($Fe_2O_3 = 3\% \pm 1$). The most common sources of each raw material are shown in Table 2.2.

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 et al. 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

Two equally important parameters that must be achieved during the formulation of a raw mix are its burnability and composition. The raw feed must be able to produce an appropriate free lime content under reasonable burning temperatures and time frame (Miller 2004). The chemical composition must also be carefully controlled in order to insure that performance of the cement is adequate. These two parameters are simultaneously controlled by factors such as the C_3S content or the lime saturation factor (LSF), the silica ratio, and the C_3A content or A/F ratio.

According to Miller (2004), about 67% of clinker by mass is composed of lime. It is for this reason that cement production facilities are typically built near large limestone deposits in order to minimize transportation costs of this material. The source of the limestone dictates its composition and thus its contribution to the raw mixture. For example, pure calcium carbonate is added in small amounts while other materials constitute the remainder of the final blend. On the other hand, a lower calcium content limestone known as “cement rock” has a composition that allows it to represent the majority of the raw mix. In-between these two extremes, an intermediate limestone will comprise roughly 80% of the raw mixture. Four different limestone sources arranged according to their CaO content are shown in Table 2.3.

As seen from Table 2.3, the silica ratio also is dependent on the source of limestone. The silica ratio, or silica modulus, is the ratio of silica content to the sum of the contents of alumina and iron. Miller (2004) reported that a silica ratio of 2.62 produces a raw feed with acceptable burnabilty and high-quality clinker. The silica content of the raw mixture must be adjusted by secondary raw materials. Materials such as clay, shale, and fly ash are argillaceous and contribute silica, alumina, and to a lesser extent iron. Lastly, to “fine tune” raw mixtures, corrective materials such as iron ore, bauxite, and sand are used because essentially only one element (iron, alumina, or silica respectively) is dominant.

Table 2.3: Typical limestone compositions (Miller 2004)

Elements, as oxides	**Pure Limestone** (mass %)	**Intermediate Limestone** (mass %)	**Siliceous Limestone** (mass %)	**Cement Rock** (mass %)
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

Once the raw materials are selected and proportioned, grinding and blending occurs prior to kiln entry. Similar to the chemical composition, the burnabilty of the raw feed is also dependant on grinding each material to its optimum fineness (Miller 2004). Raw material that is burned at an appropriate fineness reduces energy costs by using less fuel than a courser fineness (Jackson 1998). Once the appropriate fineness has been obtained, the raw materials are mixed together to form a homogeneous mixture with the predetermined chemical composition (Chatterjee 2004).

The limestone in the kiln feed, on entering zones of higher temperatures in the preheater and kiln, undergoes a process known as calcination. The limestone ($CaCO_3$), is broken down to calcium carbonate (CaO) and carbon dioxide (CO_2). The cement industry has taken measures to reduce CO_2 emissions in order to limit the harmful effects this greenhouse gas has on the environment. Withholding a portion of limestone until the clinker is ground is a typical method to limit carbon dioxide emissions, although the increased CO_2 content of the cement typically alters its primary compounds (Hendrik and Padovani 2003).

2.2.2 Pyroprocessing

Once the raw material is proportioned and ground to the appropriate fineness, the material is heated in a process known as pyroprocessing, which causes chemical and physical changes in the raw materials. The exposure to heat fuses the raw material into a single product known as clinker. Factors such as raw material composition, mineralogical composition, and time and temperature profiles of the material in the kiln all contribute to the complicated endothermic and exothermic reactions that dictate the final performance of the cement (Manias 2004).

Wet and dry kiln systems are the two processing systems used to produce cement. In the 20th century, cement production was dominated by the wet process. However, around the 1970's, as fuel costs rose, the need for a more fuel efficient system sparked the move toward wide spread use of dry kilns. Wet process kilns are less efficient compared to dry process kilns due to the raw feed entering the kiln is in a slurry form requiring additional fuel to drive off moisture prior to combustion. Another disadvantage is that wet process kilns are not capable of the same production levels as dry kilns because of mechanical limitations on equipment size (Manais 2004). For example, a large wet process kiln can produce roughly 1,500 tons per day (tpd) where as a modern, dry process systems exceed 10,000 tpd. Over the years technological innovations have lead to multiple configurations of wet and dry process kiln systems, but all fall into one of the two categories.

The kiln slope and rotational speed determines the rate raw materials pass through the kiln (Kosmatka et al. 2002). The raw materials enter at the upper end of the kiln and are moved towards the heat source at the lower end by the kiln's rotation. As mentioned earlier, at the point of entry into the kiln, the raw material has already been heated to approximately 850 °C and nearly completed the calcination process (Jackson 1998). The kiln system performs the following material transformations on the raw material starting from the feed end (Manias 2004):

1.	Evaporating free water, at temperatures up to	100 °C
2.	Removal of adsorbed water in clay materials	100 °C – 300 °C
3.	Removal of chemically bound water	450 °C – 900 °C
4.	Calcination of carbonate materials	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: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracacium aluminoferrite (C_4AF) which are commonly referred to as the Bouge compounds (Tennis and Kosmatka 2004). These compounds are often referred to as alite (C_3S), belite (C_2S), aluminate (C_3A), and ferrite (C_4AF). The Bouge compounds typically comprise 90% of cement by mass with calcium sulfate dihydrite, or gypsum filling the remainder (Tennis and Kosmatka 2004).

Figure 2.3 shows the gas and material temperatures as well as their respective retention times during the pyroporcess.

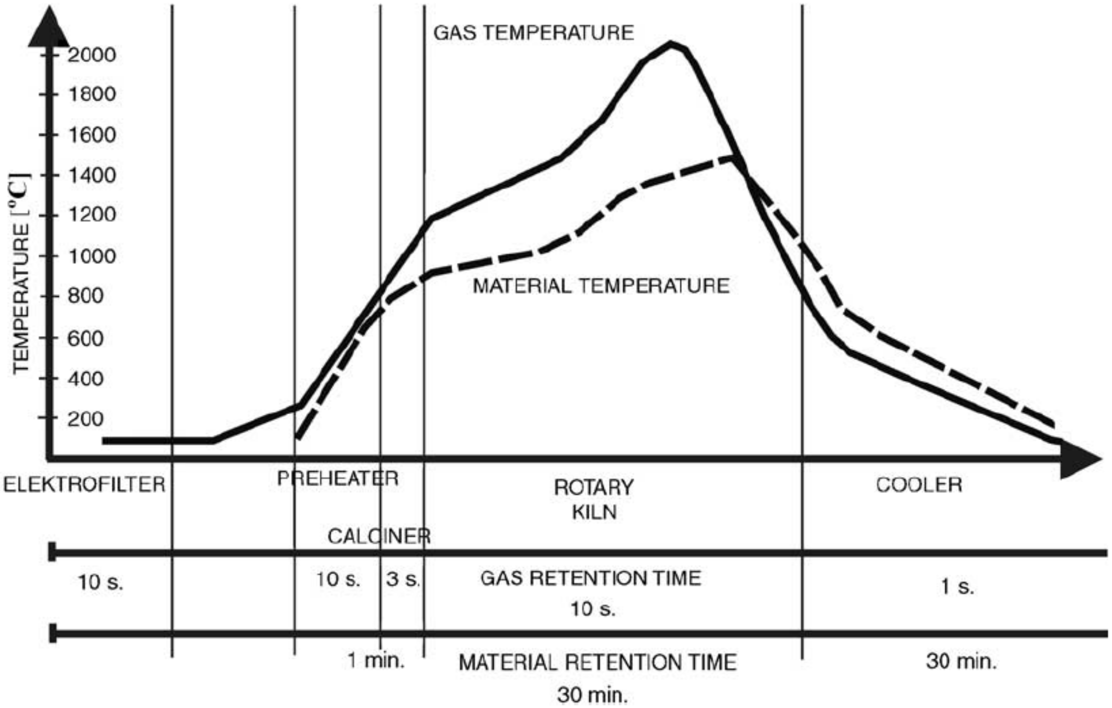

Figure 2.3: Gas and material temperature inside a typical cement kiln (Mokrzycki and Uliasz-Bocheńczyk 2003)

2.2.3 Clinker Cooling

As the newly clinkered material exits the kiln, it enters the clinker cooler. According to Steuch (2004) the most popular cooler in the U.S is the grate cooler, shown in Figure 2.4. Grate coolers are comprised of several perforated, slightly inclined grates that transport the hot bed of clinker across a series of fans that remove heat from the clinker by forcing air up through the bottom of the grates (Jackson 1998).

The rate of clinker cooling is just as important as the rate of heating. Jackson (1998) reported that slowly cooling clinker often cause alite to partially transform into belite and free lime, which negatively effects setting and strength properties. Slow cooling also contributes to the formation of large alite and belite crystals that produces a courser, less reactive cement (Manias 2004). By quickly cooling the clinker, the optimal phase composition is secured which results in adequate cementitious properties (Steuch 2004; Jackson 1998).

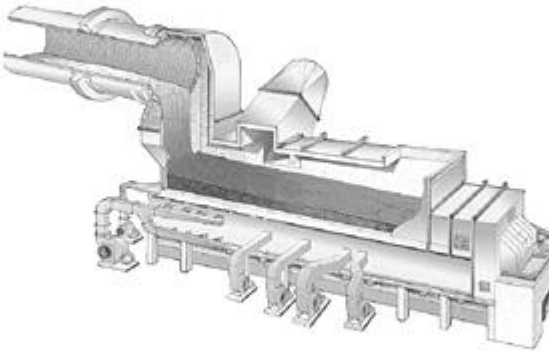

Figure 2.4: Grate cooler for cooling clinker (Network Solutions 2010)

Another function of the clinker cooler is to recycle the heat extracted from the clinker back into the kiln system. In a modern kiln system, heat extracted from the clinker cooler supplies roughly 20% of the total heat input to the burning zone and 25% of the total heat input to the calciner (Young and Miller 2004).

2.2.4 Grinding and Finishing

The clinker, once cooled, is stored in silos until it is ready for the final step in manufacturing cement: grinding. The finishing mill system reduces the clinker from several centimeters in diameter to a maximum of 100 μm ensuring consistent chemistry throughout (Strohman 2004). Consequently, approximately 30-40% of the total electrical power used for cement production is used in the finishing process. Depending on how the clinker was burned, its chemical composition, and how it was cooled determines the relative ease at which the clinker will grind (Strohman 2004).

The ball mill is the most common type of finishing system, although some facilities utilize roller mills, roller presses, or a combination of these types (Strohman

2004). A ball mill consists of a cylindrical tube that rotates about a horizontal axis. Within the tube several slotted diaphragms separate various sizes of steel balls used to crush the clinker. The cooled clinker enters the initial compartment of the mill and is broken down by large steel balls (90-100 mm). Once small enough, the clinker particles pass through the slotted diaphragm where they are broken down further by smaller balls (13-60 mm) until the required fineness is achieved (Jackson 1998). The finished product's performance is determined partially by the clinker's final gradation.

Calcium sulfate or gypsum is blended with the ground clinker in amounts typically between 3 and 8 percent to retard the formation of aluminate. This temporarily controls the rate of setting and optimizes the strength giving properties of the calcium silicates (Jackson 1998). Without the addition of sulfate, C_3A rapidly forms hydration products leading to accelerated setting times and rendering it insufficient for construction use.

After the gypsum is ground with the clinker, the finished product is portland cement. In order to maintain quality, cement facilities continuously sample the finished product. Parameters such as the Bogue compounds, silica modulus, lime saturation factor, free lime, and sulfate contents are examined to ensure the cement possesses all its intended properties. If the final chemistry is not sufficient, secondary materials are added in order to fix the inadequacies. The finished cement is then ready to be packaged, sold, and shipped to consumers.

2.3 Use of Alternative Fuels in Portland Cement Production

Traditionally, cement plants have relied on natural fossil fuels to power the pyroprocessing of raw materials. These fuels include coal, natural gas, and petroleum coke (pet coke). Due to the rising costs of fuels and the fact that up to 40% of a cement facility's budget is fuel costs, manufacturers seek fuels that optimize costs and product quality and minimize environmental impact (Jackson 1998; Greco et al. 2004). Since the 1970's, waste fuels have been utilized by the cement industry for partial replacement of traditional fuels (Karstensen 2004). Today, these waste fuels account for 20-70 % of the total energy demands at a cement facility (PCA 2009). It should be noted that the terms "alternative" and "waste" with respect to fuels are used interchangeably. Although the use of alternative fuels brings many benefits, their overall effects on the manufacturing process, performance of the cement, and environmental impact must be studied before the fuel is routinely utilized.

Coal is the most predominately used fossil fuel in the cement industry. Ancient records date the use of coal back to the Roman Empire and today it is responsible for almost a quarter of the world's energy demands (Greco et al. 2004). In the cement industry, up to 150 kg of coal is needed to produce 1 ton of cement (Mokrzycki and Uliasz-Bocheńczyk 2003). Therefore a kiln capable of producing 10,000 tpd, requires 1,600 tons of coal per day (Manias 2004). With this level of consumption and the fact that the cost of coal has nearly tripled in the past decade, cement manufactures are influenced to research and implement cheaper alternatives to reduce production costs (Shafiee and Topal 2010).

A fuel is any substance that in the presence of an initial "energetic impulse" and oxygen initiates an oxidizing chemical reaction that is rapid, self-sustainable, and exothermic (Greco et al. 2004). Many typical alternative fuels categorized by their origin are shown in Figure 2.5. Lechtenberg (2009) reported that 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 quality of the fuel must be stable enough to allow a controlled supply of energy to the kiln to produce homogeneous clinker.
3. The physical form of the fuel has to permit easy handling for transportation and 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.

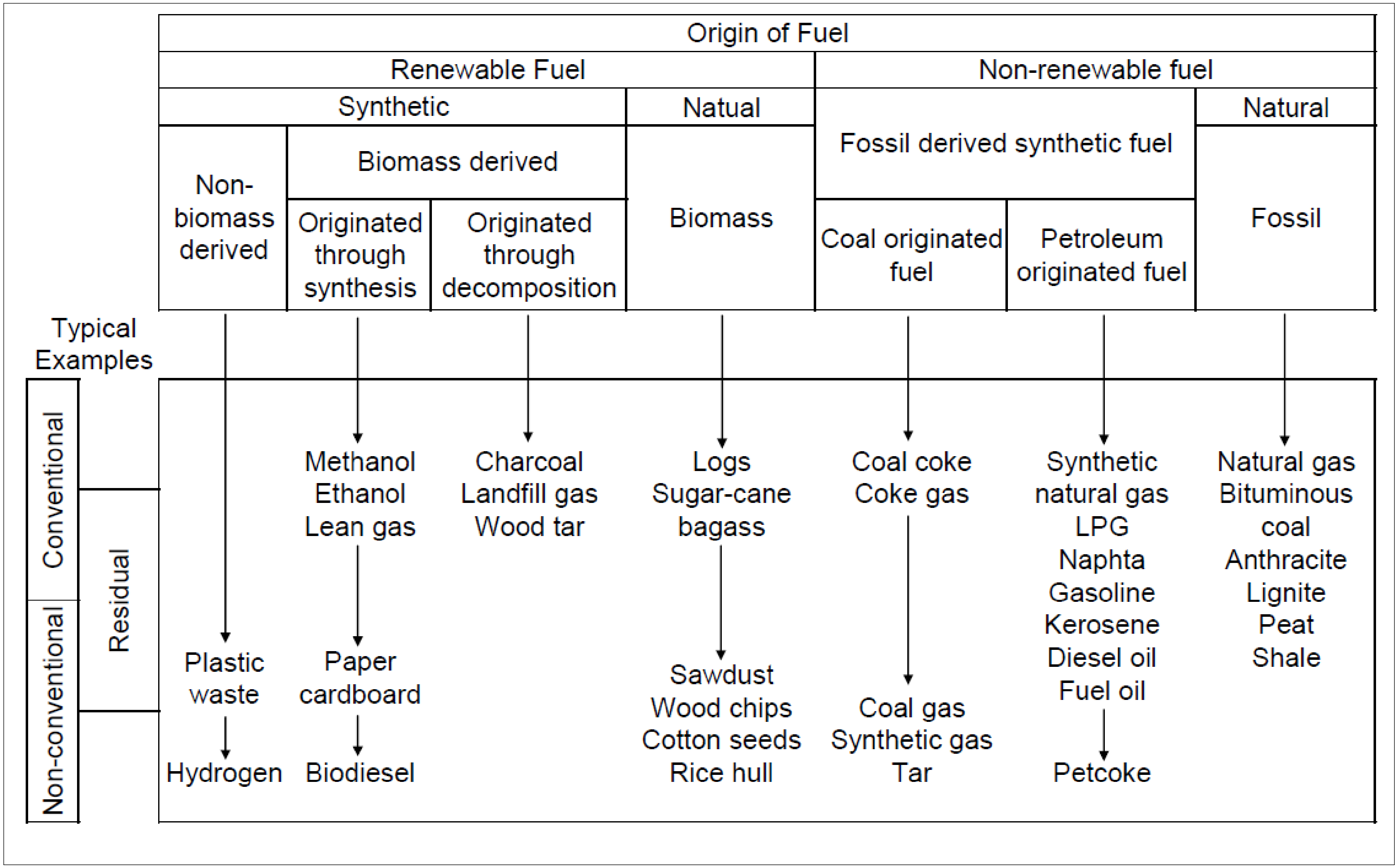

Figure 2.5: Various fuels and their origin (adapted form Greco et al. 2004)

Alternative fuels are divided into three distinct categories: solid, liquid, and gaseous fuels (Greco et al. 2004; Mokrzycki et al. 2003). Examples of each type of waste fuel commonly used are shown in Table 2.4. Each category requires specific plant modifications in order to condition, dose, and fire the alternative fuel. Replacement levels for alternative fuels vary according to physical and chemical properties and are governed differently from country to country. For example, Conesa et al. (2007) reported, Switzerland has no replacement limit while Spain is limited to 15%. However, appropriate waste fuels could represent 80 to 100 % of fossil fuel replacement according to Willitsch and Strum (2002).

The implementation of waste fuels in the cement industry resulted from diminishing resources and increased fuel costs. The effects are reduced production costs, which create a competitive edge against other cement manufacturers and a decreased environmental impact.

2.3.1 Alternative Fuels in Cement Kilns

To adequately burn waste material, sufficient oxygen and temperature must be supplied as well as retention time, and proper mixing conditions (Karstensen 2008). Greco et al. (2004) reported the following kiln characteristics that render a sufficient environment for waste disposal:

1. The residence time and the temperature exceed minimum environmental regulations,
2. During the firing process, the alkaline environment inside the kiln absorbs the majority of acid gasses produced by the oxidation of sulfur and chlorine,

3. Non-combustible compounds and other metallic oxides do not harm the production or quality of clinker, and
4. The dusting system traps and recycles most other metals.

Table 2.4: Typical waste fired in cement kilns (adapted form 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

As stated earlier, it is important to fully understand the chemical composition of a waste material before use. Excess compounds such as sulfur and nitrogen oxides can cause kiln rings and build ups that lead to kiln shutdowns. In addition, extra quality assurance measures should be taken to ensure complete combustion of material and parameter control (Greco et al. 2004). More elements and their effects are discussed in

Section 2.5. Lastly, emissions must also be carefully monitored due to costly fines completely negating the cost savings of the alternative fuel.

2.3.2 Advantages of Alternative Fuels

There are mutiple environmental advantages of substituting alternative fuels in the cement industry. Four simultaneous gains are as follows (Greco et al. 2004):

1. Reduction of production costs,
2. Preservation of fossil fuel reserves,
3. Reduction in the volume of waste disposed through landfill and incineration, and
4. Reduction of green house gasses.

In recent years, the cost of fuel and electricity has increased dramatically. As a result, production costs of cement have also soared. Fossil fuel prices from 1950 to 2008 are shown in Figure 2.6. From Figure 2.6 one can see that coal prices nearly doubled from 2006 to 2008. In 2011, coal prices exceeded $200 per short ton (McCrae 2011). In an effort to offset these increases, manufacturers employ waste fuels because their cost per unit energy is far below that of fossil fuels (Greco et al. 2004). According to Hendrik and Padovani (2003), some cement plants in the United States are even paid to take waste, which in some cases completely offsets the conventional fuel costs.

Coal, natural gas, and petroleum coke are the predominate fossil fuels used to produce cement. The conservation of fossil fuels is important because they are non-renewable resources. At the present world consumption level, coal reserves will last approximately 119 more years (WCA 2011). Although coal and other fossil fuels are

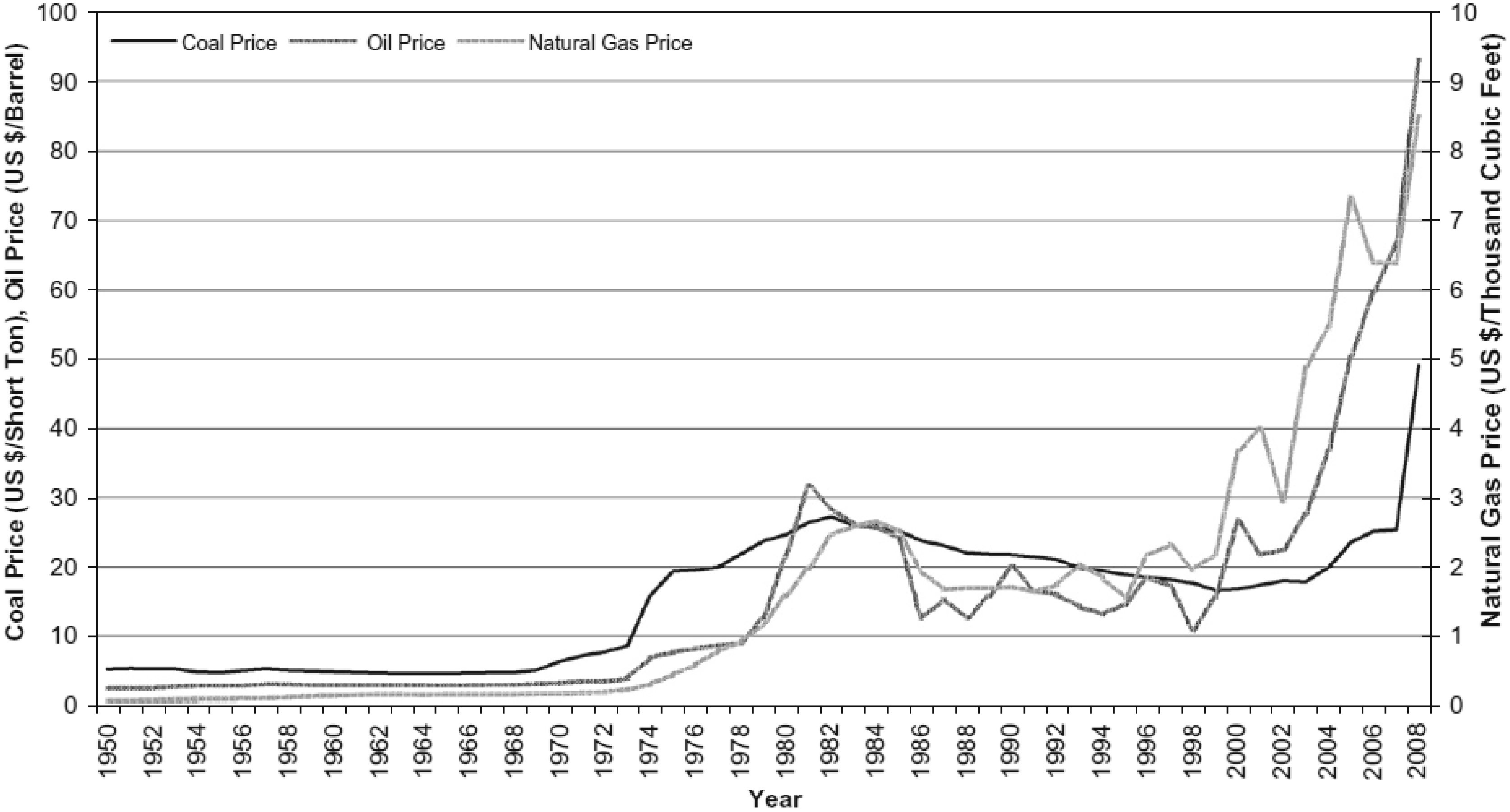

Figure 2.6: Average yearly trend of fossil fuel prices (Shafiee and Topal 2010)

extensively used in the production of cement, electricity and steel, the use of waste fuels reduces the ecological footprint made by the cement industry.

As the world's population continues to grow, landfill space is becoming scarce. Waste incineration is a typical method used to free landfill space. Waste incinerators use large quantities of fossil fuels to reach temperatures of at least 850 °C in order to break down materials. The drawback to waste incinerators is that no product, such as portland cement, is formed from the use of fuel. Waste incineration also produces higher emissions than cement kilns. The material breakdown in a cement kiln is much more complete because of the significantly higher temperatures and the longer residence times. Incidentally, Mokrzycki and Bocheńczyk (2003) point out that it is cheaper to modify an existing kiln to burn waste fuels than it is to build a new incineration plant.

Green house gasses are produced through the firing of raw materials and fuels. Carbon dioxide is one of these gasses that has come to the forefront due to its negative impact on the environment. Carbon dioxide is formed during the production of electricity, calcination of lime, and combustion of carbon-based fuels (Worrell et al. 2001). Green house gasses are of concern because they trap radiation within the atmosphere. Worrell et al. (2001) reported that the use of waste fuels may reduce the carbon dioxide emissions by 0.1 to 0.5 kg/kg of cement compared to traditional fuel emissions.

Alternative fuels can also supplement raw materials in cement production. Jackson (1998) reported that rice husk ash significantly reduces the required additions of silica in the raw feed because of its high silica content (78-90 %). Kääntee et al. (2002) also reported that iron found in the steel belts of automobile tires reduces the required iron in the raw feed.

2.3.3 Disadvantages of Alternative Fuels

Many factors such as increased emissions, altered clinker composition, and initial investment costs must be considered prior to the implementation of waste fuels. The effects of the disadvantages, if not addressed, can negate all other advantages.

The availability and cost often determines the viability of an alternative fuel (Kääntee et al. 2002). Preliminary conditioning of waste materials such as shredding, drying, and removal of detrimental contents is typically outsourced, but is critical before use and imposes a significant cost to the producer (Greco et al. 2004). The final condition of the waste material determines its energy output and replacement rate. Purchasing and installing mechanical equipment specifically designed to condition, convey, and dose the waste fuel are not only cost intensive, but if the waste material source is depleted or becomes unavailable, the need for the equipment also may become obsolete.

Metering and feeding systems must be installed to covey the waste fuel to the kiln. Although the prices vary according to capacity and precision, state of the art storage, metering, and feeding systems require large initial investments upwards of several million dollars (Lechtenberg 2009). The cost of training personnel to operate the continuous feed systems should also be considered (Willitsch and Strum 2002). The difficulty surrounding the ability to accurately monitor heterogeneous mixtures with varying densities was also noted by Willitsch and Srum (2002).

According to Hendrik and Padovani (2003), waste fuels can induce or increase kiln emissions. Chemical composition of the cement can also be altered by waste fuels. Waste fuels with high chloride concentrations can lead to the formation of sodium and potassium chloride gasses in the kiln and calcium chloride in the clinker. Updates to emission control systems as well as quality control systems may be necessary to ensure emissions remain within limits and the performance of the clinker is no altered. Build up of chloride gasses in the kiln can also cause blockages in the cyclone pipes and therefore kiln shutdowns (Lechtenberg 2009). Unnecessary kiln shutdowns reduce production rates and are an avoidable loss of revenue.

2.3.4 Alternative Fuel Options

Examples of typical waste fuels and their origins were shown earlier in Table 2.4 and Figure 2.5. These fuels are readily accessible to most geographic locations. Not only must the fuel release large amounts of energy when burnt, but there are a number of other characteristics that the fuel must possess in order to be considered for implementation. In order to validate a waste fuel's potential, the following factors should be considered (Mokrzycki and Uliasz-Bocheńczyk (2003):

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 ash content,
5. Volatile content,
6. Calorific, or heating value,
7. Physical properties (particle size, density, homogeneity), and
8. Moisture Content.

The replacement rate of a fuel is determined by a combination of the parameters listed above and is the reason why knowledge of the fuel's chemical composition is essential (Kääntee et al. 2002). For example, it would not be beneficial or make sense to replace a traditional fuel with an alternate, if the alternative fuel's low heating value requires excessive replacement rates. Although minimum requirements for a waste fuel differ among cement facilities, an example of criteria used by the Lafarge Cement Polska group is shown below (Mokrzycki et al. 2003):

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

The heating value, expressed in British Thermal Units (BTU), or calorific value, expressed in calories (cal), is the energy output upon combustion and is a key parameter in determining the viability of a fuel. The conditioning of the waste material before combustion also has a dramatic impact on the performance of the fuel. Material with a high moisture content will release less net energy than a material with a lower moisture content. This is due to extra fuel being required to remove the moisture before combustion. The approximate energy values of typical alternative fuels is shown in Table 2.5. Note the significant difference in energy values between the As-Received and Dry columns. The As-Received energy value is the energy value associated with the fuels natural moisture content.

The alternative fuels utilized in this study include construction and demolition waste, woodchips, and soybean seeds. A brief description of their historical use as alternative fuels will be discussed in the following sections. The results of using these fuels, as obtained through this study, can be found in Chapter 4. A comprehensive discussion of other alternative fuels utilized in previous studies is available, but will not be discussed further here.

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

Alternative Fuel	Approximate Energy Value	
	As-Received, BTU/lb (*kca/kg*)	**Dry,** BTU/lb (*kca/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) from municipal solid wastes	7200 (4000)	8100 (4500)

2.3.4.1 Plastic Solid Waste (PSW) as Fuel

In 2009, just over 12% of the total municipal solid waste generated in the U.S. (243 million tons) were plastics. Global plastic production in 2007 was estimated to be 260 million tons, which is over three times that produced in 1990 (Al-Salem et al. 2010). Siddique et al. (2008) reported that approximately 8% of plastic solid waste is incinerated and 7% is recycled leaving the 85% remainder to be landfilled. Low density polyethylene (LDPE) represents the largest contributor to PSW. Typical sources of PSW include packaging, industrial, and healthcare applications, and many other uses.

In order of free landfill space, multiple recovery methods have been developed. Re-extrusion, mechanical, chemical, and energy recovery are four categories that recycle these materials for productive application. The use of plastics for the manufacture of cement falls under the energy recovery category.

Before solid wastes enter the combustion chamber, the material must be conditioned (Greco et al. 2004). Drying, shredding, and mixing the material are examples of conditioning. It is also necessary to separate incombustible substances such as metals and glass, as well as any materials with organic impurities (Willitsch and Sturm 2002). An optimal moisture content of 0.5 - 2.0 % and maximum edge length of 10 *mm* produce the most desirable results (Greco et al. 2004; Willitsch and Sturm 2002). Feeding systems are also needed to transport the solid material from the storage facility to the preheating tower. The material is typically transported by the use of conveyor belts and injected into the combustion chamber by compressed air. It is also common that plastic solid waste be comprised from multiple sources to create an optimum blend (Greco et al. 2004). A comparison of coal and polyethylene is shown in Table 2.6.

As can be seen in Table 2.7, polyethylene contains significantly more volatile matter than coal. This could adversely affect kiln functionality, emissions, and the replacement rate utilized. The heating value shown represents pure polyethylene, not a PSW blend. Al-Salem et al. (2010) reported that the heating value typical of a PSW blend would be roughly 14,000 BTU/lb.

Table 2.6: 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 main impurities found in plastic solid wastes are chlorine, cadmium, lead, and zinc (Willitsch and Sturm 2002) which are detailed in Section 2.5.

Plastic solid waste has a high chlorine content with is one of the main contributors to its high volatile content. High chlorine contents are known to lead to blockages in ducts and fans, corrode kiln lining, and reduce the quality of the clinker. Sorting PSW according to chlorine content is one method of managing the chlorine content (Kikuchi et al. 2008). Another benefit of PSW is lower transportation costs. Plastic solid waste has a lesser density than coal, which reduces fuel consumption during transportation (Siddique et al. 2008).

Currently, little research exists discussing the effects that plastics have on portland cement quality and production. In an first phase of this project, two fuel scenarios were evaluated at a full scale cement plant during 3-day trial periods. The baseline burn consisted of only coal, whereas the trial burn consisted of a blend of coal, plastics and waste tires. The results of the trial were that concrete compressive strengths increased slightly, CO emissions were reduced, and NO_x, SO_2, and VOC were increased compared to the coal only burn (Swart 2007). These results, however, are not known to be directly linked to the change in fuel as conditions at the plant throughout the study were inconsistent. In the second phase of this project, Akkapeddi (2008) concluded that the tested alternative fuels could not be linked to changes in cement chemistry.

2.3.4.2 Biomass as Fuel

As the first fuel source harnessed by mankind, biomass fuels are defined as combustible materials that are the result of growing plants or raising animals (Abbas 1996). According to Cuiping et al. (2004), biomass accounts for 14 percent of the world's energy consumption and is used as a primary energy source by more than half the world's population. Biomass fuels are unique with respect to fossil fuels because they are gathered from a large area and transported to a concentrated area for use whereas fossil fuels are produced from a single location (i.e., a coal mine) and dispersed over a large area for use. Typical biomass fuels include wood, rice hulls, coffee grounds, sewage sludge, and manure. Abbas (1996) reported that the energy stored in biomass through photosynthesis is almost 10 times that of the world energy consumption. Biomass fuels with moisture contents less than 10 percent are better suited for thermal energy conversion, while biomass with higher moisture contents produce better results from biochemical processes such as fermentation (Cuiping et al. 2004). Since biomass fuels have lower concentrations of nitrogen and sulfur, oxides produced during the combustion process are significantly less than emissions produced by fossil fuels (Cuiping et al. 2004). Cuiping et al. (2004) also reported that the levels of carbon dioxide produced from the combustion of biomass will not contribute to global warming. The biomass fuels utilized in this study include portions of the construction and demolition waste, wood chips, and soy beans. The following are typical traits of a biomass fuel and the reasons why they are not widely used as reported by Abbas (1996):

1. Has compositional variability similar to coal,
2. Has a lower calorific content than coal – one-half by mass and one-fifth by volume,
3. Contains many of the same potential pollutants (sulfur, nitrogen, chlorine, etc.) found in coal, although in lower concentrations,
4. Expensive storage costs associated with providing a constant supply due to seasonal availability, and
5. Raising crops for energy purposes instead of food production creates a moral dilemma.

Woodchips are solid fuels made from woody biomass and are a byproduct of the timber industry. Woodchips are typically made from waste wood, saplings, and logging operations. Because it is a renewable energy source and locally available, woodchips are one of the least expensive fuels (Maker 2004). In Table 2.7, woodchip fuel costs are compared to coal, as reported by Maker (2004). Although conventional fuel system require less capital initially than a woodchip system, the substantial cost savings from using woodchips pays for the initial costs in a time period significantly less than the life of the system.

Table 2.7: Comparative fuel cost for woodchips (adapted from Maker 2004)

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

Note: MBTU – 1 Million BTUs

There are not significant amounts of literature available on the use of woodchips as fuel in cement production. Therefore, only the characteristics and chemical compositions will be discussed in this section.

Much like PSW, woodchips must be conditioned before use. Shredding woodchips to an optimal particle size of 6 mm is a cost intensive process. This conditioning, however, is required to achieve the most efficient feeding and combustion characteristics for the woodchips (Willitsch and Sturm 2002). Another cost associated with biofuel is storage. Proper storage is necessary to minimize smell, bacterial growth, and heat development. Controlling the moisture content is also critical due to lower heating values and inefficient combustion resulting from higher moisture contents.

As stated above, the heating value of woodchips depends heavily on its moisture content. The species of wood also determines the heating value. Maker (2004) reported that the average dry value of a woodchip stream was roughly 8,500 BTUs/lb. Typical dry-sample heating values from certain wood species are shown in Table 2.8.

Dry sample heating values are achieved in a laboratory setting and do not represent actual heating values. Table 2.9 shows the effect that increasing moisture content has on gross heating values. Since this moisture content of wood usually falls between 35 – 40 %, a heating value of 5,100 BTUs/lb is a typical figure for woodchip fuel. In an earlier phase of this project, Akkapeddi (2008) conducted a trial burn that utilized coal, tires, and woodchips. The average moisture content and heating value of the wood specimens tested were 36.5 % and 8,388 BTU/lb., respectively.

Table 2.8: Dry sample heating values for woodchips (adapted from Maker 2004)

Species	**Heating Value**		
	Average	**Low**	**High**
Hardwoods			
Ash, white	8583	8246	8920
Birch, White	8335	8019	8650
Elm	8491	8171	8810
Hickory	8355	8039	8670
Maple	8288	7995	8580
Oak, red	8364	8037	8690
Oak, white	8490	8169	8810
Poplar	8616	8311	8920
Softwoods			
Cedar, white	8090	7780	8400
Hemlock, eastern	8885	NR	NR
Pine, white	8603	8306	8900

Note: NR -- Not Reported

Table 2.9: Heating values for woodchips corresponding to moisture content (adapted from Maker 2004)

Species	**Heating Value**		
	Average	**Low**	**High**
Hardwoods			
Ash, white	8583	8246	8920
Birch, White	8335	8019	8650
Elm	8491	8171	8810
Hickory	8355	8039	8670
Maple	8288	7995	8580
Oak, red	8364	8037	8690
Oak, white	8490	8169	8810
Poplar	8616	8311	8920
Softwoods			
Cedar, white	8090	7780	8400
Hemlock, eastern	8885	NR	NR
Pine, white	8603	8306	8900

Note: NR -- Not Reported

A dry chemical analysis of woodchips performed by Teislev (2002) produced the following results: Carbon 50.00%, Hydrogen 6.17%, Oxygen 42.64%, Nitrogen 0.17%, and ash 1.00%. The high amounts of volatiles and low ash content produce favorable results in a kiln atmosphere. The low ash content has minimal effects on the quality of the clinker produced. Woodchips produce NO_x, CO, and VOC emissions during combustion that are comparable to fossil fuels (Maker 2004). Sulfur emissions, however, are basically nonexistent due to woodchip's low sulfur content.

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 NOx 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 throughout the study, the change in fuel was thought to be of some contribution to these effects.

The EPA reported that there were 72.7 million acres of soybeans harvested in 2000, making corn and soybeans the largest grown crops in the U.S. Over 50% of the worlds soybeans are grown in the U.S. on over 350,000 farms. In 2010, soybeans accounted for 58% of the world's oilseed production (Soystats 2011). Soybeans have multiple uses including food manufacturing, anti-corrosion agents, soaps, paints, diesel fuel, and livestock feed. Since there is not much literature available for use of soybeans as fuel in the cement industry, only characteristics and chemical composition of soybeans will be discussed in this section.

As shown above in Table 2.9, the fuel's heating value is heavily dependent on its moisture content. Other parameters that are shown in Table 2.10 – 2.12 can also impact the feasibility of a fuel. A comparison study of 21 agriculture and forestry biomass fuels in China was conducted by Cuiping et al. in 2004. The reported values in Tables 2.10 – 2.12 are the average of three specimens along with their respective standard deviations. Similar parameters for bituminous coal were also presented for comparison.

The proximate, ultimate, and combustion analysis of soybeans and coal are shown in Table 2.10. The ash content of bio-fuels is significantly influenced by chemical composition (Cuiping et al. 2004). Operational problems stemming from the chemical composition of the ash include slagging, fouling, sintering, and corrosion. Ash forming elements are shown in Table 2.11. From Table 2.10, it can be seen that compared to coal, soybeans contain higher proportions of hydrogen and oxygen. Cuiping et al. (2004) reported that the higher proportions of hydrogen and oxygen decrease the heating value of a fuel due to carbon – hydrogen and carbon – oxygen bonds containing less energy than carbon – carbon bonds. The significantly lower nitrogen and sulfur content of soybeans when compared to coal is also important for environmental protection.

Trace elements found in soybean are presented in Table 2.12. A detailed discussion of how the elements presented in Table 2.10 – Table 2.12 affect cement are discussed in Sections 2.4 and 2.5.

Table 2.10: Chemical characteristics of soybeans and coal (adapted from Cuiping et al. 2004)

Test	Parameter	Soybeans	Bituminous Coal
		Value (wt. %)	Value (wt. %)
Proximate Analysis	Ash	6.08 ± 1.10	20.08 ± 3.49
	Fixed Carbon	15.62 ± .017	49.08 ± 2.12
	Moisture	9.34 ± 1.88	2.83 ± 0.66
	Volatile Matter	68.95 ± 1.74	28.33 ± 1.89
Ultimate Analysis	Carbon	43.16 ± 1.13	63.78 ± 2.33
	Hydrogen	6.9 ± 0.13	3.97 ± 0.38
	Nitrogen	0.95 ± 0.28	1.13 ± 0.01
	Oxygen	44.76 ± 2.42	10.08 ± 4.66
	Sulfur	0.2 ± 0.4	0.97 ± 0.19
Heat Value (BTU/lb)		7295	14625

Table 2.11: Ash-forming elements (adapted from Cuiping et al. 2004)

Ash - Forming Elements	Soybeans
	Value (ppm)
Al	1336 ± 1013
Si	14.66 ± 12.57
Ca	16159 ± 1181
Fe	1500 ± 899
K	9986 ± 2773
Mg	7613 ± 996
Na	161 ± 73
P	1559 ± 579

Table 2.12: Trace elements found in soybeans and coal (adapted from Cuiping et al. 2004)

Trace Elements	**Soybeans**	**Bituminous Coal**
	Value (ppm)	**Value (ppm)**
As	**0.58 ± 0.31**	**14.5**
Ba	**56.08 ± 17.78**	**na**
Cd	**0.28**	**0.19**
Co	**0.56 ± 0.31**	**8.5**
Cr	**3.41 ± 1.53**	**36.8**
Cu	**10.05 ± 1.75**	**27.5**
Mn	**68.33 ± 26.93**	**na**
Mo	**2.5 ± 0.36**	**na**
Ni	**2.48 ± 1.31**	**13.9**
Pb	**12.32 ± 7.39**	**20.9**
Ti	**80.68 ± 73.56**	**na**
V	**4.15 ± 4.2**	**76.5**
Zn	**11.96 ± 3.85**	**na**

2.4 Emissions

The cement industry follows guidelines set by local, state, and federal agencies to minimize its environmental impact (Greer et al. 2004). Harmful pollutants emitted into the atmosphere can be transferred directly to humans through air inhalation as well as indirectly through pathways such as drinking water, skin absorption, and contaminated food (Conesa et al. 2008; Schuhmacher et al. 2004). The dominate types of emissions formed during the manufacture of cement are particulate matter (PM), produced from the acquisition and preparation of raw materials, and gaseous pollutants, produced during the pyroprocess. The formation and control of particulate matter is discussed in more detail in latter sections. Jackson (1998) reported that a cement facility producing 1 million tons of cement a year will also produce approximately 1.5 billion cubic meters of gasses. These gaseous pollutants include carbon dioxide (CO_2), nitrogen and sulfur oxides (NO_x, SO_x), volatile organic compounds (VOCs), metals, and other minor pollutants (Greer et al. 2004; Schuhmacher et al. 2004). The quantity and composition of emissions for a particular cement plant are determined by a combination of the physical and chemical properties of the raw materials and fuels as well as the kiln type and configuration.

Air pollution control devices (APCD) are used to control the harmful emissions from the kiln. The most common being electrostatic precipitators (ESP), which are closely spaced, positively charged plates paired with negatively charged woven wires in between the plates. The wires ionize the stack gases, which in turn causes the dust particles in the gas to become negatively charged and stick to the plates. Periodically the plates are cleaned and the waste particles disposed of (Jackson 1998).

Using alternative fuels not only can lower emissions and free space in landfills, but some plants in the United States are reimbursed to take waste. In some cases this revenue offsets the remaining costs of the conventional fuels (Hendrik and Padovani 2003). Cement kilns incinerate waste materials more efficiently, and emit less harmful emissions while producing a final product when compared to a typical waste incinerator that has no final product, burns at a lower temperature, and uses fossils fuels merely to free landfill space. Although the economics of using an alternative fuel can be easily justified, before use, the fuel’s environmental effects must also be considered along with its effect on cement quality. The following sections will discuss the primary emission components as they pertain to the scope of this project.

2.4.1 Carbon Emissions

The carbon emissions that the cement industry and environmental agencies are most concerned with are carbon monoxide (CO) and carbon dioxide (CO_2). As previously mentioned, CO_2 is the primary agent responsible for the “green house effect,” and is therefore monitored by environmental agencies around the world. Carbon credits are rewarded to companies that do not exceed the emission limits. These credits can be sold or traded to other companies that exceed the carbon emission limits (Lechtenberg 2009). Worrell (2001) reported that the global cement industry contributes roughly 5% to the total anthropogenic CO_2 emissions. The percentages of carbon dioxide produced by particular countries are shown in Figure 2.7.

Carbon monoxide is formed when there is incomplete combustion of carbon-rich fuels due to insufficient oxygen at the combustion site and/or the oxidation process is left incomplete due to rapid cooling (Greer et al. 2004). Carbon dioxide is unavoidable and results from the combustion of carbon rich fuel and the decarbonization of calcareous raw materials. Decarbonization or calcination is the process of heating limestone ($CaCO_3$) and converting into carbon dioxide (CO_2) and calcium oxide or lime (CaO). Decarbonization is typically carried out in the preheater, which may also be known as a precalciner. The calcium oxide (CaO), once in the kiln, becomes one of the primary components of the clinker while the CO_2 is released into the atmosphere. The amount of CO_2 produced is more dependent on the kiln conditions rather than the type of fuel being used (Worrell et al. 2001). The carbon dioxide produced from the fuel and raw materials is roughly equal. It is also accepted that for every ton of clinker produced, one ton of CO_2 is produced (Chen and Juenger 2009; Greer et al. 2004).

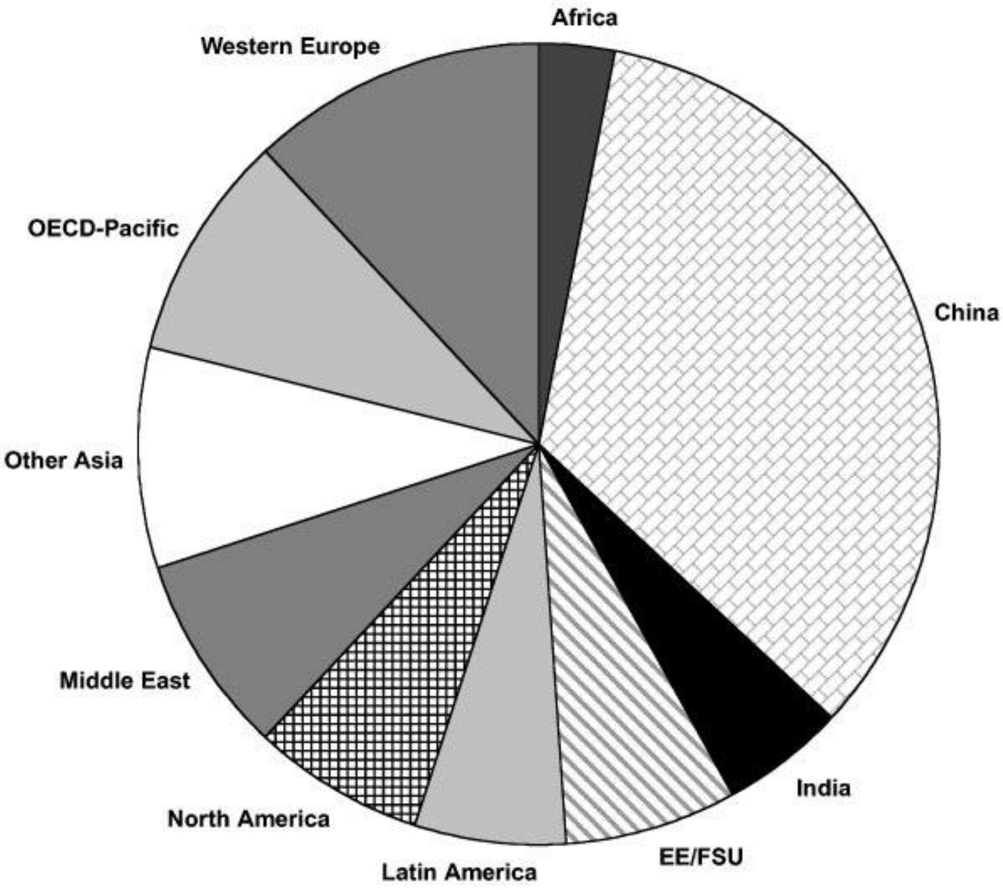

Figure 2.7: Share of carbon emissions from global cement production (Worrell et al. 2001)

There are a number of ways that cement manufactures can reduce their carbon emissions. The use of fly ash and blast furnace slag are typical ways carbon emissions can be reduced. Fly ash, which is a byproduct from coal burning power plants, and blast furnace slag, a byproduct from steel production, are both calcium-bearing waste materials that can be substituted into the raw materials for natural limestone. Fly ash and blast furnace slag can replace a portion of the cement in a concrete mixture and therefore are referred to as supplementary cementitious materials (SCMs). Chen and Juenger (2009) reported that fly ash and blast furnace slag can successfully replace limestone up to

27.5% and 35.0% respectively without compromising the mechanical properties of the cement.

Carbon dioxide emissions can also be reduced with the use of alternative fuels during production. CO_2 emissions can be reduced by 0.1 to 0.5 kg per kg of cement produced by substituting waste fuels for fossil fuels (Worrell et al. 2001). Syverud (1994) reported that in 1987, a plant in Norway partially replaced coal with chipped tires. The CO, NO_x, and SO_x emissions were recorded during the 56-hour study. Reductions of up to 50% were recorded in CO emissions. The Taiheiyo Cement Group, a Japanese company, replaced 20% of raw materials and 9% of fossil fuels with industrial waste and raw materials from around the county. As a result, the carbon dioxide emissions were reduced by 14% (Taniguchi 2001).

2.4.2 Nitrogen Oxide Emissions

Nitrogen oxides (NO_x) are a family of nitrogen-based compounds that are formed through nitrogen oxidation from the combustion of fuels and raw materials in the presence of atmospheric air (Greco et al. 2004; Walters et al. 1999). Nitrogen oxide (NO) and Nitrogen dioxide (NO_2) are the two most common forms of NO_x and comprise roughly 90% and 10% of NO_x respectively (Greer 2004). Once nitrogen oxide is formed, it is quickly oxidized again to form nitrogen dioxide. Naik (2005) reported that for every ton of cement produced, 1.5 to 10 kg of NO_x is emitted into the atmosphere. The fuel type, feed rate, air flow, and kiln temperatures influence the quantity of emissions. In order to accurately document NO_x emissions, several measurements over closely spaced time intervals are needed.

Nitrogen oxides are formed through four mechanisms: thermal, fuel, feed, and prompt (Greco et al. 2004; Hendrik and Padovani 2003). Thermal NO_x makes up around 70% of the total NO_x that occurs when the atmospheric nitrogen begins to oxidize around temperatures of 1200°C. Rapid formation starts to occur at slightly hotter temperatures of 1600°C (Hendrik and Padovani 2003). Thermal NO_x forms around the main burner in the sinistering zone and the amount of thermal NO_x formed primarily depends on the amount of available oxygen.

Fuel NO_x is formed from the oxidation of nitrogen within fuels such as coal during combustion. Fuel NO_x forms at any temperature above the ignition temperature of the fuel. Due to the lower temperatures in the precalciner, the oxidation temperature of thermal NO_x has not been reached. Therefore, fuel NO_x is more prevalent at this location (Greco et al. 2004; Hendrik and Padovani 2003). On the other hand, the quantity of nitrogen is much more prevalent in the atmosphere than in fuel which means that in the sinistering zone thermal NO_x dominates. As mentioned above, the contribution of fuel NO_x is relatively small compared to thermal NO_x. However, Greer (1986) reported that if all other factors controlling NO_x formation are held constant, the total amount to NO_x can be altered by controlling the nitrogen content in the fuel.

Feed NO_x is formed when the nitrogen that is chemically attached to the feed is released and oxidized. Greco et al. (2004) reported that feed NO_x has only been generated in a laboratory by slowly heating raw materials to 300-800°C in the presence of oxygen. Older technology, such as wet and long dry kilns may exhibit an increase in feed NO_x because of the slow temperature rise of the raw material (Greco et al. 2004; Hendrik and

Padovani 2003). Feed NO_x has a minimal impact on total NO_x production in the kiln due to the small quantities of the nitrogen present in the feed.

Finally, prompt NO_x refers to NO that is formed in excess of what is expected from thermal NO_x and is generated from fuel derived radicals, a fuel rich flame and elemental nitrogen (Greer et al. 2004; Hendrik and Padovani 2003). Similar to feed NO_x, prompt NO_x are considered minor contributors to total NO_x generation.

Although 70% of NO_x consist of nitrogen oxide, according to Greer (2004), the predominate "environmental evil" is nitrogen dioxide. Nitrogen dioxide creates two main problems. When nitrogen dioxide is mixed with water, nitrous acid (HNO_2) and nitric acid (HNO_3) are formed. The result of these highly corrosive acids is acid rain, which is the main contributor to building and vegetation destruction (Greco 2004). Smog, an atmospheric pollutant, is the resultant of a photochemical reaction between nitrogen dioxide, hydrocarbons, and solar radiation. On November 7, 1997, the Environmental Protection Agency instated a law requiring up to 70% reductions of mass NO_x emissions that would apply to cement plants in 22 states. An emission credit system similar to carbon emission credits was also instated (Walters et al. 1999).

The majority of NO_x produced in cement kilns comes from thermal NO_x. The use of alternative fuels cannot significantly change its concentration in either direction. Fuel NO_x, however, can be controlled by the use of fuels low in nitrogen concentrations. The study conducted by Prisciandaro et al. (2003) shows and increase in NO_x emissions in Plant 1, and a decrease in NO_x emission at Plant 2, as shown in Figure 2.8. Chipped tires were utilized to partially replace coal in the study conducted by Syverud (1994). NO_x emissions were reduced by 45%.

2.4.3 Sulfur Oxide Emissions

In cement manufacturing, sulfur oxides (SO_x) are formed from the combustion of sulfur bearing compounds in the fuels and raw materials (Hendrik and Padovani 2003). The most prevalent SO_x in the cement industry are sulfur dioxide (SO_2) and sulfur trioxide (SO_3), which begin to form at a temperature range of 300 to 600 °C (Greer et al. 2004; PCA 2009). SO_2 is more abundant than SO_3 because it forms at higher temperatures (Greco et al. 2004). Sulfur dioxide is a colorless gas with a strong odor that can be harmful to the respiratory tract of humans and damage vegetation (Greco et al. 2004; Greer 1986). Sulfur dioxide, when combined with water forms sulfuric acid (H_2SO_4) rain (Greco et al. 2004).

Although the amount of SO_x production varies from plant to plant, a large measure, more than 50 to 90% is absorbed by the kiln feed, clinker, cement kiln dust, or left in the kiln as a coating that helps preserve the brink lining (Greer 1986; Hendrik and

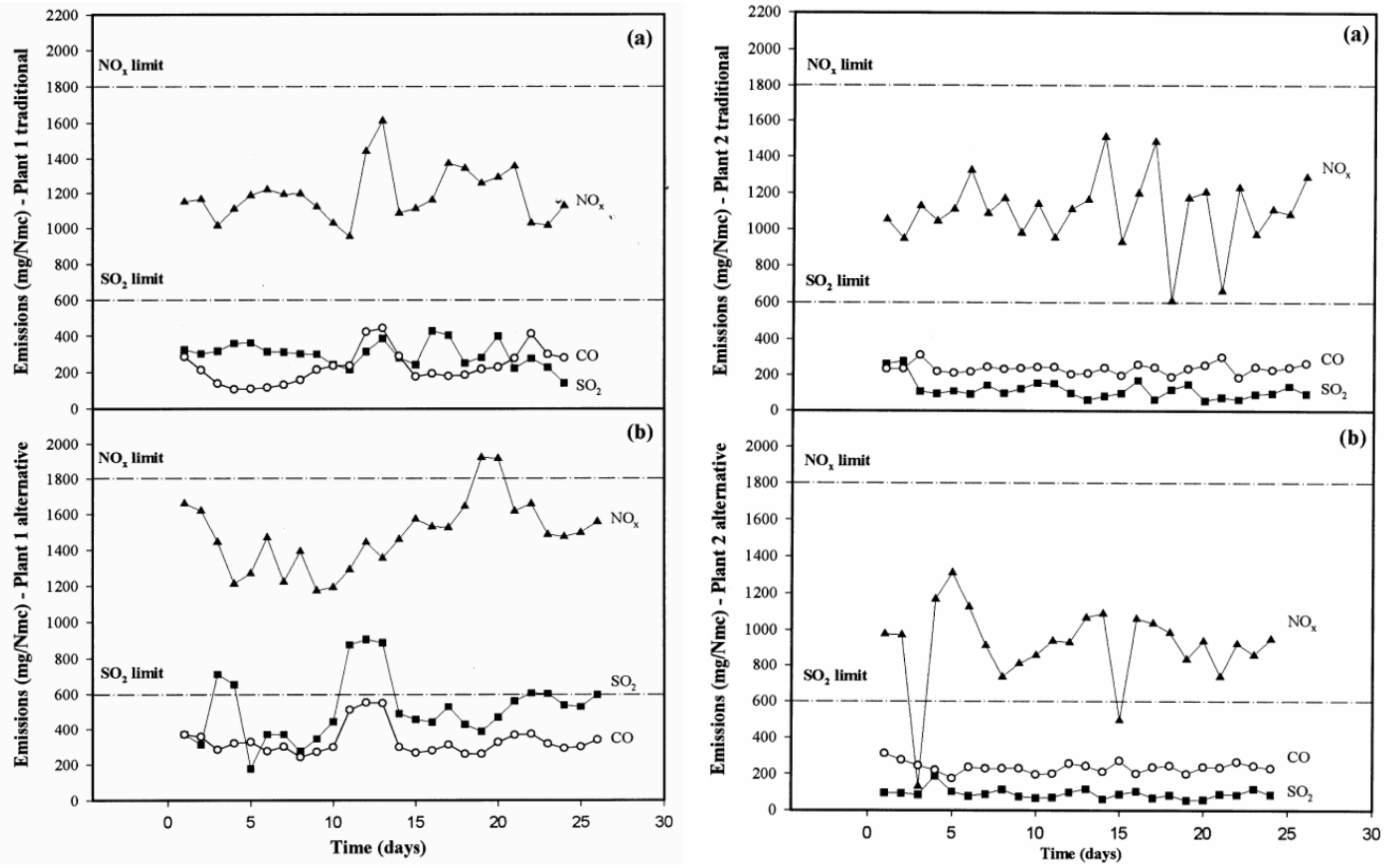

Figure 2.8 : Change in emission levels due to changes in fuel types (Prisciandaro et al. 2003)

Padovani 2003). The clinkering process removes the majority of the SO_x build up on the inside of the kiln. This is beneficial to the cement producer because less gypsum can be added later during clinker grinding. If excessive SO_x buildup accumulates on the inside of the kiln, blockages can impede material movement causing kiln shutdowns (Hendrik and Padovani 2003).

During the 56-hour trial Syverud (1994) mentioned earlier, chipped tires were used as an alternative fuel to partially replace coal. Over the 56-hour period, the SO_2 levels dropped 25%. However, the plant experienced operational problems from the rapid increase in SO_3 levels that caused build-up and the smell of sulfur in the preheater.

2.4.4 Other Problematic Emissions

Many other compounds may be created in the kiln system and emitted into the atmosphere in addition to the three predominate emission types previously discussed. There is a lack of literature directly relating alternative fuels and emissions of these compounds, so a brief discussion of their formation and potential dangers will be presented in the following sections.

2.4.4.1 Dioxins and Furans

Polychlorinated dibenzodioxins (dioxins) and polychlorinated dibenzofurans (furans) are byproducts from the combustion of organic compounds mainly found in the raw materials. Dioxins and furans will be denoted PCDD and PCDF respectively hereafter. PCDD and PCDF are considered unintentional persistent organic pollutants (POPs) and measures were taken to minimize these pollutants by the Cement Sustainability Initiative (CSI) (Loo 2007). PCDD and PCDF form between 290-790°C with the latter forming at a temperature greater than 700°C (Bech and Mishulovich 2004).

These temperatures concentrate the formation of PCDD/PCDF to the preheater zone and post preheater zone, which includes the particulate matter control device (PMCD). Karstensen (2008) reported that temperatures in the preheater and post preheater zones range from 850-1250°C and 250-290°C respectively. The control of PCDD/PCDF emissions is possible and can be reduced if the number of stages in the preheater is increased, thus reducing the flu gas temperature below the formation threshold of 260°C (Bech and Mishulovich 2004). According to Conesa et al. (2008) and others, the type of fuel used does not significantly impact the amount of PCDD or PCDF formed in the preheater or post preheater (Loo 2008, Karstensen 2008).

Dioxins and furans are transported to humans through the food chain as well as dermal absorption and inhalation (Kirk 2000). PCDD/PCDF are a known animal carcinogen and probable human carcinogen. Once ingested, short term effects of PCDD/PCDF can include allergic dermatitis, eye irritation, and gastrointestinal disturbances. Long term effects include liver and kidney damage and reproductive affects (Kirk 2000).

2.4.4.2 Metals

Metals are present in small concentrations in both fuels and raw materials used during the production of cement (Schuhmacher et al. 2004). Metals that are not adsorbed into the clinker are either collected by particulate matter control devices with the cement kiln dust or emitted to the atmosphere through stack emissions (Conesa et al. 2008). The toxicity of some heavy metals in stack emissions raises concern for public heath. Three classes of metals were formed to differentiate between their toxicity levels. The classes are as follows:

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)

Class I contains the metals that are most toxic and Class III contains the least toxic. The volatility of the metals is determined by their behavior in the kiln and how they exit the kiln. The majority of the metals are carried out by the clinker, but metals such as mercury is of concern because it remains volatile, cannot be controlled by dedusting, and exits the kiln in a vaporous form (Conesa et al. 2008). Conditioning alternative fuels by removing metals that could disrupt the mechanical operation or cause environmental concerns is necessary and considered a method for reducing metallic emissions (Bhatty 2004).

2.4.4.3 Particulate Matter and Cement Kiln Dust (CKD)

Particulate matter is created throughout the entire process of cement manufacturing. Grinding, crushing, and pyroprocessing create particles that range from 1-100 µm in diameter (Richards 2004). To add perspective to size, a human hair's diameter is roughly 50 µm (Richards 2004). The dividing line between coarse and fine particles is 10 µm (PM_{10}). The former can cause respiratory problems due to the potentially toxic concentrations of metals and other compounds, while coarse particles tend not to cause health concerns and are considered merely a public nuisance (Hendrik and Padovani 2003). In 1997 the Environmental Protection Agency (EPA) revised the

National Ambient Air Quality Standard to include a 50% cut point for particulate matter with diameters less than 2.5 μm ($PM_{2.5}$). The EPA deemed that particles of this size are of greater concern because they can efficiently penetrate deeply into the respiratory track (Richards 2004).

Particulate mater control device (PMCD) is any device such as a fabric filter or electrostatic precipitators (ESP) used to collect cement kiln dust (CKD). Today, these filters are quite efficient and have the ability to collect upwards of 99% of CKD (Hendrik and Padovani 2003). Since the captured CKD is nearly identical chemically to the kiln feed, rerouting it from the baghouse to the kiln reduces energy and material costs (Hendrik and Padovani 2003).

Cement kiln dust is a loosely labeled material referring to the unburned and partially burned particles from the kiln feed, clinker and interior lining of the kiln (Hendrik and Padovani 2003). The particle size and chemistry greatly vary depending on the raw materials, fuel, pyroprocessing type, and equipment layout (Hawkins et al. 2004). Cement kiln dust is typically collected by fabric filters and electrostatic precipitators (ESP) from stack emissions, alkali bypass systems and clinker coolers (Hendrik and Padovani 2003). The majority, if not 100% of CKD, is typically recycled back into the kiln feed unless the alkali or sulfur contents are excessively high. In this case, the CKD is used for other purposes that are discussed later or landfilled (Hawkins et al. 2004).

Although there is not much information on total quantities of CKD produced by cement plants, the Portland Cement Association (PCA) conducted several decade-long U.S. industry-wide surveys to follow the production and disposition of CKD. Hawkins et al. (2004) reported that the total amount of CKD disposed of from 1990 to 2000 decreased by 16% and the CKD landfilled per unit of clinker decreased from 60 kg/Mg to 32 kg/Mg while the quantity of clinker produced over the same time period increased by 55%. A generic chemical breakdown of CKD is shown in Table 2.13.

Table 2.13: 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

Cement kiln dust that is not recycled back into the kiln due to high alkali or sulfate concentrations has beneficial uses in alternative applications and industries. Due to high potassium and lime concentrations’ ability to counter act acidic soils, CKD is commonly used as a fertilizer. Cement kiln dust is also used for soil stabilization and consolidation for the construction of streets and highways because of lime’s ability to harden when exposed to moisture. Other common uses include landfill liners, gas scrubbing, and wastewater neutralization (Hawkins 2004).

2.5 Effects of Major and Minor Elements on Portland Cement

During the manufacture of portland cement, there are major and minor elements at hand. These elements are either integrated into the clinker or emitted into the atmosphere. Several of the major elements are discussed in the following sections and Table 2.14 tabulates minor elements along with their possible effects on cement manufacturing.

2.5.1 Alkalies (Sodium and Potassium Oxide)

Sodium (Na) and Potassium (K) are typically addressed together because they share similar behavior characteristics in cement manufacture and they are both found in the raw materials. They are also the most common alkalies in portland cement. Clay or shale is the predominate carrier for sodium and potassium but they can also be found in alternative raw materials such as fly ash and blast furnace slag (Bhatty 2004).

Alkalies are incorporated into the clinker with varying percentages depending on the amount of sulfur present in the clinker. Bhatty (2004) stated that “potassium compounds are more volatile than sodium compounds.” In the kiln, alkalies volatilize from 1400-1500°C and condense in cooler sections of the kiln. Rings or blockages can form inside the kiln causing kiln shutdown. This can be avoided by using an alkali bypass system in which alkali sulfates and chlorides may be removed and reside in the CKD. This is one reason that CKD typically exhibits higher alkali contents.

Table 2.14: Summary of possible effects of minor elements on cement manufacturing (adapted from Bhatty 2004)

Elements	Possible Effects
Antimony, Sb	Incorporate in clinker as calcium antimonates under oxidizing conditions and at high temperatures, reduced alite and belite size
Argon, Ar	No known effect
Arsenic, As	Volatile, goes to CKD, also incorporated in clinker as low-volatile calcium arsenates, reduces C_3S formation
Barium, Ba	Reduces melt temperature, replaces Ca in all clinker phases except ferrite, also improves clinker mineralogy
Beryllium, Be	In traces, decomposes alite, produces dentritic belite
Bismuth, Bi	No known effect
Boron, B	Decomposes C_3S, stabilizes βC_2S, promotes free-lime formation
Bromine, Br	Volatile, may form bromine alinites
Cadmium, Cd	Forms volatile halides/sulfides, 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
Chlorine, 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
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_3S to form tricalcium germinate (C_3G) that reduces to dicalcium germinate (C_2G) and free-lime
Helium, He	No known effect
Hydrogen, H	No known effect
Indium, In	In traces, volatile
Iodine, I	In traces, volatile
Krypton, Kr	No known effect
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
Manganese, Mn	Goes to ferrite, can replace Si and Ca in C_3S, gives dark brown to blue color

Table 2.14 (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 solutions with C_3S and C_2S, replaces Ca in C_3S and C_2S
Neon, Ne	No known effect
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 clinkers)
Phosphorus, P	Decomposes C_3S to C_2S and free lime, reduces negative effects of alkalies
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 clinker or emissions, may also form unstable selenates
Silver, Ag	In traces, no known effect
Sodium, Na	Lowers melt temperature, promotes initial 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, colaile, 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 phases, 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 crystals
Uranium, U	Gets uniformly distributed in clinker, shows little volatilization
Vanadium, V	Goesn into alite, forms larger crystals, produces ragged belite, reduces melt viscosity, free lime, effects grindability and lining, imparts tan color
Xenon, Xe	No known effect
Yttrium, Tb	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

Alkalies increase the concentration of hydroxide ions in the clinker. This increases the rate of hydration and allows for the formation of calcium hydroxide (CH). When the hydration rate is accelerated, the setting and strength development are also effected. The hydration of portland cement is discussed in more detail in Section 2.6. The increased concentration of OH^- also helps maintain the high pH required for a stable paste (Tennis and Kosmatka 2004). Jackson (1998) reported that for cements containing alkali contents over 0.8 %, early strength increases ~10 % and 28 day strengths fall ~10-15 %. It was also noted that high alkali contents typically increase drying shrinkage characteristics and reduce setting times (Lawrence 1998).

Compressive strengths and setting times are shown in Tables 2.15 and 2.16 as reported by Lawerence (1998). Both tables show the relationships between a control mixture and a mixture with increasing additions of sodium or potassium oxides. In Table 2.15, an increase of sodium oxide actually retards the setting times, which conflicts with Jackson's findings. However, an increase of potassium oxide accelerates the initial and final setting times.

The effects of alkalies on compressive strength can be seen in Table 2.16. Addition of sodium oxide lowers the compressive strength at all ages. Lawrence and Jackson found that additions of potassium oxide increases early-age strength and decreases long-term strength.

Table 2.15: Setting times of cement with varying alkali contents (Lawrence 1998b)

Cement + sodium or potassium oxide in clinker		**Setting Time (min)**	
	H_20 %	**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 2.16: Compressive strength of cement with varying alkali contents (Lawrence 1998b)

Cement + sodium or potassium oxide in clinker	**Compressive Strength (MPa)**			
	1 Day	**3 Day**	**7 Day**	**28 Day**
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

Excessive alkali contents, when coupled with reactive silica in the same aggregate causes a phenomenon known as alkali-silica reaction (ASR). Some aggregates contain a particular type of silica that in the presence of alkalies and moisture, react together forming an expansive gel that causes cracking from the inside of concrete. This reaction continues until either all the alkali or the silica is consumed. Bhatty (2004) reported that the alkali-silica reaction can be resolved with the addition of sulfates in the kiln feed or during grinding.

2.5.2 Chlorine (Cl)

Chlorine (Cl) can be found in raw materials such as clay and limestone, and in primary and secondary fuels such as coal and waste derived fuels (Bhatty 2004). Bhatty reports chlorine concentrations of 10-2800 ppm in traditional fuels, 0.02% in kiln feed, and 90 ppm in clinker. Chlorine readily combines with sodium and potassium forming alkali chlorides. These chlorides, like the alkalies, form kiln rings by volatizing in the burning zone of the kiln and condensing in the cooler sections. It is for this reason that a limit of 0.015% is used for the total amount of chloride introduced to the system (Jackson 1998). According to Bhatty (2004), if a preheater is used, then 99% of the chlorine is recaptured by the kiln feed in the calcining zone. Modern kilns are also typically equipped with alkali by-pass systems that redirect alkali chlorides to dust collectors.

Alkali chlorides are regarded to have insignificant effects on the properties of cement. Clinker typically contains less than 0.03% chlorine because it is volatile. Alkalies are also reduced in the presence of chlorines. In low alkali cements, additional chlorine is added to increase alkali volatilization and removal (Bhatty 2004).

In waste derived fuels such as scrap tires and waste oils, concentrations of chlorine are high enough to cause significant operational problems even if by-pass systems are used. Chloride condensation plumes in emission stacks are difficult to remove and are caused by high chloride concentrations. High chloride levels can also have a deleterious effect on the brick lining of kilns.

Waste derived fuels as mentioned above contain high concentrations of chlorine. Kikuchi et al. (2008) reported on the methods used to group plastics according to their chlorine content in the European Union. Kikuchi proposes that plastics be divided into two groups; one with low chlorine content (<0.5%) and the other with higher chlorine content. The lower chlorine content plastics would be used for waste to energy applications such as cement manufacturing and the chlorine rich products would be land filled. With the current sorting practices in the EU, of the total mixed waste plastics, 13% are recycled for energy use and 52% is land filled. With the sink-float separation system, which is a density-based test to separate chloride rich from chloride poor material, 47.5% of the plastics could be used for energy and 16.9% would be land filled.

Jackson (1998) stated that typical portland cement standards limit chlorine present to 0.1% in order to limit the corrosive effects chlorides have on reinforcing steel. However, problems on the cement production side would occur long before this limit was reached.

2.5.3 Magnesium (Mg)

Magnesium (Mg) is a derivative of magnesium carbonates that are found in limestone. Clay and shale also contribute magnesium to a lesser extent. In a typical clinker sample, magnesium's concentration is 8900 ppm and constitutes for 0.63% of the kiln feed (Bhatty 1994). Magnesium, in small quantities provides beneficial effects but in larger concentrations, negatively impacts cement properties.

Magnesium is limited to 6% in cement by ASTM C 150 to minimize the deleterious effects that lager quantities of magnesium have. Bhatty (1995) reports that when levels of magnesium oxide exceed 2%, large periclase crystals form and react with water causing expansion and the deterioration of concrete. On the other hand, in small quantities, magnesium improves the burnability of clinker in the pyro-process (Christensen 1978).

Magnesium's characteristics depend on the rate of clinker cooling (Bhatty 1995; Lawerence 1998). When cooled slowly, only a small portion of magnesium is retained (~1.5%) and the remainder transforms into large periclase crystals. Rapid cooling has the opposite effect. Most of the magnesium is retained in ferrite and aluminate phases. In

Table 2.17, compressive strengths were collected from concrete samples containing varying amounts of magnesium and either rapidly or slowly cooled clinker. According to Lawerence (1998), several researchers found that magnesium content did not significantly affect strength. The results do show, however, that slowly cooled clinker decreases the compressive strength compared to rapidly cooled clinker.

Table 2.17: Compressive Strengths results from clinker cooled at different rates with various MgO content (adapted from Lawerence 1998)

MgO (%)	**Compressive Strength (MPa)**			
	2 Day	**7 Day**	**28 Day**	**90 Day**
Rapidly Cooled Clinker				
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
Slowly Cooled Clinker				
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 found in raw materials such as limestone, shale, sands, and clays. It also occurs in various slags and flyash that are used in kiln feed (Bhatty 1994). Phosphorus typically constitutes 0.04% of the kiln feed and has a concentration of 440 ppm in clinker (Bhatty 2004). With proper proportioning, phosphorus will improve cement properties, but in excess, hydration and strength parameters are affected.

Jackson (1998) reports that phosphorus levels up to 0.3% in the clinker improve cement hydraulic properties and increases setting time approximately 20 minutes. According to Nurse (1952), high phosphorus concentrations cause C_3S (alite) to decompose into C_2S (belite) and excess lime. Although, high levels of phosphorus inhibit the formation of C_3S, additions of fluorine allow the formation of C_3S to continue (Jackson 1998). Jackson (1998) reports that phosphorus in excess of 1%; each additional percent decreases the C_3S content by 10%. In addition to fluorine, additions of chlorides supplement the stabilization of phosphorus in C_3S. With the proper phosphorus levels, the negative effects of alkalies on strength are reduced.

2.5.5 Sulfur (S)

Sulfur (S) is found in both raw materials and fuels. Respective examples of each include limestone and coal. In the raw materials, sulfur is in the form of sulfates or sulfides. Both are volatile compounds that oxidize at different temperatures (Jackson 1998). According to Bhatty (2004), sulfur constitutes 0.06% by weight of the kiln feed, up to 6% by mass in some coal, and 3200 ppm in clinker.

Sulfides oxidize between 400-600°C. At theses temperatures, 15-40% of sulfide is converted into sulfur dioxide and escapes into the atmosphere because temperatures are too low for sufficient calcium oxide to bind with the sulfur (Neilson 1991). On the other hand, sulfates oxidize between 900-1000°C. At these temperatures, sulfur reacts with volatized alkalies and calcium oxides. The alkali sulfates and calcium sulfates are combined into the clinker and removed from the interior of the kiln (Jackson 1998). Some of the lower melting point alkali and calcium sulfate can lead to blockages around the preheater (Jackson 1998).

Sulfur vaporizes and condenses in the varying temperatures of the kiln. Sulfur and alkalies typically condense in the cooler, upper portion of the kiln onto the incoming feed increasing the sulfur and alkali contents of the feed in the middle portion of the kiln.

This problem can be minimized with the use of an alkali by-pass system, although the by-pass dust typically must be discarded instead of recirculated because of the high sulfur and alkali contents (Bhatty 1995).

According to Strunge et al. (1985) increasing the sulfate content increases C_2S and decreases C_3S with a constant silica modulus. The silica modulus or ratio is a measure of burnability. The higher the ratio, the more energy required to combine the raw materials in the system. Reports vary on the effect that sulfates have on hydraulic properties of cement. Gartner 1980 reports that the sulfate in clinker is unreactive and does not contribute to control setting or hardening. Gartner suggests that even high sulfate clinker would need gypsum additions to control set. The quantity of gypsum added depends on the amount of C_3A in the cement but should not exceed specifications set by ASTM C 150.

2.5.6 Zinc (Zn)

Zinc (Zn) is a trace element found in both raw materials and fuels. Concentrations range from 22-24 ppm for limestone, 59-115 ppm for clay and shale, 16-220 ppm for coal and 96 ppm for clinker. In alternative fuels such as tires, zinc concentrations rise as high as 10,000 ppm (Bhatty 2004). Although zinc is a trace element, changes in concentration significantly impact the performance of clinker.

Hornain (1971) reported that zinc is "preferentially retained in ferrite, followed by alite, aluminate, and belite." Odler (1998) stated that amounts of C_3S and $C_2(AF)$ increase while C_2S and C_3A decrease with additions of zinc oxide. Approximately 80-90% of zinc oxide from the kiln feed is incorporated into the clinker (Sprung et al. 1978;

Knöfel 1978). Roughly half of the zinc is distributed to the silicates, mainly C_3S, and the other half is taken by the aluminates, mainly ferrite (Knöfel 1978; Rsuboi et al. 1972).

Several sources agree that reductions in free lime, slowing hydration, and reducing strength are all effects of zinc oxide in excess of 1% (Jackson 1998; Odler et al. 1980; and Knöfel 1978). Olmo et al. (2001) conducted research on the influences that zinc has on the setting time and strength development of portland cement. It was found that zinc oxide increased initial and final setting times by 21.7 and 10.7 minutes respectively. The unconfined compressive strength also decreased significantly at early ages but the effect of the zinc oxide decreased at later ages compared to control mixes.

2.6 Hydration of Portland Cement

The hydration of portland cement begins once water comes in contact with cement. Through exothermic reactions, new hydration products are formed. The role of the hydration products is to glue the aggregates together. The main compounds of cement can be formed into two distinct groups: Calcium Silicates and Aluminates. The Calcium silicate group includes Tricalcium silicate (C_3S) (alite) and Dicalcium silicate (C_2S) (belite). Alite and belite are the primary cement compounds and make up 70 to 75% of cement. They begin to hydrate within an hour of adding water to the cement and are responsible for the rate of strength development (Mehta and Monteiro 2006). The aluminates include tricalcium aluminate (C_3A) and tetracalcuim aluminaferrite (C_4AF). Tricalcium aluminate and tetracalcium aluminoferrite control setting times and account for 25 to 30 percent of portland cement.

Hydration of the aluminates is immediate in the presence of water. Since the aluminates are responsible for setting, this reaction must be retarded in order for cement to be used as a construction material. Typically, gypsum, a source of sulfate, is added to slow the hydration of C_3A and allow time for placement of the concrete. Equation 1 shows that calcium sulfoaluminate hydrate (ettringite) is the product formed from the C_3A, water, and gypsum reaction.

$$C_3A + \text{Gypsum} + H_2O \rightarrow \text{Ettringite} + 1350\ \text{J/g} \qquad (1)$$

Ettringite remains stable as long as sulfates are present. After several hours, all the gypsum is consumed and ettringite becomes unstable and converts into monosulfate hydrate (MSH) (Equation 2). The presence of MSH allows the hydration of C_3A to continue.

$$\text{Ettringite} + C_3A + H_2O \rightarrow \text{MSH} + 0\ \text{J/g} \qquad (2)$$

The rate of hydration is controlled by the reactivity of the C_3A in the clinker and the availability of sulfate in the solution (Mehta and Monteiro 2006). The effects that different combinations of C_3A and sulfate have on the hydration of cement are shown in Figure 2.9.

As mentioned earlier, the calcium silicates begin to hydrate within an hour of combining water and cement. The silicate hydration equations are shown below:

$$C_3S + H_2O \rightarrow \text{C-S-H} + 3\text{CH} + 500\ \text{J/g} \qquad (3)$$

$$C_2S + H_2O \rightarrow \text{C-S-H} + \text{CH} + 260\ \text{J/g} \qquad (4)$$

Calcium silicate hydrate (C-S-H) and calcium hydroxide are the two reaction products formed. Because varying water cement ratios, age of hydration, and temperature alter the chemical composition of the calcium silicates, a notation is used that does not imply a fixed chemical composition (Mehta and Monteiro 2006). The microstructure of C-S-H is very strong and dense which is the reason for the adhesive properties of silicates. On the other hand,

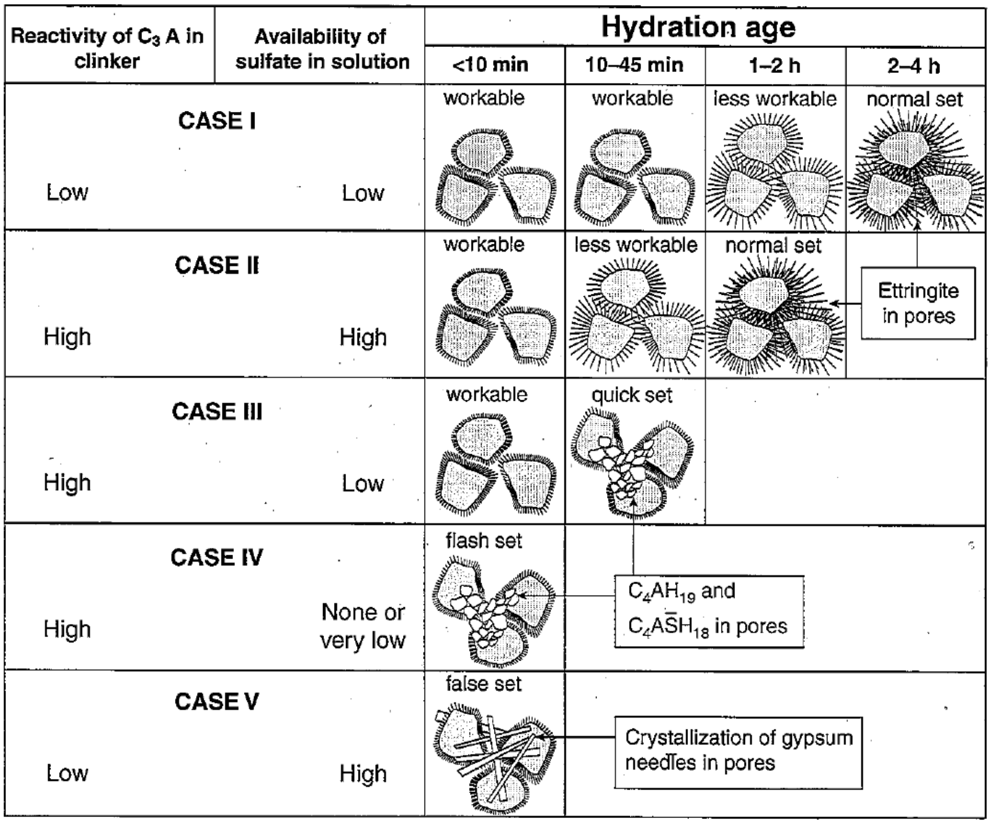

Figure 2.9: Influence of A/S on setting characteristics of portland cement (Mehta and Monteiro 2006)

calcium hydroxide is weak and soluble. The hydroxide ions do however minimize corrosion because of a high basic pH.

2.6.1 Chemical Admixture Effects on Portland Cement

The American Concrete Institute (ACI) defines an admixture as any ingredient in concrete that is added to the batch before or during mixing other than water, cement, aggregate, or fiber reinforcement to enhance fresh, setting, or hardened concrete properties. The use of admixtures dates back to the earlier forms of concrete and before any scientific knowledge of the subject. For example, blood was used as an air entrainer, animal fats improved workability and urine was used to vary setting rates (Edmeades and Hewlett 1998). Admixtures are typically categorized as active, interactive, or passive. Active admixtures alter the rate of hydration by reacting with the cement components. Accelerators and retarders are within this category. Interactive admixtures, which include water reducers and air entrainers, are surfactants meaning that the admixtures work at the solid-liquid and air-liquid interfaces respectively. Passive admixtures do not change form passing into solution or remaining in suspension. Passive admixtures mainly affect physical properties of concrete such as viscosity, light adsorption and reflection (Edmeades and Hewlett 1998).

Common types of admixtures, the ASTM classification, and their typical effects on concrete mixtures are listed in Table 2.18. Other types of admixtures not listed in the table, but are in use today are corrosion inhibitors, shrinkage reducers, alkali-silica reactivity inhibitors. These admixtures will not be discussed as they do not pertain to the focus of this study.

Desirable fresh property modifications are retarding or accelerating setting times, increasing workability, reducing segregation, and decreasing the water content. Similarly, improved resistance to freezing and thawing, the alkali-silica reaction, and reduction of drying shrinkage, and permeability are several hardened concrete properties that can be modified by chemical admixtures. Over the past 50 years, the admixture industry has rapidly grown to accommodate the increasing demand and it is not uncommon in developed countries that at least one admixture is incorporated in 80 to 90 percent of the concrete made today (Mehta and Monteiro 2006). Kosmatka et al. (2002) states the following reasons to use admixtures:

- Decrease construction costs,
- Effectively achieve certain concrete properties, and
- Sustain quality of concrete during mixing, transporting, placing, and curing in adverse weather.

Table 2.18: Common admixtures and their functions
(adapted from Kosmatka et al. 2002)

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

2.6.1.1 Air-Entraining Admixtures

Air-entraining admixtures are surfactants that work at the liquid-air interface by decreasing water tension and promoting a stable air void system. Air-entrained concrete has better workability and freeze-thaw resistance than non air-entrained concrete because the air bubbles reduce friction between cement and aggregate particles and create a void system that water can expand into as it freezes. The admixture is characterized by its hydrophobic tail, a hydrocarbon chain, and its hydrophilic head, usually a carboxylic or sulfonic acid. The tail is oriented toward the air and the head is oriented toward the liquid. The negatively charged heads surrounding the air bubbles serve to lower the surface tension of the water, enable more bubbles to form during mixing, prevent the coalescence of bubbles, and form a stable, cohesive mixture. According to Kosmatka et al. (2002), air-entrainment in concrete improves its durability and resistance to surface scaling caused by chemical deicers as well as reducing or eliminating segregation and bleeding of fresh concrete.

Cement hydration is typically not affected by air-entrainers except in high dosages. According to Edmeades and Hewlett, high dosage can cause retardation of C_3S while accelerating C_3A. Another consequence from increasing air content is that concrete strength decreases with increasing air content. By rule of thumb, for every 1% increase in air, the strength decreases by 5%. Other factors that alter the performance of air-entraining admixtures are alkali content and fineness of the cement, carbon content of the admixture, and any organic impurities.

2.6.1.2 Water-Reducing Admixtures

Water-reducing admixtures are also surfactants. These surfactants work between the cement and liquid interface dispersing cement flocculation and freeing entrapped water. Using water-reducing admixtures allows a reduction in the amount of mixing water necessary to reach a particular slump. Water-reducing admixtures are classified into three groups depending on the percentage of water the admixture replaces. The types of water-reducing admixtures are low-range, mid-range, and high-range. Water-reducing admixtures can account for 5% to 30% of the mixing water. High-range water reducers fall into ASTM C494 Types F and G and can reduce water demand 12% to 30% (Kosmatka et al. 2002). The majority of superplasticisers are long chains of water soluble polymers made from synthetic chemicals. These negatively charged polymers adsorb in the surface of the cement grain and push away from adjacent negatively charged cement grains forming an even dispersion. The dispersion of cement grains before and after addition of a high-range water reducer is shown in Figure 2.10.

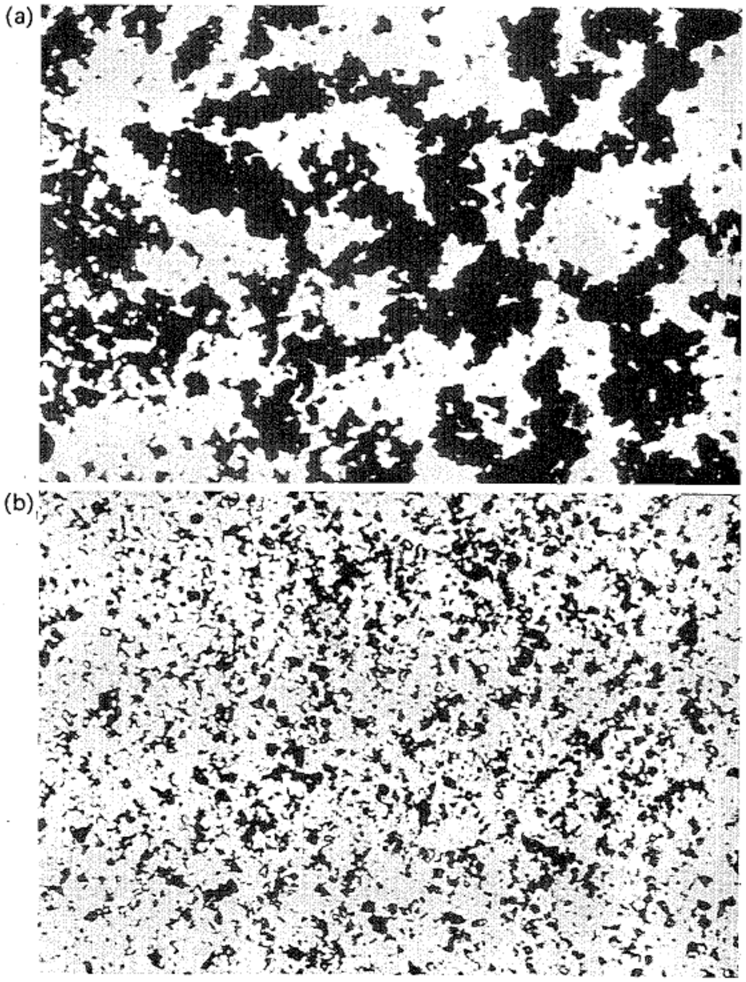

Figure 2.10: Effect of superplasticizer on cement grains (Edmeades and Hewlett 1998)

Slump loss is common problem with high-range water reducers because hydration products are formed more quickly due to the highly dispersed cement. Edmeades and Hewlett acknowledge this problem and remedy it by withholding the superplasticiser for a few minutes. This time laps allows ettringite to form, which slows the formation of reaction products, from the reaction between the clinker and the gypsum. Benefits from high-range water reducer are increased strength and decreased permeability if water reductions are made. Also a more debatable effect is that freeze-thaw resistance also is increased (Edmeades and Hewlett 1998).

2.7 Concluding Remarks

Fossil fuels have been traditionally used in the production of cement manufacturing. Immense quantities of these fuels are needed to in order to heat the raw materials to temperatures exceeding 1600 °C. As fuel prices continue rise, cement producers have started implementing alternative sources of fuels to reduce cost, emissions, and the demand for fossil fuels.

Waste or alternative fuels are by-products from other industries that come in many forms and can benefit both the cement producer and the environment. Since alternative fuels can replace both fuels and raw materials, production costs can be significantly reduced. Environmental benefits include reduced demand for fossil fuels, landfill waste disposal, and greenhouse gases. However, not all waste fuels are beneficial, and therefore each fuel needs to be thoroughly investigated before utilization.

Utilizing non-traditional fuels or materials in the manufacture of cement introduces new chemical compositions into the kiln environment. These changes could possibly alter the chemical composition of the cement and thus its final cement properties. Also, any variation in the composition of the alternative fuel could have adverse effects on the final cement properties. If successfully utilizing alternative fuels, the final composition of the cement would be a near match to cement produced with traditional fuels.

Emissions are heavily dependent on the fuels used during production. In the transition from fossil fuels to waste fuels, harmful gases produced in the pyroprocess can be reduced. Testing emissions produced by alternative fuels allows limits to be determined for feasible replacement rates as well as environmental protection. Emissions must also be continuously monitored throughout production to ensure environmental limitations are not exceeded.

Every alternative fuel produces a unique effect on the production of cement and final product. Effects can also differ between cement facilities. The geographical location of the cement plant, availability of fuel alternatives, and plant modification costs are considerations that must be addressed prior to implementing any fuel. Informed use of alternative fuels can benefit not only the manufacturer, but the rest of society.

Chapter 3
Experimental Plan

3.1 Introduction

The production of portland cement is a complex process involving many systems and materials working in synchronization. In Section 2.2, the production process was discussed in detail. The objective of this study was to determine if the partial replacement of a traditional fuel by an alternative fuel affects the manufacture and/or the cement performance. A comprehensive testing program was developed in order to achieve the objectives of this project. The remainder of the chapter details the experimental work regarding each objective.

In this study, traditional and alternative fuels were used simultaneously to produce cement. Two of the three alternative fuels tested were fired continuously over a 3-4 day period. The third fuel was fired over a 6-day period with the replacement rate of the alternative fuel increasing every two days. Lafarge North America's Roberta cement plant, a full-scale cement manufacturing facility in Calera, Alabama, conducted the trial burns. The cement plant conducted four separate trials, or burns, with each burn utilizing a different alternative fuel. A short description of each burn is provided below. Note that there are three trial burns and one baseline burn. "B" denotes the baseline burn with the remaining letters serving as an acronym for the fuel utilized.

1. B-CP – Coal (C) and plastics (P) were the fuels utilized during this burn period. This was the baseline burn to serve as reference for the construction and demolition (C&D), variable feed wood chips (VF), and soybean seed (Soy) trial burns shown below. This was a 72-hour continuous burn that took place in June of 2010. A sample of the waste plastic blend is shown in Figure 3.1.

2. C&D – Coal (C), plastics (P), and construction and demolition waste (C&D) were the fuels utilized during this trial burn. The types of wood utilized include dimensional lumber, plywood, and pallets. The paper included corrugated boxes and miscellaneous paper materials. The plastic consisted of solid and cellular foam and polyethylene film. This was an 80-hour continuous burn that took place in June of 2010. A sample of the construction and demolition waste is shown in Figure 3.2.

3. VF – Coal (C), plastics (P), and variable feed (VF) woodchips were the fuels utilized during this trial burn. This was a 148-hour, continuous burn that took place in July of 2010. This trial was broken into three phases, each representing an increased substitution percentage of wood chips. The phases are denoted according to their substitution rates as follows: VF 5%, VF 10%, VF15%. A sample of woodchips is shown in Figure 3.3.

4. Soy – Coal (C), plastics (P), and soybean seeds (Soy) were the fuels utilized during this trial burn. This was a 72-hour continuous burn that took place in October of 2010. A sample of the soybean seeds is shown in Figure 3.4.

Figure 3.1: Waste plastic blend

The fuels utilized during this study are categorized in Figure 3.5. Plastics represent a combination of alternative fuels and traditional fuels. Although plastics are considered an alternative fuel by the industry, they are a part of the Roberta Plant's normal operation and thus considered a traditional fuel for this study. Construction and demolition waste, woodchips, and soybean seeds are the only alternative materials evaluated throughout the remainder of this study.

Figure 3.2: Construction and demolition waste

Figure 3.3: Woodchip waste

Figure 3.4: Treated soybean seeds

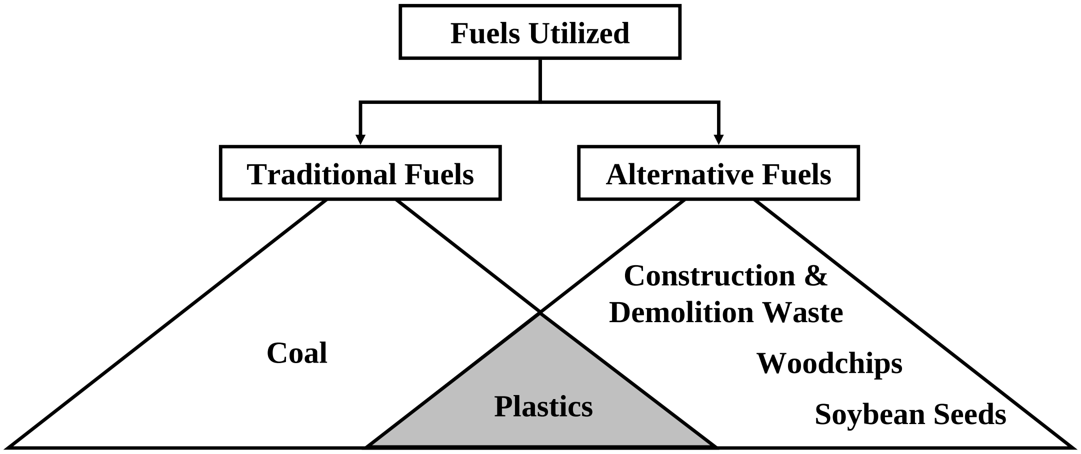

Figure 3.5: **Classification of the fuels utilized during the study**

The first phase of the testing program was to collect samples of all of the materials involved in the process. For convenience and simplicity, a sampling plan was developed to match the materials, sample quantities, and frequencies already established by the cement plant.

The actual testing of the sampled material made up the second half of the testing program. To be as thorough as possible, many different tests were conducted. The specific tests are detailed in the appropriate sections that follow.

It should be noted that this study is a continuation of previous work (Swart 2007; Akkapeddi 2008; Folta 2010). Therefore, previous findings may be mentioned or briefly discussed throughout the remainder of this document.

3.1.1 Definitions

All materials involved in the manufacturing of cement are collectively labeled as process inputs or process outputs. Process inputs refer to materials placed in the system such as raw material and fuel. Process outputs refer to products that exit the system such as clinker, cement kiln dust (CKD), and emissions. It should be noted that some materials fall into both categories. CKD falls into both categories because the dust is collected throughout the manufacturing process and is typically recycled back into the kiln feed.

The process of sampling refers to methods used to isolate a portion of material from a larger source. A specimen refers to a portion of a sample that will be tested. Discrete and composite specimens were the two types of specimens collected. A discrete specimen refers to a portion of a single sample collected from a single source and time.

A composite specimen refers to a portion of multiple samples collected from one source over a particular time period.

3.2 Sampling and Testing Overview

A sampling plan was developed and detailed throughout this chapter in order to better understand and carry out the objectives of this project. The plan consists of sampling all process inputs and outputs throughout production in order to evaluate the overall effects of utilized alternative fuels. A diagram of this plan is depicted in Figure 3.6. This section provides a general overview of the sampling and testing performed during this study. Sampling and testing are detailed in Sections 3.3 and 3.4, respectively.

Throughout this study, three organizations worked together in order to compile and validate test results and fulfill study obligations. These organizations included the cement plant, an external laboratory, and Auburn University. Many tests were performed by multiple parties in order to validate test results with the exception of the fresh and hardened properties of concrete made from the cement. Auburn University was the only party involved in concrete testing.

Lafarge North America’s Robert cement plant was responsible for process input and output sample collection and the manufacturing of the cement. All of the cement was produced and distributed under normal production operations. When necessary, in order to accommodate the alternative fuels, modifications were made by the cement plant. The plant’s laboratory conducted chemical analysis on all of the raw materials used in addition to performing tests on cement paste and mortar. Alternative fuels utilized during the burns were not analyzed by the cement plant. The clinker and cement underwent additional testing at the cement plant’s specialty lab. Plant emissions were also closely monitored to ensure environmental and production regulations were met.

An external laboratory was used in order to perform chemical analyses on the raw materials, fuels, and final products. The samples collected by the cement plant were shipped to the external laboratory by Auburn University. The results from the external laboratory were used to determine how the alternative fuel affected process inputs and outputs during operation. To determine various parameters of each material, several test methods were used and are explained in Section 3.4.

A chemical analysis was the predominate test conducted on all materials. The cement plant and the external laboratory used X-Ray Fluorescence (XRF) to determine the chemical properties of all the materials except RM3 and the plant emissions. A Prompt Gamma Neutron Activation Analyzer (PGNAA) was used by the cement plant to assess the properties of RM3. In addition to XRF testing, the external laboratory conducted a proximate, ultimate, and combustion analysis as well as determining the ash content for each fuel. Details on emissions testing are detailed in Section 3.4.4.

Auburn University was the final party involved in this study. Samples collected by the cement plant were collected, conditioned, and shipped to the external laboratory by Auburn University. Cement from each burn was also collected by Auburn University for the purpose of conducting tests on paste, mortar, and concrete. All the results from the cement plant and the external laboratory were collected and compiled by Auburn University in order to be presented in this document.

3.3 Sampling

Cement plant personnel collected samples of all materials used during the trial burns. The sampling plan developed by Auburn University followed an in situ-plan used by the cement plant and was modified to include all fuels. The sampling plan used by the cement plant with its respective burn is shown in Table 3.1. All of the process inputs and outputs were collected in one-gallon tin containers with the exception of the cement and liquid fuel. The cement was collected in one-gallon plastic containers and the liquid fuel was collected in 16-ounce, high-density polyethylene bottles.

The projected total number of samples collected during each burn is shown in Table 3.1. It should be noted that fewer samples may have been collected due to the plant's staffing during the burns. The raw materials were sampled once during each burn. The remaining materials were sampled at a regular frequency.

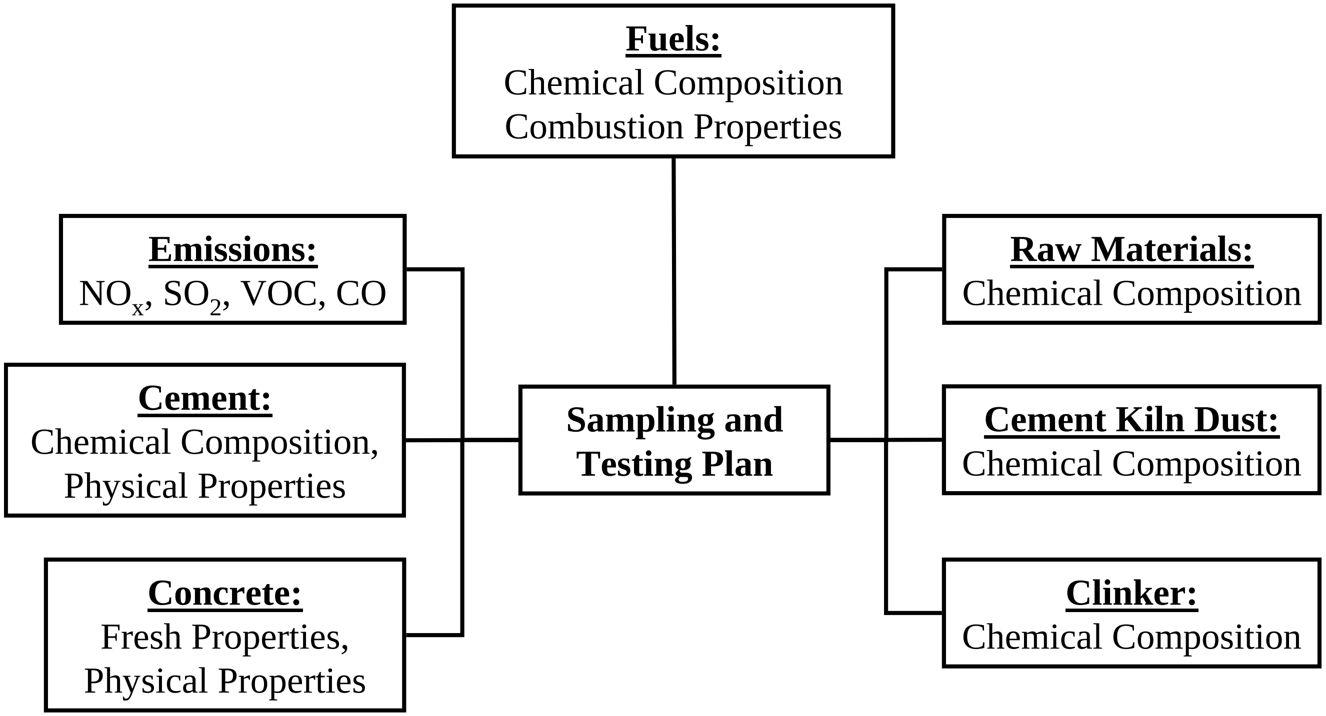

Figure 3.6: **Sampling and testing plan (adapted from Folta 2010)**

Table 3.1: Sampling plan

Material	**Samples per burn**			
	Trial Burn			
	B-CP (June 2010)	**C&D** (July 2010)	**VF** (July 2010)	**Soy** (Oct. 2010)
RM1 - RM5	1	1	1	1
Kiln Feed	6	6	12	6
Pulverized Coal	6	6	12	6
Cement Kiln Dust	6	6	12	6
Clinker	36	36	72	36
Plastics	24	24	48	24
Alternative Fuel	NA	24	48	24
Material	**Samples per grinding period**			
RM6	6	6	12	6
Cement	10	10	20	10

Notes: RM – Raw Material
NA – Not applicable

For example, the baseline burn lasted 72 hours. Plastics were collected at a frequency of 8 samples every 24 hours, which equals 24 total samples. The frequency at which a sample was taken was determined the expected variability of each material. The plastic feed comprises material from multiple sources that is blended into a homogeneous stream to produce an ideally constant energy value. Plastic samples are taken every 3 hours in order to gain a better understanding of the actual energy values provided by the plastic fuel. Clinker was sampled at the highest frequency because it is the final product before finishing occurs and any chemical variation in the clinker can cause significant changes to final properties of cement. A generic schematic of a cement plant and specific sampling points from which materials are taken is shown in Figure 3.7. In the following section, details are provided for each material sampled.

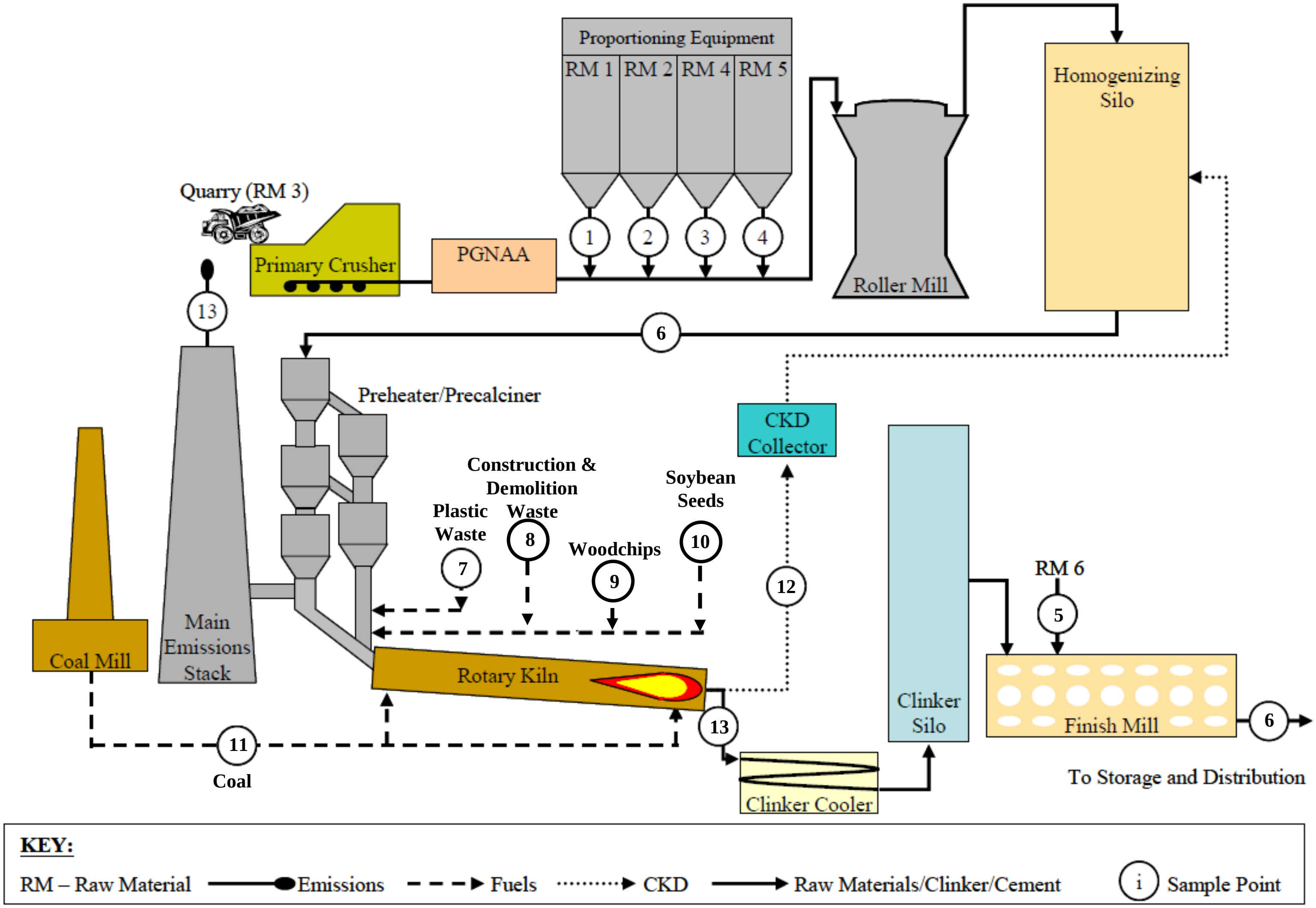

Figure 3.7: Schematic of cement plant operation (adapted from Folta 2010)

3.3.1 Sample Collection

From Table 3.1, it can be seen that six raw materials were used during the production of cement at this plant. Due to sources of the raw materials being deemed proprietary information, they will not be disclosed and will be referred to as RM1 – RM6 hereafter. The primary raw material RM3 is quarried and shipped to the plant where it is crushed to a manageable sized and its chemical composition is determined by a Prompt Gamma Neutron Activation Analyzer (PGNAA). From this point the material is either stockpiled or sent directly to the proportioning equipment. The chemical composition of the RM1, RM2, RM4, and RM5 are determined by X-Ray Fluorescence (XRF) and proportioned appropriately to meet the targeted cement chemical composition by the proportioning equipment. Each of the raw materials were sampled at their respective sampling points once per burn. A raw material sampling point is shown in Figure 3.8.

Figure 3.8: **Raw material sampling point**

Once proportioned, RM1 - RM5 are sent to the roller mill where the appropriate fineness for optimum burnability is achieved. The raw materials are then sent to the homogenizing silo where they are combined with cement kiln dust (CKD) and mixed to form a homogeneous blend know as kiln feed. Prior to entering the homogenizing silo, the CKD is collected at sampling point 12. The kiln feed is sampled at sampling point 6 before entering into the preheating tower. A kiln feed sampling point is shown in Figure 3.9. During each burn the kiln feed and the CKD were sampled approximately six times each.

All fuels were sampled throughout each burn, though the alternative fuels more frequently than the traditional fuels. There are two locations in the kiln system where fuels are introduced.

Figure 3.9: Kiln feed sampling point

The upper end of the kiln consumes the majority of the coal and alternative solid fuels such as plastics, woodchips, and C&D waste. These fuels are used to partially calcinate the kiln feed before its entry into the kiln. The remaining coal and liquid fuels are injected into the lower end of the kiln. The burner at the lower end of the kiln is responsible for the remainder of the pyroprocess.

The alternative fuels are transported from the storage facility by conveyer to the alternative fuel injection point depicted in Figure 3.7 at sampling points 7-10 and Figure 3.10. Once the ASF is transported to a bin above the injection point, a screw feeds the alternative fuel into the kiln system at a controlled rate.

Coal was collected approximately six times each burn. Samples were taken from sampling point 11 shown in Figure 3.7 by an automated plunger system that removes the pulverized material from the injection stream. The automated plunger system is shown in Figure 3.11. At the lower end of the kiln, the kiln feed has undergone a chemical transformation and has become a homogeneous molten mass known as clinker. The clinker exits the lower end of the kiln and falls onto a revolving grate that cools the clinker. The clinker is sampled at point 13 in Figure 3.7 and process is depicted in Figure 3.12.

Once the clinker is cooled, it is transferred to a silo until it is ready to be ground. Raw material six is added to the clinker during the finishing process. RM6 is sampled in a similar manor to the raw materials and is collected at sampling point 5 in Figure 3.7. The finished portland cement sample is removed by an automated plunger at sampling point 6 in Figure 3.7. The process is depicted in Figure 3.13.

Figure 3.10: Alternative fuel conveyer and injection system

Figure 3.11: **Automated plunger system**

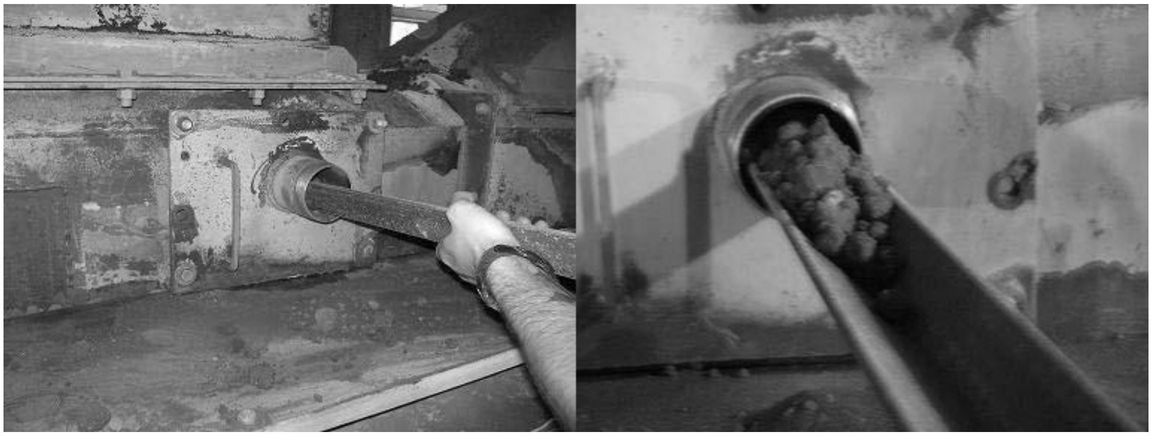

Figure 3.12 : Clinker sampling point

Figure 3.13: Portland cement sampling point.

3.3.2 Sample Conditioning, Shipping, and Storage

Once all the samples were collected from the trial burn at the cement plant, they were transported to Auburn University for further conditioning. All the samples were removed from the aluminum containers and placed into heavy-duty re-sealable bags to prevent the sample's moisture from corroding the insides of the containers and disturbing the *in-situ* chemistry of the material. Each plastic bag was labeled with the material content and the date and time the sample was taken. Samples were then prepared for shipping and testing.

Prior to shipping, the samples were organized into discrete and composite specimens. As previously discussed, a discrete specimen refers to a portion of a sample that was collected from a single source and time period. A composite specimen consists of a single source of material collected over multiple time periods. Regardless of the type of specimen made, the materials were placed into smaller re-sealable plastic bags and labeled with specific identification numbers for reference purposes.

Discrete samples were made from the types of materials that were thought to have the most compositional variability over the burn period. Sample types include the alternative solid fuel, clinker, and CKD. To prepare a discrete specimen, a sample was vigorously shaken and a random portion of material was taken from the original sample, and transferred to a re-sealable bag corresponding to its contents.

Composite samples were made from the types of materials that were thought to have the least compositional variability over the burn period. Sample types include the cement, kiln feed, and coal. Two types of composite samples were prepared. A daily composite specimen consisted of portions of samples collected over a 24-hour time period. A 3-day composite specimen consisted of portions of samples collected over a 72-hour time period. To prepare a composite specimen, a random portion of material was taken from the original samples over a 24-hour or 72-hour time period and transferred to a re-sealable bag corresponding to its contents.

All the specimens were boxed and shipped to appropriate laboratories to undergo chemical analysis. The remaining samples were placed into labeled, steel 55-gallon drums and transported to a temperature and moisture controlled storage facility in the event more specimens were needed for further testing.

3.4 Test Methods

In order to evaluate the possible effects of utilizing each alternative fuel, numerous materials in the production process were tested and evaluated. An effort was made to keep production parameters as consistent as possible in order to isolate the trial fuel as the independent variable. It is, however, inevitable that variations in the process conditions exist at a full-scale cement facility, and therefore a certain degree of deviation is expected. As a result, the addition of alternative fuels may only partially contribute to the variability in test results.

Physical properties of the cement were determined by the cement plant and Auburn University. Concrete was also mixed by Auburn University to evaluate its fresh and physical properties. Emissions were monitored by the cement plant to evaluate the impact of alternative fuels, as well as to ensure that environmental regulations were met.

Chemical analyses of all the raw materials and finished products were conducted by the cement plant and the external laboratory.

All the test results were gathered 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 chapter details the testing methods used to satisfy the objectives of this study.

3.4.1 Chemical Compositions

The combination of all material inputs determines the chemistry and performance of the process outputs. The primary method for determining chemical makeup was with the use of 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 a particular parameter in question. Since the parameters in question are typically small, reporting the results in ppm is most convenient.

The cement plant and the external laboratory performed chemical analyses on the materials. There was a slight difference between the standard parameters obtained by the two. The standard parameters collected by both parties are shown in Table 3.2. All the parameters in Table 3.2 were determined by XRF with the exception of Na_2O_{eq}. Na_2O_{eq} was determined by calculations provided in ASTM C 150 that incorporate the concentrations of Na_2O and K_2O. The detection limits that the external laboratory used for XRF are presented in Table 3.3.

3.4.1.1 Raw Materials and Kiln Feed

During the burns, there were six raw materials (RMs) collected. Due to the sources of these materials being proprietary and the request of the cement plant they will not be disclosed. RM1 – RM5 were each sampled once per trial before grinding and mixing and discrete specimens for each material was prepared for testing by the external laboratory. RM6 was sampled approximately 6 times during each trial and was sampled prior to being ground with the clinker. A 3-day composite specimen of RM6 was prepared for the external laboratory for each trial.

Table 3.2: Standard chemical parameters

Standard cement plant parameters (wt. %)	**Standard External laboratory parameters**	
	(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	Detection Limit (wt. %)	Parameter	Detection Limit (ppm)
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

The kiln feed consisted of a blend of RM1 – RM5 and was sampled approximately 6 times per trial. A 3-day composite specimen was prepared for testing by the external laboratory for each trial. As discussed earlier, with the exception of RM3, RM1 – RM5 were chemically analyzed by the cement plant and external laboratory utilizing XRF to acquire the standard parameter listed in Table 3.2. RM6 is typically not tested by the cement plant. RM3 is analyzed at the cement plant by using a Prompt-Gamma Neutron Activation Analyzer (PGNAA). The PGNAA obtains immediate compositional results that allow the remaining raw materials to be proportioned correctly.

The cement plant did not test all the raw materials during each burn. Reasons for this include the source of the material remaining constant or the tests just never being conducted. All the data provided by the cement plant, however, are the most recent available.

3.4.1.2 Cement Kiln Dust (CKD)

As stated previously, cement kiln dust is a unique material in that it is a process input and a process output. During the pyroporcess, dust is collected and recycled into the kiln feed if its chemical composition is acceptable. Approximately six samples were taken during each trial and tested as discrete specimens by both laboratories. XRF was used to determine each parameter listed in Table 3.2 except for moisture and Loss on Ignition (LOI). The external laboratory was the only entity to include these parameters.

3.4.1.3 Fuel Sources

As shown in Table 3.1, each alternative fuel was sampled approximately 8 times each day. In addition to using XRF for each fuel, proximate and ultimate analyses were conducted by the external laboratory. A list of parameters for the proximate and ultimate analyses is shown in Table 3.4. A calorific value was also collected by measuring the energy released through combustion. This value was reported on a dry basis and expressed in BTU/lb. The ash resulting from combustion was tested using XRF to determine the parameters listed in Table 3.2.

Coal was sampled six times over each burn period. The external laboratory tested 3-day composite specimens prepared from the samples collected. The results consisted of all the parameters listed in Table 3.2 and Table 3.4, in addition to the combustion and ash analysis previously discussed. Coal was the only fuel that the cement plant tested.

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

Construction and demolition waste was sampled in accordance with Table 3.1. C&D waste was sampled at a relatively high frequency because the fuel was comprised of a blend of material originating from multiple sources. Discrete specimens were prepare from the collected samples and were tested by the external laboratory to acquire all the fuel parameters discussed.

Woodchips were sampled in accordance with Table 3.1. Woodchips were sampled at a relatively high frequency due to their varying moisture contents. Discrete specimens were prepares from the collected samples and were tested by the external laboratory to acquire all the fuel parameters discussed.

Soybeans were sampled in accordance with Table 3.1. Soybeans were sampled at a relatively high frequency in order to identify any compositional variability in the fuel. Discrete specimens were prepared from the collected samples and were tested by the external laboratory to acquire all the fuel parameters discussed.

3.4.1.4 Clinker

Clinker samples were collected approximately every three hours each trial burn. In addition to meeting the parameters listed in Table 3.2, the cement plant calculated the equivalent alkali content and Bogue compounds in accordance with ASTM C 150 (2007). The free lime content (FCaO) of each sample was also determined by the cement plant.

Daily composite samples were prepared by Auburn University and tested by the external laboratory to determine the standard parameters shown in Table 3.2. Based on the data provided, Auburn University calculated the Bogue compounds in accordance with ASTM C 150 (2007).

The cement plant’s specialty laboratory was also sent similar composite specimens to determine the four major clinker phases using Rietveld analysis. Rietveld analyses typically provide more accurate results than the Bogue calculations specified by ASTM C 150 (2007).

3.4.1.5 Portland Cement

Portland cement was sampled in accordance with Table 3.1 and tested by the cement plant to obtain the parameter shown in Table 3.2 as well as the equivalent alkali content and Bogue compounds in accordance with ASTM C 150 (2007). The free lime content (FCaO) and Blaine SSA (Specific Surface Area) were also determined by the cement plant for each sample.

Daily composite samples were prepared by Auburn University and tested by the external laboratory to determine the standard parameters shown in Table 3.2 as well as total organic compounds (TOC) using a TOC analyzer. Based on the data provided, Auburn University calculated the Bogue compounds in accordance with ASTM C 150 (2007).

The cement plant's specialty laboratory was also sent similar composite specimens to determine the four major clinker phases using Rietveld analysis. Rietveld analyses typically provide more accurate results than the Bogue calculations specified by ASTM C 150 (2007).

Limestone is commonly added to portland cement to adjust its final composition. The added limestone increases the carbon dioxide (CO_2) of the cement and must be accounted for in the Bogue calculations specified in ASTM C 150 (2007). The cement plant reported this additional parameter for all trial burns.

3.4.2 Cement Physical Properties

The cement plant, Auburn University, and the cement plant's specialty lab determined various physical properties of the cement produced during each trial. For comparison purposes, Auburn University and the cement plant conducted several of the same tests. The cement plant used cement sampled from each trial to conduct their tests. The tests performed by the cement plant, as well as the units and ASTM specifications associated with each test are listed in Table 3.5. Auburn University received bags of cement produced from each trial for further testing. The tests conducted by Auburn University to determine the physical properties of each cement are shown in Table 3.6.

The cement plant's specialty lab received composite specimens of cement comprised of samples collected by the cement plant. In addition to performing the Rietveld analysis, the cement plant's specialty lab also determined the particle size distribution of each cement by laser diffraction.

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)
Mortar 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.	

3.4.3 Concrete Properties

Each trial burn was bagged in accordance with normal procedures at the cement plant. Auburn University collected approximately 15 bags of cement from each trial for mixing and testing concrete. Concrete was mixed in order to establish any link between fuels used to produce the cement and the concrete properties.

Table 3.6: Cement physical properties determined by Auburn University

Property	ASTM Specification
Autoclave expansion, %	C 151 (2005)
Mortar 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)

Two concrete mixtures were developed and used throughout the study. The first mixture (Mix 0.37) had a water cement ratio (w/c) of 0.37 and used No. 78 crushed limestone and natural river sand as aggregate. The second mixture (Mix 0.44) had a w/c of 0.44 and used No. 57 crushed limestone and natural river sand as coarse and fine aggregate, respectively. A summary of mixture proportions for the first and second mix are shown in Tables 3.7 and 3.8.

The concrete produced at Auburn University was mixed in the structures laboratory in accordance with ASTM C 192 (2007). Due to the required volume of Mix 0.37 and 0.44, each mix was divided into two batches of approximately equal volumes. Fresh concrete properties were tested for each batch mixed prior to preparing test specimens listed in Figure 3.9. The tests conducted for each mixture in addition to the ASTM specifications followed for each are shown in Figure 3.9.

The slump and air content of the concrete was tested in both batches in accordance with ASTM C 192 (2007). Tolerances set by Section 9.2 of ASTM C 192 (2007) to ensure consistency between the two batches were also followed.

Table 3.7: Proportions for Mix 0.37 (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

Table 3.8: Proportions for Mix 0.44 (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 3.9: 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)

During the first batch of each mixture, twelve 6 x 12-in. cylinders were made. Ten were used for splitting tensile tests and the remaining two were used for a compressive strength comparison to the second batch. Six 4 x 8-in. cylinders were also prepared for a rapid chloride ion penetration test (RCPT). Eleven 6 x 12-in. cylinders, three 3 x 3 x 11.25-in. prisms, and a setting test were prepared during the second batch. Ten of the 6 x 12-in. cylinders were used for compressive testing. The remaining cylinder was used for a semi-adiabatic (heat of hydration) test. The prisms were prepared for drying shrinkage development. A setting specimen was also prepared to determine initial and final setting times of the trial cement.

3.4.4 Plant Emissions

In order to satisfy limits set by the Alabama Department of Environmental Management (ADEM), plant emissions were monitored by a Continuous Emissions Monitoring System (CEMS). The main stack emissions monitored were carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2) and volatile organic compounds (VOCs). The emissions data, though continuously monitored, was reported in average tons per hour. In order to normalize these data, the production data detailing the amount of clinker produced per hour were used. Emission quantities were reported in tons per ton of clinker. These data were used to evaluate the effects of utilizing alternative fuels.

3.5 Concluding Remarks

Four individual burns were conducted at a full-scale cement plant during this phase of the alternative fuels study, each yielding portland cement from different fuel scenarios. Two of the trials conducted utilized a constant feed rate. Unique to this study, one trial utilized a variable feed rate which consisted of 5, 10, and 15 percent replacement of woodchips. This chapter described all testing plans and methods used to satisfy objectives the of this study.

The cement plant’s laboratory and external laboratory were responsible for testing all material input and outputs. Material inputs included raw material, and fuels. Material outputs included CKD, clinker, and cement. Chemical analyses of the input and output materials were used to determine if there were significant differences that could be attributed to the utilization of alternative fuels

Physical properties of cement were tested by the cement plant as well as Auburn University. Cement produced during each trial was collected by Auburn University for fresh and physical concrete property testing.

Emissions were monitored continuously during each trial to ensure environmental regulations were met and evaluate the impact of alternative fuels on portland cement. The emissions monitored during each trial were carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and volatile organic compounds (VOCs).

Chapter 4
Data Presentation and Analysis

4.1 Introduction

A summary of all collected data in addition to an analysis and discussion of the results are presented in the chapter. The data pertaining to each material follow the same order of presentation used in Chapter Three. Each material's results as reported from the testing laboratories are discussed separately. Similar analyses between entities are compared where necessary. Results from trial burns are compared to these obtained from the baseline burn.

In the first part of this chapter, a summary of all available data collected throughout this study is presented. The data are presented in tabular or graphical form depending on which method provides the best representation. Where sufficient data are available, statistical analyses were conducted.

The overall objective of this study is to determine the effects of alternative fuels on portland cement. This objective was fulfilled by analyzing available data and comparing results from trial burns to those from the baseline burn.

The third and final objective of this chapter is the discussion of the results. Where there are significant differences between the data from the trial and control burns, these are highlighted. There is also discussion if there are any correlations between literature reviewed and results found.

An analysis plan was developed in order to fulfill objectives of this study. Figure 4.1 depicts the analysis plan. It should be noted that the construction and demolition waste, variable feed woodchip, and soybean seed burns represent the trial burns. The trial burns are compared to the baseline burn.

4.2 Statistical Analysis Background

In this chapter, data pertaining to each test or parameter are presented. Where more than ten data points are available for a data set, statistical analysis results are also presented for the data.

It should be noted that the term *significant* is used frequently throughout this chapter. This could indicate that there is a large change or difference between two or more results. Also, the terms *statistical* significance and *practical* significance are used. Statistical significance implies the result is supported by statistical analysis and unlikely to have occurred by chance. Practical significance is based on the performance of a cement or concrete. Data may show any combination of these two types of significance.

The normality of all applicable data was tested using the Anderson-Darling test (Gingerich 1995). Since the overwhelming majority of data were not normally distributed, those p-values are not presented in this chapter and can be found in Appendix F. The Wilcoxon rank-sum test, which is not dependent on sample size or normality, is presented in this chapter for applicable data (Bridge and Sawilowsky 1999).

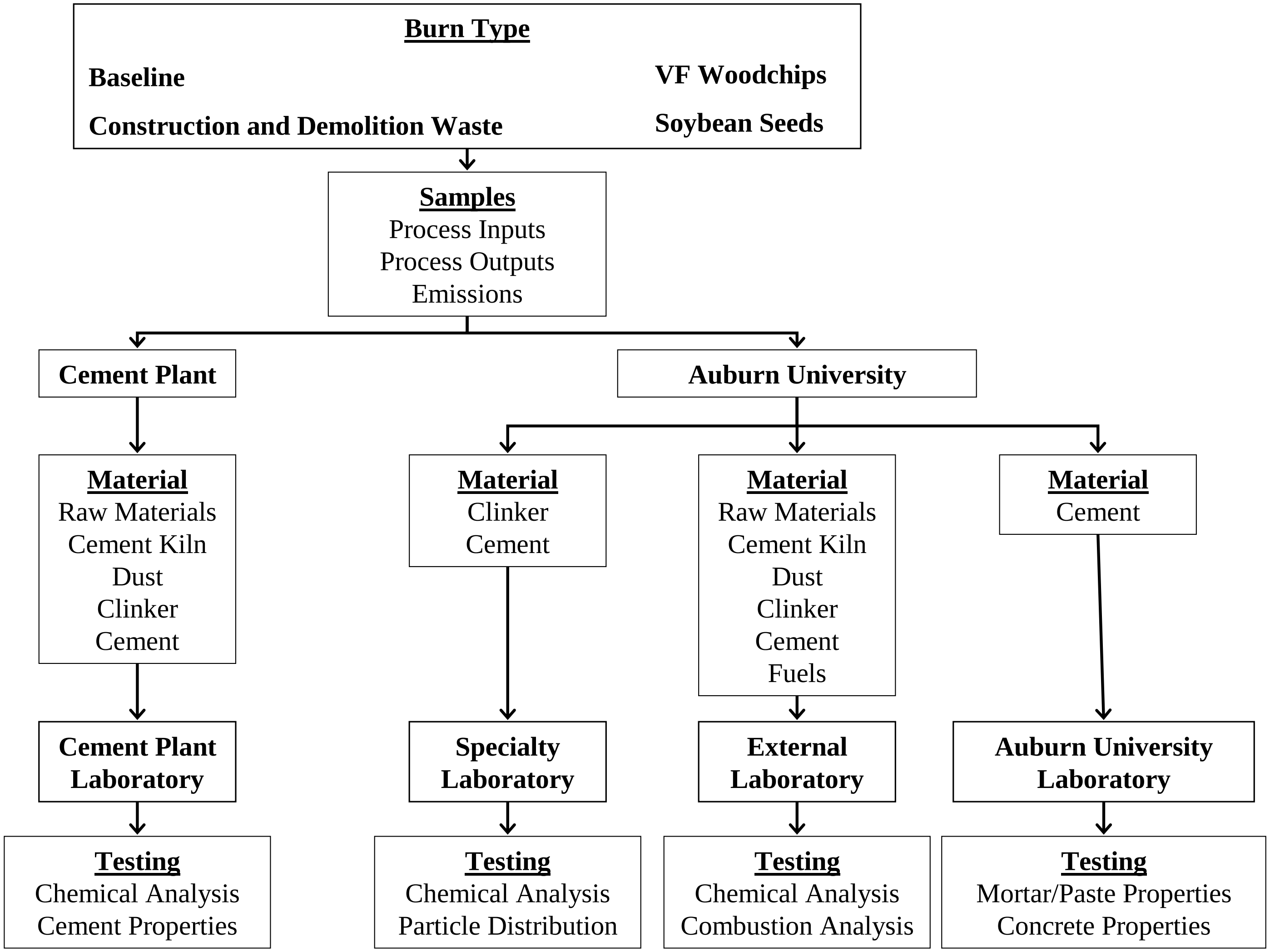

Figure 4.1: Analysis plan

The Anderson-Darling and Wilcoxon rank-sum tests are both based around two competing hypotheses: a null hypothesis (H_o), which is considered true until statistics proves otherwise, and an alternative hypotheses (H_a) (Gingerich 1995). A p-value is the probability of failing to reject the null hypotheses in favor of the alternative hypothesis. A confidence level of 90 % was used for both statistical tests because most of the sample sizes in this study are small. If the p-value calculated is less than the confidence level, the null hypothesis is rejected for the alternative hypothesis.

The Anderson-Darling statistic for all the applicable data was calculated with Statistical Analysis Software (SAS 9.2) utilizing the following hypotheses:

H_o: The data follow a normal distribution, and

H_a: The data do not follow a normal distribution.

The 90 % confidence level was represented by a limiting alpha value of 0.1. A p-value less than 0.1 indicates that the null hypothesis is likely to be false, and thus the data do not follow a normal distribution. All values resulting from the Anderson-Darling statistic presented in this study that do not follow a normal distribution are indicated by a superscript when presented in tabular from.

The Wilcoxon rank-sum test was used to determine the statistical significance between means of two samples. The Wilcoxon rank-sum test for all the applicable data was calculated with Statistical Analysis Software (SAS 9.2) and utilized the following hypotheses:

H_o: The means of the two data sets are equal, and

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

The 90 % confidence level was represented by a limiting alpha value of 0.1. A p-value less than 0.1 indicates that the null hypothesis is likely to be false, and thus the means between the trial and the baseline are different. All trial values that possess statistically different means compared to the baseline mean are indicated by a superscript.

4.3 Research Conditions

This study is a continuation of previous research, succeeding three 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 viable fueling options. Finally, Folta (2010), examined the effects of forest trimmings, railroad ties, and glycerin as alternative fuels.

From the initial study conducted by Swart (2007), it was determined that conclusions were difficult to establish between the utilized fuel and cement properties due to the extended periods of time between baseline or control burns. By decreasing the time between baseline burns and trial burns, Akkapeddi reduced variation caused by changes in plant conditions. This practice was followed throughout Folta’s research and throughout this study.

The burns conducted for this study were described in Chapter three. All trial fuels were used to partially replace traditional fuels and were co-fired with traditional fuels over a 3-6 day period. The burns are briefly notated again below.

1. B-CP – Coal (C) and plastics (P) were the fuels utilized during this burn period. This was a baseline burn to serve as a reference for the

construction and demolition waste (C&D), variable feed woodchips (VF), and soybean seed (Soy) trials shown below.

2. C&D – Coal (C), plastics (P), and construction and demolition waste (C&D) were the fuels utilized during this burn period. The construction and demolition waste was composed of wood, paper, and plastics. The types of wood utilized include dimensional lumber, plywood, and pallets. The paper included corrugated boxes and miscellaneous paper materials. The plastic consisted of solid and cellular foam and polyethylene film.

3. VF – Coal (C), plastics (P), and variable feed woodchips (VF) were the fuels utilized during this burn period.

4. Soy – Coal (C), plastics (P) and soybeans seeds (Soy) were the fuels utilized during this burn period. The soybean seeds that were used in this trial burn were treated with herbicide.

Each 3-day burn lasted between 72 and 80 hours. The variable-feed 6-day burn lasted 148 hours. Although efforts were made to maintain consistent plant conditions, changes that may have occurred include process inputs such as raw material sources, fuel feed rates, and production rates. These changes are unavoidable with respect to the study and necessary for the cement facility to maintain its normal operations. The range of values for the rates of process inputs and outputs are presented in Table 4.1. It should be noted that the alternative solid fuel incorporates the plastic blend as well as the alternative fuel utilized during the burn.

Values presented in Table 4.1 were calculated using production data from the cement plant. The alternative fuel replacement rates were reported in production data obtained from the cement plant.

Table 4.1: Summary of plant conditions during each burn

Burn	**B-CP**	**C&D**	**VF 5%**	**VF 10%**	**VF 15%**	**Soy**
Period	**Jun-10**	**Jul-10**	**Jul-10**	**Jul-10**	**Jul-10**	**Oct-10**
Kiln Feed (tph)	250-320	250-300	293-301	214-311	250-303	298-321
Clinker Production (tph)	140-250	100-275	184-237	106-264	126-324	152-254
Coal Feed (tph)	13-22	9.1-29	20-23	7.3-34	12-25	7.0-24
Alternative Solid Fuel Blend (tph)	6.5-8.2	6.5-7.9	7.7-7.8	5.6-8.1	6.5-7.8	7.8-8.2
Alternative Fuel Replacement (%)[1]	0	5.0	5.0	12	15	7.0

Note: [1]Replacement % based on average total energy as reported from the cement plant

4.4 Data Presentation and Analysis

Specific notations designated for each of the participating parties involved in this study are shown below. Each set of data will be labeled with this notation to identify the origin of the data. The notations that will be used throughout the remainder of this chapter are as follows:

- Cement Plant Results (CPR) refers to the results obtained from the cement plant laboratory,
- External laboratory results (ELR) refers to the data obtained from the external laboratory,

- Specialty lab results (SLR) refers to the results obtained from the cement plant’s specialty laboratory, and
- Auburn University results (AUR) refers to the results collected by Auburn University personnel.

The tables and figures presented in this chapter represent a summary of the raw data collected from its corresponding entity. The term *Value* corresponds to a material represented by a single sample. The abbreviation *Avg.* corresponds to the average value representing multiple samples. The percent difference of the trial result relative to the baseline result is abbreviated, *%Diff*. It should be noted that the percent difference compares trial data to the baseline data collected by the same entity.

Appendices A – D provide the raw data used to produce the summaries presented in this chapter. Only data not presented in Chapter four are presented in the appendices.

4.4.1 Chemical Composition of Raw Materials

The results from RM1 – RM6 are reported in Table 4.2 though 4.7. It should be noted that the raw material values represent one specimen. The percent difference also is provided to compare the trial burn to the baseline. Testing only one specimen between burns can increase the percent difference relative to the baseline due to the fluctuations in material chemistry. Since these data are represented by one specimen, they are not shown in the appendices.

The external laboratory results for raw material 1 are tabulated in Table 4.2. The most noticeable decrease is in the SO_3 content. A decrease in SO_3 could affect emissions and cement physical properties. Notable trace elements include arsenic (As) and mercury

(Hg). Their levels significantly vary from the baseline results. The effects from the fluctuations in all raw materials will be determined from the final cement composition.

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

Property	B-CP	C&D		VF		Soy	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	25.7	NR	-	25.6	-0.3	26.3	2.5
CaO (wt. %)	2.58	NR	-	2.64	2.7	2.67	3.5
Fe_2O_3 (wt. %)	12.1	NR	-	12.2	0.6	11.4	-5.9
K_2O (wt. %)	2.39	NR	-	2.38	-0.6	2.39	0.0
MgO (wt. %)	1.13	NR	-	1.16	2.6	1.17	3.7
Na_2O (wt. %)	0.63	NR	-	0.63	0.2	0.48	-24
P_2O_5 (wt. %)	0.60	NR	-	0.60	0.2	0.64	7.3
SiO_2 (wt. %)	45.0	NR	-	44.8	-0.3	45.2	0.5
SO_3 (wt. %)	0.30	NR	-	0.07	-76	0.03	-91
TiO_2 (wt. %)	1.32	NR	-	1.32	-0.5	1.32	-0.4
Moisture (wt. %)	22.9	NR	-	18.4	-19	16.3	-29
LOI (wt. %)	7.83	NR	-	8.1	3.4	7.9	0.8
As (ppm)	156	NR	-	236	51	449	190
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6.00	NR	-	6.00	0.0	6.00	0.00
Cl (ppm)	57.0	NR	-	46.0	-19	22.0	-61
Co (ppm)	63.0	NR	-	65.0	3.2	57.0	-9.5
Cr (ppm)	180	NR	-	283	57	163	-9.3
Cu (ppm)	365	NR	-	381	4.4	253	-31
Hg (ppm)	0.01	NR	-	0.05	920	0.12	2200.0
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	28.0	NR	-	22.0	-21	22.0	-21
Ni (ppm)	111	NR	-	115	3.6	132	18.9
Pb (ppm)	151	NR	-	158	4.6	343	130.0
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	3.00	NR	-	2.00	-33	2.00	-33
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	368	NR	-	355	-3.5	384	4.3
Zn (ppm)	145	NR	-	191	32	200	38

Notes:

NR - Not Reported

[1] Relative to B-CP

The external laboratory results for raw material 2 are tabulated in Table 4.3. The most noticeable decrease is in the SO_3 content. A decrease in SO_3 could affect emissions and cement physical properties. Notable trace elements that significantly varied from the baseline include As, Hg, Cu, Ni, Pb, and Zn.

Table 4.3: ELR – Chemical composition of RM2 for all burns

Property	**B-CP**	**C&D**		**VF**		**Soy**	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	0.30	NR	-	0.27	-12	0.38	27
CaO (wt. %)	55.0	NR	-	54.3	-1.4	53.3	-3.2
Fe_2O_3 (wt. %)	0.10	NR	-	0.09	-14	0.14	36
K_2O (wt. %)	0.06	NR	-	0.06	-2.7	0.08	38
MgO (wt. %)	0.93	NR	-	0.78	-17	1.23	31
Na_2O (wt. %)	0.00	NR	-	0.00	-	0.00	-
P_2O_5 (wt. %)	0.00	NR	-	0.01	-	0.01	-
SiO_2 (wt. %)	1.12	NR	-	1.04	-7.3	1.58	41
SO_3 (wt. %)	0.57	NR	-	0.09	-84	0.08	-86
TiO_2 (wt. %)	0.00	NR	-	0.00	-	0.00	-
Moisture (wt. %)	1.01	NR	-	0.31	-69	2.09	110
LOI (wt. %)	41.8	NR	-	43.4	3.7	43.2	3.2
As (ppm)	13.0	NR	-	13.0	0.0	5.0	-62
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6.00	NR	-	6.00	0.0	6.00	0.0
Cl (ppm)	72.0	NR	-	39	-46	40	-44
Co (ppm)	6.00	NR	-	6	0.0	6	0.0
Cr (ppm)	25.0	NR	-	16	-35	22	-12
Cu (ppm)	5.00	NR	-	5	0.0	67	1200
Hg (ppm)	0.01	NR	-	0.03	580	0.08	1400
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	5.00	NR	-	10.0	100	5.00	0.0
Ni (ppm)	3.00	NR	-	3.00	0.0	24.0	700
Pb (ppm)	5.00	NR	-	5.00	0.0	42.0	740
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	2.00	NR	-	2.00	0.0	2.00	0.0
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	8.00	NR	-	10.0	25	5.00	-38
Zn (ppm)	5.00	NR	-	21.0	320	19.0	280

Notes:

NR - Not Reported

[1] Relative to B-CP

The external laboratory results for raw material 3 are tabulated in Table 4.4. The most noticeable fluctuations were in the Fe_2O_3, K_2O, MgO, Na_2O, SiO_2, and SO_3 contents. The large fluctuations observed in RM3 are most likely due to testing one sample. Notable trace elements that significantly varied from the baseline include As, Hg, Cu, Ni, and Pb. The external laboratory results for raw material 4 are tabulated in Table 4.5. RM4 stayed fairly consistent over the trial burns. The most noticeable fluctuations were in the K_2O, Na_2O, and SO_3 contents. The only trace element that varied significantly from the baseline was Hg. The external laboratory results for raw material 5 are tabulated in Table 4.6. The most noticeable fluctuations were in the Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, SiO_2, and SO_3 contents. The large fluctuations seen in RM5 are most likely attributable to testing only one sample. Notable trace elements that significantly varied from the baseline include As, Cr, Hg, Ni, Pb, V, and Zn.

The external laboratory results for raw material 6 are tabulated in Table 4.7. The most noticeable fluctuations were in the Al_2O_3, CaO, Fe_2O_3, K_2O, MgO, P_2O_5, and SO_3 contents. The large fluctuations seen in RM6 are most likely from testing one sample. Notable trace elements that significantly varied from the baseline include As, Cr, Cu, Hg, Ni, and Zn. Effects of the increases of trace elements will be determined from the final cement composition.

Table 4.4: ELR – Chemical composition of RM3 for all burns

Property	**B-CP**	**C&D**		**VF**		**Soy**	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	9.12	NR	-	6.11	-33	10.0	9.9
CaO (wt. %)	22.6	NR	-	25.6	13	0.50	-98
Fe_2O_3 (wt. %)	1.88	NR	-	3.62	93	10.5	460
K_2O (wt. %)	0.37	NR	-	0.47	28	0.73	96
MgO (wt. %)	2.69	NR	-	0.47	-82	0.34	-88
Na_2O (wt. %)	0.04	NR	-	0.05	23	0.07	97
P_2O_5 (wt. %)	0.09	NR	-	0.03	-66	0.10	13
SiO_2 (wt. %)	38.9	NR	-	40.7	4.4	70.4	81
SO_3 (wt. %)	0.12	NR	-	0.11	-10	0.02	-85
TiO_2 (wt. %)	0.55	NR	-	0.48	-12	1.01	85
Moisture (wt. %)	1.59	NR	-	0.75	-53	2.27	43
LOI (wt. %)	23.5	NR	-	22.3	-5.0	5.96	-75
As (ppm)	21.0	NR	-	38.0	81	60.0	190
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6.00	NR	-	6.00	0.0	6.00	0.0
Cl (ppm)	67.0	NR	-	101	51	6.00	-91
Co (ppm)	10.0	NR	-	7.00	-30	32.0	220
Cr (ppm)	62.0	NR	-	130	110	104	67
Cu (ppm)	47.0	NR	-	35	-26	80.0	70
Hg (ppm)	0.01	NR	-	0.03	480	0.09	1800
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	5.0	NR	-	12.0	140	5.00	0.0
Ni (ppm)	32.0	NR	-	26.0	-19	34.0	6.3
Pb (ppm)	59.0	NR	-	5.0	-92	74.0	25
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	2.00	NR	-	2.00	0.0	2.00	0.0
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	87.0	NR	-	137	57	166	91
Zn (ppm)	40.0	NR	-	38.0	-5.0	55.0	38

Notes:

NR - Not Reported

[1] Relative to B-CP

Table 4.5: ELR – Chemical composition of RM4 for all burns

Property	**B-CP**	**C&D**		**VF**		**Soy**	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	2.76	NR	-	2.80	1.4	2.71	-1.8
CaO (wt. %)	18.56	NR	-	20.1	8.1	16.5	-11
Fe_2O_3 (wt. %)	51.03	NR	-	45.8	-10	51.6	1.1
K_2O (wt. %)	0.09	NR	-	0.10	18	0.14	63
MgO (wt. %)	4.01	NR	-	4.6	15	4.56	14
Na_2O (wt. %)	0.04	NR	-	0.04	-1.7	0.09	104
P_2O_5 (wt. %)	0.22	NR	-	0.25	14	0.28	31
SiO_2 (wt. %)	8.80	NR	-	10.1	15	10.6	20
SO_3 (wt. %)	0.57	NR	-	0.57	-0.2	0.36	-37
TiO_2 (wt. %)	0.29	NR	-	0.38	30	0.28	-3.9
Moisture (wt. %)	6.37	NR	-	9.26	45	12.6	98
LOI (wt. %)	12.2	NR	-	13.6	12	11.4	-5.8
As (ppm)	21	NR	-	29	38	19	-9.5
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	12	NR	-	13	8.3	17	42
Cl (ppm)	240	NR	-	210	-13	254	5.8
Co (ppm)	36	NR	-	42	16.7	56	56
Cr (ppm)	858	NR	-	1600	86	845	-1.5
Cu (ppm)	214	NR	-	209	-2.3	237	11
Hg (ppm)	0.005	NR	-	0.018	260	0.12	2300
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	18	NR	-	25	39	16	-11
Ni (ppm)	34	NR	-	48	41	78	130
Pb (ppm)	219	NR	-	183	-16	62	-72
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	2	NR	-	2	0.0	2	0.0
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	276	NR	-	336	22	278	0.7
Zn (ppm)	1870	NR	-	1790	-4.3	2800	50

Notes:

NR - Not Reported

[1] Relative to B-CP

Table 4.6: ELR – Chemical composition of RM5 for all burns

Property	B-CP	C&D		VF		Soy	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	0.89	NR	-	1.42	59	3.41	280
CaO (wt. %)	0.12	NR	-	0.35	200	0.53	350
Fe_2O_3 (wt. %)	0.28	NR	-	1.32	370	1.77	540
K_2O (wt. %)	0.09	NR	-	0.13	49	0.30	250
MgO (wt. %)	0.01	NR	-	0.22	1900	0.13	1100
Na_2O (wt. %)	0.00	NR	-	0.03	-	0.05	-
P_2O_5 (wt. %)	0.00	NR	-	0.02	-	0.07	-
SiO_2 (wt. %)	98.1	NR	-	95.6	-2.6	92.5	-5.7
SO_3 (wt. %)	0.16	NR	-	0.05	-69	0.01	-94
TiO_2 (wt. %)	0.12	NR	-	0.19	59	0.24	100
Moisture (wt. %)	20.0	NR	-	3.45	-83	4.86	-76
LOI (wt. %)	0.13	NR	-	0.60	370	0.90	590
As (ppm)	9	NR	-	12	33	18	100
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6	NR	-	6	0.0	6	0.0
Cl (ppm)	83	NR	-	52	-37	142	71
Co (ppm)	6	NR	-	6	0.0	6	0.0
Cr (ppm)	11	NR	-	41	270	51	360
Cu (ppm)	34	NR	-	32	-5.9	123	260
Hg (ppm)	0.005	NR	-	0.005	0.0	0.07	1300
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	5	NR	-	5	0.0	5	0.0
Ni (ppm)	3	NR	-	3	0.0	35	1100
Pb (ppm)	7	NR	-	5	-29	25	257
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	2	NR	-	2	0.0	2	0.0
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	8	NR	-	23	190	17	110
Zn (ppm)	8	NR	-	60	650	43	440

Notes:

NR - Not Reported

[1] Relative to B-CP

Table 4.7: ELR – Chemical composition of RM6 for all burns

Property	**B-CP**	**C&D**		**VF**		**Soy**	
	Value	Value	% Diff.[1]	Value	% Diff.[1]	Value	% Diff.[1]
Al_2O_3 (wt. %)	0.08	0.29	270	0.15	97	0.26	240
CaO (wt. %)	17.2	32.5	88.8	37.9	120	32.8	90
Fe_2O_3 (wt. %)	0.04	0.16	320	0.06	72	0.17	350
K_2O (wt. %)	0.00	0.03	660	0.02	341	0.02	290
MgO (wt. %)	0.12	0.27	120.0	0.26	113	0.31	150
Na_2O (wt. %)	0.00	0.00	-	0.00	-	0.02	-
P_2O_5 (wt. %)	0.00	0.02	280.0	0.01	121	0.01	93
SiO_2 (wt. %)	0.30	0.73	140.0	0.55	81	0.44	46
SO_3 (wt. %)	23.2	44.8	93.6	50.9	120	44.9	94
TiO_2 (wt. %)	0.00	0.00	-	0.00	-	0.00	-
Moisture (wt. %)	24.1	6.93	-71	18.7	-22	0.00	-100
LOI (wt. %)	59.1	21.1	-64	10.1	-83	21.1	-64
As (ppm)	13	5	-62	5	-62	5.00	-62
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6	6	0.0	6	0.0	6.00	0.0
Cl (ppm)	58	28	-52	25	-57	68.0	17
Co (ppm)	6	6	0.0	6	0.0	6.00	0.0
Cr (ppm)	5	16	220	34	590	23.20	360
Cu (ppm)	19	5	-74	5	-74	36.0	89
Hg (ppm)	0.008	0.05	550	0.16	1900	0.16	1900
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	5	5	0.0	5	0.0	5.00	0.0
Ni (ppm)	3	3	0.0	3	0.0	13.0	330
Pb (ppm)	5	5	0.0	14	180	5.00	0.0
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	17	16	-5.9	18	5.9	19.0	12
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	5	5	0.0	5	0.0	5.00	0.0
Zn (ppm)	5	12	140	6	20	23.0	360

Notes:

NR - Not Reported

[1] Relative to B-CP

4.4.2 Chemical Composition of Kiln Feed

Kiln feed comprises specific proportions of ground raw materials and recycled cement kiln dust and is the primary process input into the kiln system. Changes in the chemical composition of any of the raw material can influence the chemical composition of the kiln feed. Throughout this study, kiln feed was sampled twice per day in order to obtain the average chemical composition. The average percent by weight (*Avg. wt. %*) and the percent difference relative to the baseline (*%Diff.*) for all burns collected by the cement plant are tabulated in Table 4.8. Summary statistics are not presented for the kiln feed due to the limited number of samples collected.

The percent differences between the trial burns and the baseline burn as reported by the cement plant are shown in Figure 4.2. Most of the parameters are seen to be relatively consistent with the baseline conditions. The greatest difference is seen in the increase of SO_3 content over all the burns conducted. This increase may be attributed to the significantly higher sulfite contents of the cement kiln dust for each trial burn compared to the baseline. The SO_3 was elevated in the cement kiln dust over 400 % for all the trial burns. These results are shown in Figure 4.3 B.

The results from the external laboratory are presented in Table 4.9. Compared to the cement laboratory results, the external lab results showed more variability in most compounds in the kiln feed throughout this study. The sulfite levels reported by the external laboratory for the trial burns are similar to the cement plant laboratory findings. Hg and Cr were increased over all burns. Pb, Cu, and Zn varied over all the burns. Cl and V were decreased over the trial burns compared to the baseline's results.

Table 4.8: CPR – Kiln feed compositions for all burns

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Average (wt. %)	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.
Al2O3	3.12	3.29	5.46	3.09	-0.96	3.00	-3.65	2.98	-4.44	3.18	2.17
CaO	42.52	43.27	1.78	42.69	0.41	42.91	0.93	42.88	0.86	42.59	0.17
Fe2O3	1.91	1.84	-3.73	1.92	0.59	1.86	-2.66	1.89	-1.46	1.90	-0.59
K2O	0.29	0.35	19.12	0.31	8.03	0.31	6.69	0.31	5.51	0.28	-4.49
MgO	2.30	2.03	-11.50	2.14	-6.91	2.18	-5.17	2.34	1.76	2.31	0.63
Na2O	0.05	0.05	-2.86	0.05	3.57	0.05	0.50	0.06	10.00	0.05	-6.67
Na2Oeq	0.24	0.28	15.49	0.26	6.77	0.25	3.69	0.26	6.44	0.23	-4.94
SiO2	13.56	13.34	-1.63	13.12	-3.27	13.03	-3.90	13.12	-3.25	13.18	-2.82
SO3	0.15	0.21	43.27	0.17	13.65	0.19	27.63	0.21	39.66	0.19	30.13
LOI	35.87	36.27	1.10	36.05	0.49	36.15	0.77	36.21	0.93	35.95	0.21

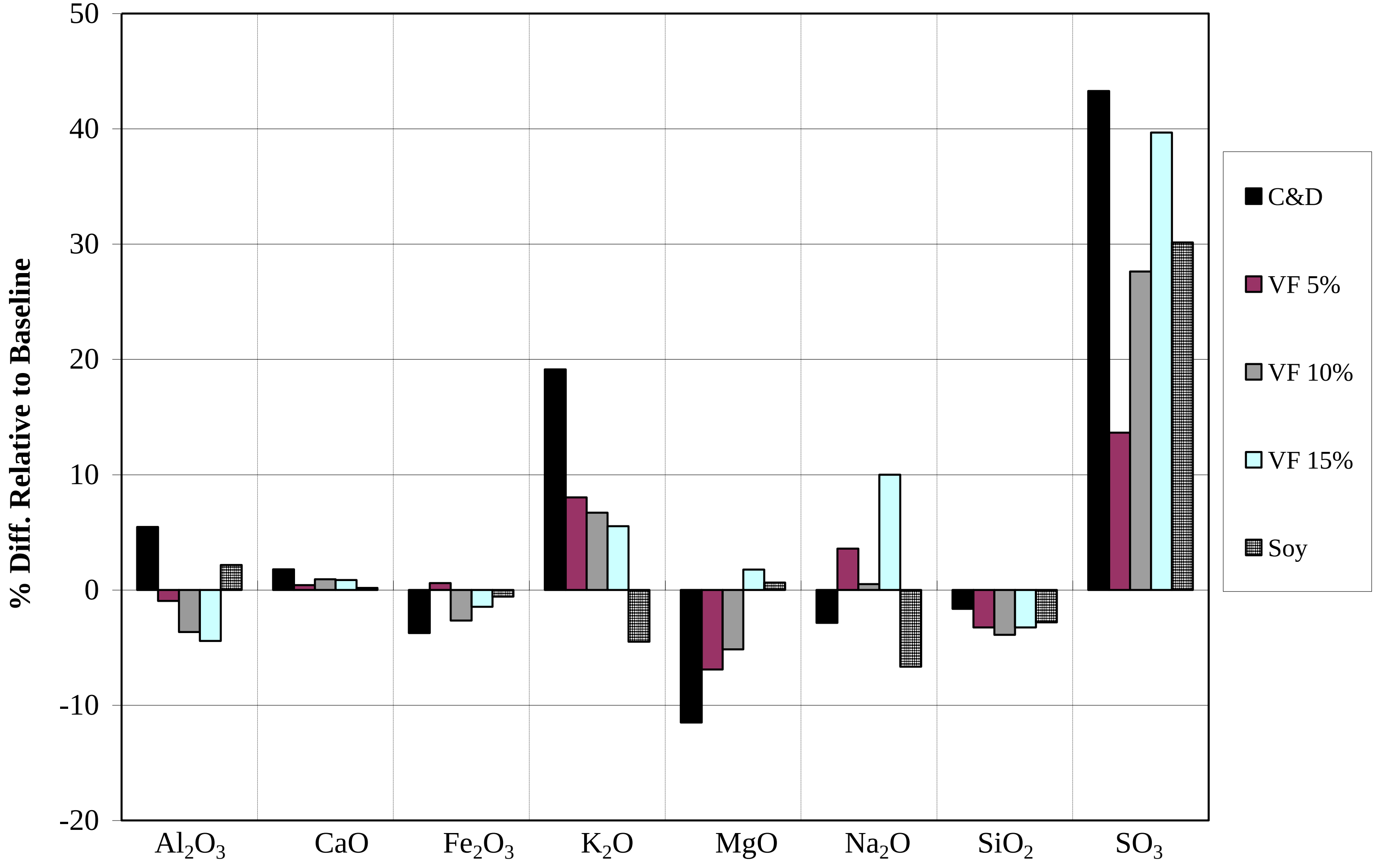

Figure 4.2: CPR – Percent difference in kiln feed composition relative to baseline

Table 4.9 A: ELR – Kiln feed compositions and percentage difference relative to baseline for all burns

Property	**B-CP**	**C&D**		**Soy**	
	Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Al_2O_3	3.1	4.6	48.7	3.3	7.5
CaO	42.1	56.7	34.7	41.7	-1.1
Fe_2O_3 (wt. %)	1.9	2.6	34.9	1.9	2.2
K_2O	0.3	0.5	74.1	0.3	4.9
MgO	2.3	2.9	24.5	2.5	7.4
Na_2O	0.0	0.0	12.8	0.0	-16.5
P_2O_5	0.0	0.1	89.5	0.0	40.2
SiO_2	13.8	18.5	34.9	13.7	-0.7
SO_3	0.3	0.2	-16.2	0.2	-38.0
TiO_2	0.1	0.2	35.4	0.2	18.4
Moisture	0.3	0.2	-23.4	0.0	-100.0
LOI	36.0	13.6	-62.2	36.1	0.4
Property	**Value (ppm)**	**Value (ppm)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
As	19.0	5.0	-73.7	13.0	-31.6
Ba	NR	NR	-	NR	-
Cd	6.0	6.0	0.0	6.0	0.0
Cl	110.0	77.0	-30.0	68.0	-38.2
Co	13.0	14.0	7.7	6.0	-53.8
Cr	44.0	58.0	31.8	73.0	65.9
Cu	42.0	5.0	-88.1	69.0	64.3
Hg	0.0	0.0	880.0	0.2	3480.0
Mn	NR	NR	-	NR	-
Mo	9.0	5.0	-44.4	5.0	-44.4
Ni	13.0	16.0	23.1	31.0	138.5
Pb	23.0	81.0	252.2	74.0	221.7
Sb	NR	NR	-	NR	-
Se	2.0	2.0	0.0	2.0	0.0
Sr	NR	NR	-	NR	-
V	51.0	43.0	-15.7	37.0	-27.5
Zn	61.0	65.0	6.6	115.0	88.5

NR – Not Reported

Table 4.9 B: ELR – Kiln feed compositions and percentage difference relative to baseline for all burns

Property	B-CP	VF 5%		VF 10%		VF 15%	
	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Al_2O_3	3.1	3.1	-0.2	3.0	-1.8	3.0	-3.3
CaO	42.1	42.5	1.1	42.5	0.9	42.4	0.8
Fe_2O_3 (wt. %)	1.9	1.9	1.0	1.9	0.7	1.9	0.4
K_2O	0.3	0.3	6.4	0.3	7.7	0.3	8.9
MgO	2.3	2.3	-1.8	2.3	1.3	2.4	4.4
Na_2O	0.0	0.0	-0.6	0.0	-17.2	0.0	-33.7
P_2O_5	0.0	0.0	39.1	0.0	29.2	0.0	19.3
SiO_2	13.8	13.4	-2.4	13.4	-2.3	13.5	-2.1
SO_3	0.3	0.2	-26.7	0.2	-27.8	0.2	-29.0
TiO_2	0.1	0.2	8.4	0.2	8.4	0.2	8.4
Moisture	0.3	0.2	-46.5	0.2	-42.4	0.2	-38.3
LOI	36.0	36.0	-0.1	36.0	0.0	36.0	0.0
Property	**Value (ppm)**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
As	19.0	35.0	84.2	30.0	57.9	25.0	31.6
Ba	NR	NR	-	NR	-	NR	-
Cd	6.0	6.0	0.0	6.0	0.0	6.0	0.0
Cl	110.0	115.0	4.5	98.0	-10.9	81.0	-26.4
Co	13.0	11.0	-15.4	9.5	-26.9	8.0	-38.5
Cr	44.0	61.5	39.7	58.0	31.9	54.6	24.1
Cu	42.0	47.0	11.9	43.5	3.6	40.0	-4.8
Hg	0.0	0.0	160.0	0.0	150.0	0.0	140.0
Mn	NR	NR	-	NR	-	NR	-
Mo	9.0	5.0	-44.4	6.0	-33.3	6.0	-33.3
Ni	13.0	10.0	-23.1	10.5	-19.2	11.0	-15.4
Pb	23.0	5.0	-78.3	20.0	-13.0	20.0	-13.0
Sb	NR	NR	-	NR	-	NR	-
Se	2.0	2.0	0.0	2.0	0.0	2.0	0.0
Sr	NR	NR	-	NR	-	NR	-
V	51.0	48.0	-5.9	50.0	-2.0	52.0	2.0
Zn	61.0	54.0	-11.5	58.0	-4.9	62.0	1.6

NR – Not Reported

4.4.3 Chemical Composition of Cement Kiln Dust

Dust collected throughout the pyroprocess is known as cement kiln dust (CKD). Since CKD is primarily comprised of calcinated and partially calcinated kiln feed, it is often recycled into the kiln feed. During this study, CKD samples were collected twice daily and tested as discrete specimens by both chemical analysis laboratories. Statistical analysis was not conducted for the cement kiln dust due to an insufficient number of samples collected.

The average weights and percent difference relative to the baseline for each CKD parameter collected over the duration of this study are presented in Table 4.10. The loss on ignition (LOI) and moisture content parameters of the CKD specimens were not determined by the cement plant. A graphical representation of the percent difference is shown in Figure 4.3. From Figure 4.3, it can be seen that most of the parameters show consistency with the baseline burn. The MgO and SO_3 contents are increased from the baseline burn. Both the laboratories show an increase in MgO for the VF 15% burn. RM5 also showed elevated MgO contents relative to the baseline conditions. Similar to the kiln feed, the SO_3 content is drastically elevated over the baseline. External laboratory results also show a significant SO_3 increase over baseline conditions.

The External laboratory results are shown in Table 4.11. All the burns exhibited significant decreases in Hg, Cl, and Pb. The results from Cu, Cr, V, and Zn varied greatly for all the trial burns. Some of the same fluctuations were noticed with the kiln feed as well. This is expected due to typical incorporation of CKD into the kiln feed.

Table 4.10: CPR – CKD compositions for all burns

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Average (wt. %)	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.	Average (wt. %)	% Diff.
Al2O3	3.70	3.55	-3.92	3.47	-6.06	3.60	-2.68	3.50	-5.32	3.86	4.42
CaO	44.1	46.8	6.25	46.3	5.13	45.6	3.56	45.8	4.02	44.7	1.55
Fe2O3	2.03	1.80	-11.2	1.87	-7.5	1.91	-5.93	1.87	-7.82	1.95	-3.54
K2O	0.38	0.43	11.8	0.40	4.15	0.42	9.39	0.44	15.3	0.40	3.93
MgO	1.44	1.50	4.05	1.61	11.5	1.66	14.8	1.89	31.1	1.63	12.8
Na2O	0.09	0.09	3.70	0.10	8.33	0.10	13.9	0.10	14.8	0.08	-7.41
SiO2	11.8	11.0	-7.44	11.2	-5.41	11.2	-5.41	11.5	-2.66	10.9	-8.17
SO3	0.13	0.97	645	0.83	537	0.82	527	1.13	769	0.68	421

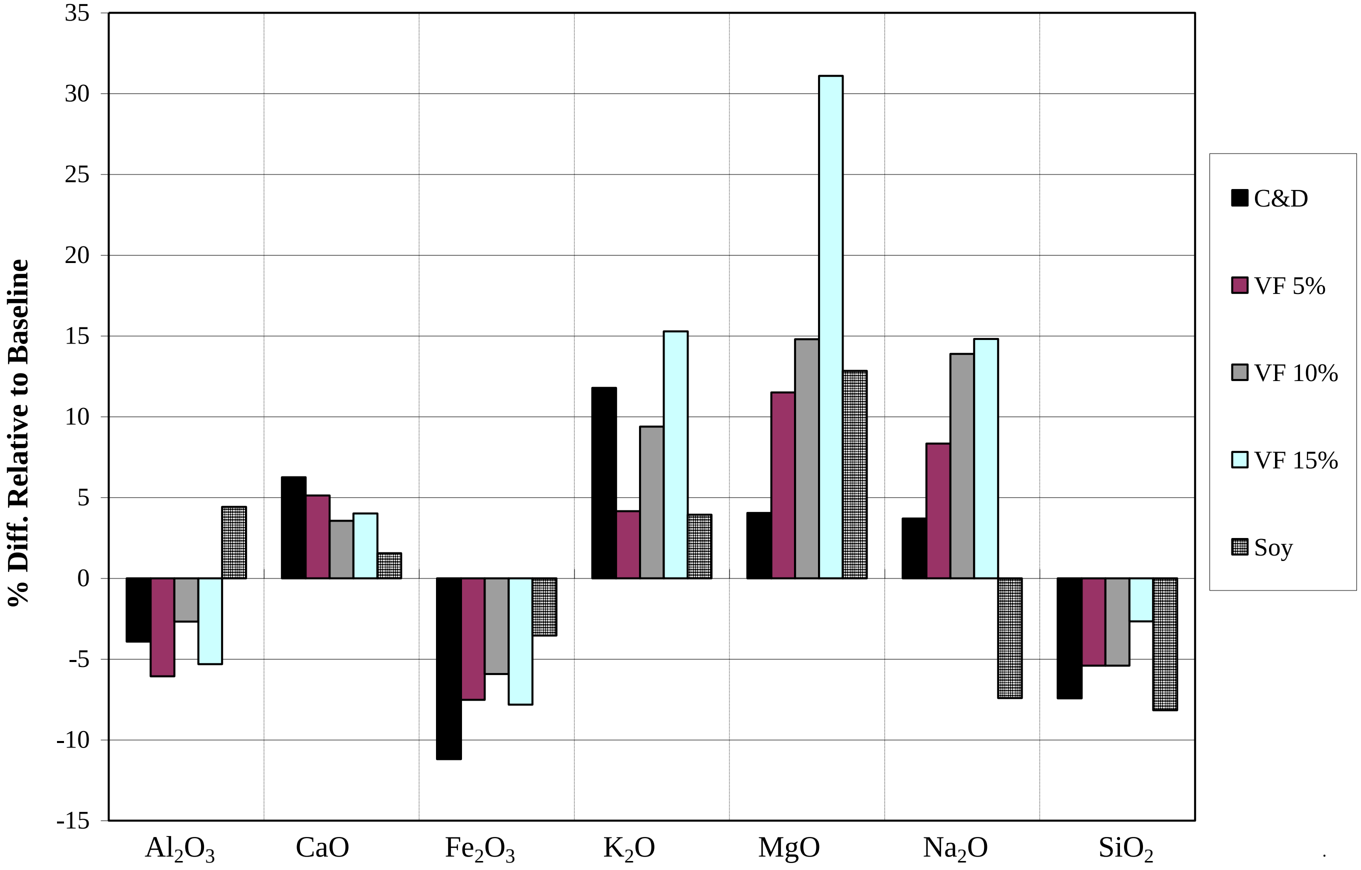

Figure 4.3 A: CPR—CKD compositions relative to baseline for all burns

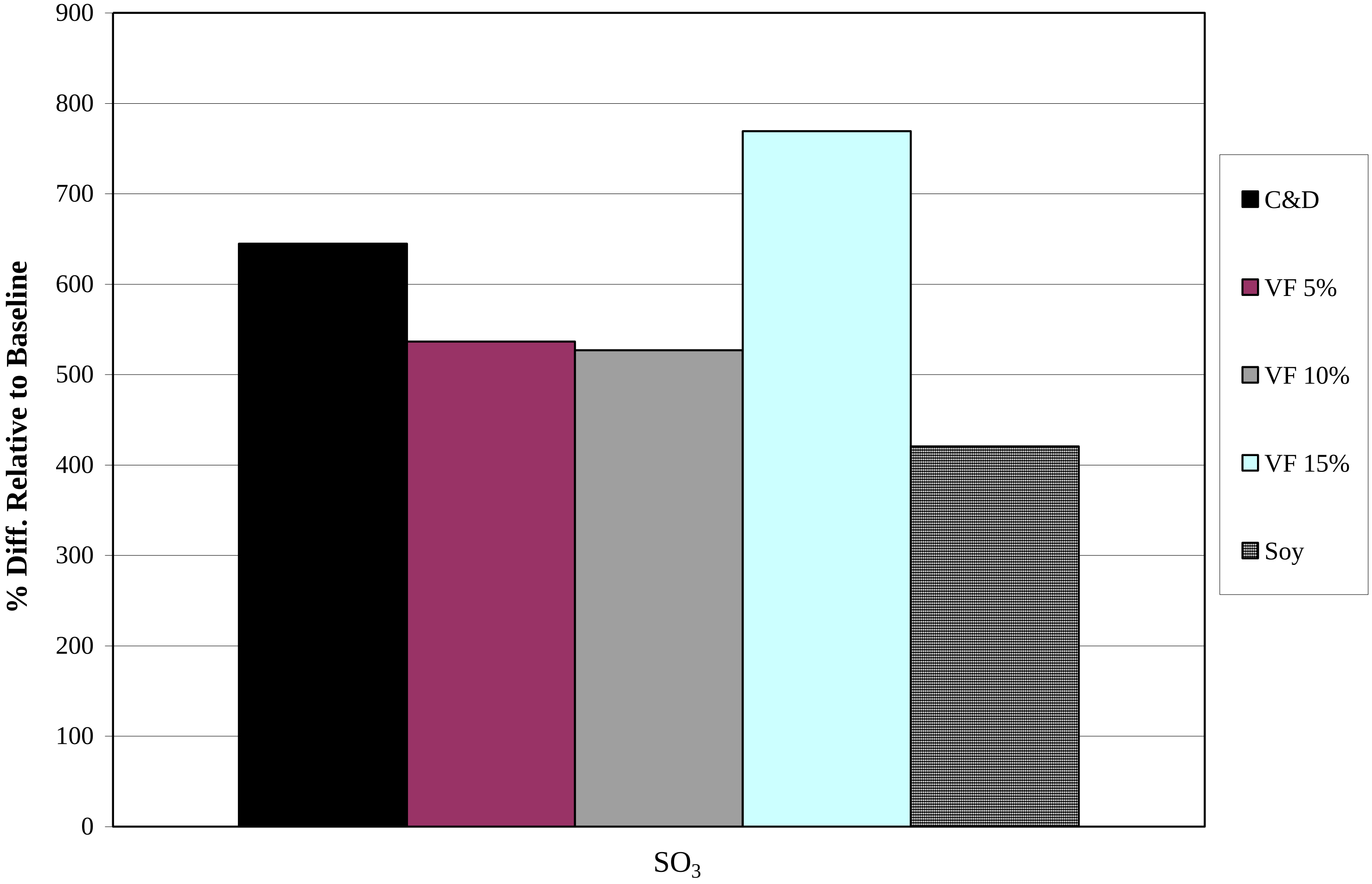

Figure 4.3 B:CPR—CKD compositions relative to baseline for all burns

Table 4.11 A: ELR – CKD compositions and percentage difference to baseline for all burns

Parameter	B-CP	C&D		Soy	
	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Al_2O_3 (wt. %)	3.90	3.78	-2.88	4.07	4.54
CaO (wt. %)	43.9	46.0	4.68	44.3	0.94
Fe_2O_3 (wt. %)	1.97	1.83	-7.00	1.94	-1.35
K_2O (wt. %)	0.37	0.36	-2.29	0.35	-4.01
MgO (wt. %)	1.45	1.60	10.1	1.84	27.2
Na_2O (wt. %)	0.05	0.06	21.8	0.04	-26.9
P_2O_5 (wt. %)	0.04	0.13	191	0.06	26.1
SiO_2 (wt. %)	11.6	11.3	-2.95	11.6	-0.28
SO_3 (wt. %)	0.21	0.97	363	0.61	192
TiO_2 (wt. %)	0.19	0.16	-16.06	0.21	11.04
Moisture (wt. %)	0.49	0.18	-63.9	0.10	-78.8
LOI (wt. %)	36.2	33.7	-6.77	34.8	-3.71
As (ppm)	26.7	37.8	41.8	42.2	58.1
Ba (ppm)	NR	NR	-	NR	-
Cd (ppm)	6.00	6.00	0.00	6.00	0.00
Cl (ppm)	229	166	-27.5	117	-48.9
Co (ppm)	11.0	15.0	36.4	12.0	9.09
Cr (ppm)	51.2	87.6	71.2	55.6	8.70
Cu (ppm)	44.5	24.8	-44.4	62.2	39.7
Hg (ppm)	0.51	0.05	-90.5	0.21	-59.4
Mn (ppm)	NR	NR	-	NR	-
Mo (ppm)	6.67	5.00	-25.0	5.00	-25.0
Ni (ppm)	15.7	24.8	58.3	30.0	91.5
Pb (ppm)	46.5	21.8	-53.2	35.8	-23.0
Sb (ppm)	NR	NR	-	NR	-
Se (ppm)	2.00	2.00	0.00	2.00	0.00
Sr (ppm)	NR	NR	-	NR	-
V (ppm)	61.3	65.4	6.63	50.0	-18.5
Zn (ppm)	87.2	77.0	-11.7	124	42.3

Table 4.11 B: ELR – CKD compositions and percentage difference to baseline for all burns

Parameter	**B-CP**	**VF 5%**		**VF 10%**		**VF 15%**	
	Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Al_2O_3 (wt. %)	3.9	3.78	-2.9	3.92	0.5	3.88	-0.5
CaO (wt. %)	43.9	47.1	7.1	47.40	88.9	46.84	6.6
Fe_2O_3 (wt. %)	2.0	1.86	-5.3	1.93	-1.0	1.93	-2.0
K_2O (wt. %)	0.4	0.36	-1.3	0.42	1.3	0.45	20.7
MgO (wt. %)	1.4	1.60	10.1	1.75	7.6	1.98	36.4
Na_2O (wt. %)	0.0	0.05	-3.9	0.05	0.0	0.05	11.2
P_2O_5 (wt. %)	0.0	0.05	15.5	0.05	0.2	0.05	16.8
SiO_2 (wt. %)	11.6	11.05	-5.0	10.98	-16.6	11.61	-0.2
SO_3 (wt. %)	0.2	0.81	285	1.04	21.3	1.14	444
TiO_2 (wt. %)	0.2	0.19	-0.5	0.19	0.0	0.20	5.3
Moisture (wt. %)	0.5	0.11	-77.6	0.08	-10.5	0.06	-87.7
LOI (wt. %)	36.2	33.1	-8.5	32.2	-102	31.8	-12.1
As (ppm)	26.7	38	43.4	42	394	45	67.5
Ba (ppm)	NR	NR	-	NR	-	NR	-
Cd (ppm)	6.0	6	0.0	6	0.0	6	0.0
Cl (ppm)	229	192	-16.1	245	415	173	-24.3
Co (ppm)	11.0	14	27.3	12	25.7	12	12.1
Cr (ppm)	51.2	71	39.2	61	257	71	38.4
Cu (ppm)	45	70	57.3	37	-183.9	50	13.1
Hg (ppm)	0.5	0	-89.2	0	-12.0	0.02	-95.5
Mn (ppm)	NR	NR	-	NR	-	NR	-
Mo (ppm)	6.7	5	-25.0	8	34.2	8	12.5
Ni (ppm)	15.7	17	8.5	23	180	54	245
Pb (ppm)	46.5	26	-43.5	32	-381	28	-40.9
Sb (ppm)	NR	NR	-	NR	-	NR	-
Se (ppm)	2.0	2	0.0	2	0.0	2	0.0
Sr (ppm)	NR	NR	-	NR	-	NR	-
V (ppm)	61.3	61	-0.1	70	222	274	346
Zn (ppm)	87.2	65	-25.1	79	-218	61	-29.6

4.4.4 Chemical Composition of Fuels

In this section, chemical compositions and properties of each fuel will be presented and evaluated. Throughout the duration of the study, fuel samples were taken according to the sampling plan defined in Table 3.1. First, a short summary of the fuels utilized in each burn will be presented. Next, the results of the traditional fuels used will be discussed. Finally, the results of the alternative fuels utilized in each trial burn will be discussed.

The specifications for the as-received alternative fuels listed below were targeted by this particular cement plant during this study (Akkapeddi et al. 2008).

1. Energy value ≥ 5,000 BTU/lb,
2. Chlorine content ≤ 0.2 %,
3. Sulfur content ≤ 2.0 %
4. Nitrogen content ≤ 1.4 %,
5. Moisture content ≤ 14%, and
6. Ash content ≤ 18 %.

The average heating values and percent utilization are shown in Table 4.12. The as-received heating value is calculated from the moisture content of the material and the dry heating value provided by the external laboratory. It should be noted that the woodchips utilized in the variable feed trials do not meet the minimum energy or moisture content requirements specified in the list above. This is due to the woodchip's high moisture content. With a lesser moisture content, research has proven that higher heating values can be achieved (Maker 2004). The Construction and demolition waste and soybean seed fuels met the target fuel specifications listed above.

Heating values for each fuel are graphically presented in Figure 4.4. The bar labeled *Alt. Fuel* represents the respective alternative fuel utilized in each trial. During the baseline burn, the only fuels utilized were coal and plastics, thus no alternative fuel bar is shown. Throughout this study, coal and plastics are considered traditional fuels. Coal possessed the highest energy content followed closely by the plastic blend for the traditional fuels. During the variable feed and the soybean seed burns, coal and plastics nearly shared the same energy values. The soybean seeds possessed the highest energy content for the alternative fuels followed by the construction and demolition waste and finally, the woodchips.

The fuel utilization for each burn in this study is graphically presented in Figure 4.5. The percent utilization for each fuel was obtained from average cement plant production data. It should be noted that the percent utilization of the alternative fuel during the variable feed trials increases approximately 5 % during each stage. The waste plastic utilization for all trial burns was held fairly constant. Coal was the most utilized fuel during all burns. The plastics and the trial fuels accounted for approximately 15 – 30 % of the energy used for the pyroprocess.

.

Table 4.12: ELR – Fuel heating values and percent utilization

Fuel	**B-CP**	**C&D**	**VF 5%**	**VF 10%**	**VF 15%**	**Soy**
	Avg. (BTU/lb)[1]	**Avg. (BTU/lb)**[1]	**Avg. (BTU/lb)**[1]	**Avg. (BTU/lb)**[1]	**Avg. (BTU/lb)**[1]	**Avg. (BTU/lb)**[1]
Coal	12090	11860	10860	10840	10820	11460
Plastics	10150	8855	9865	10430	10720	10780
Alt. Fuel	NA	6033	4625	4750	4850	9150
Fuel	**Utilization (%)**[2]	**Utilization (%)**[2]	**Utilization (%)**[2]	**Utilization (%)**[2]	**Utilization (%)**[2]	**Utilization (%)**[2]
Coal	89	84	80	73	70	77
Plastics	11	12	15	15	15	16
Alt. Fuel	0	5	5	12	15	7

Notes:

[1] Based on as-received heating values

[2] Utilization % based on average fuel energy as reported from the cement plant

NA – Not applicable

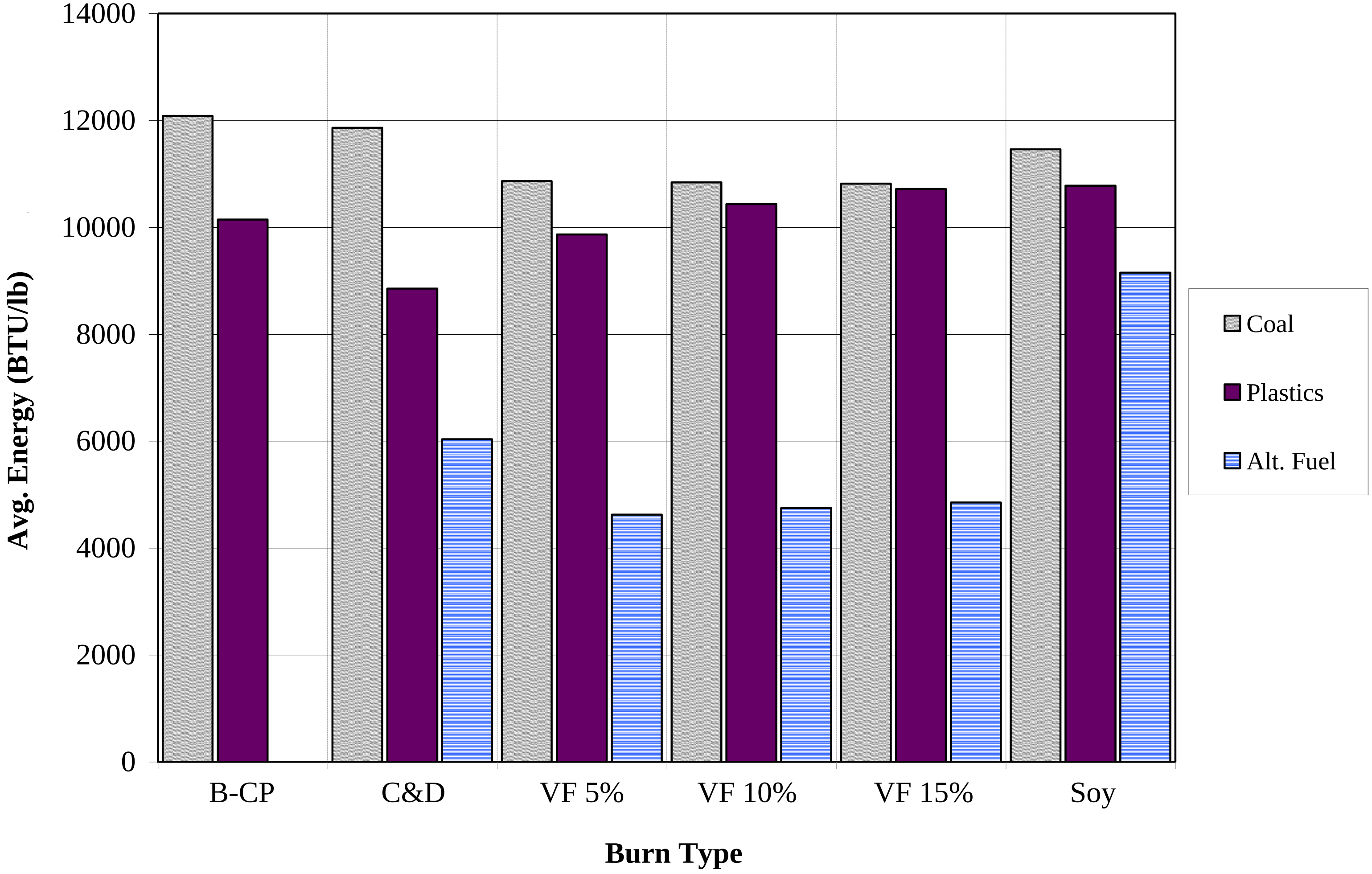

Figure 4.4: Fuel heating values based on as-received conditions

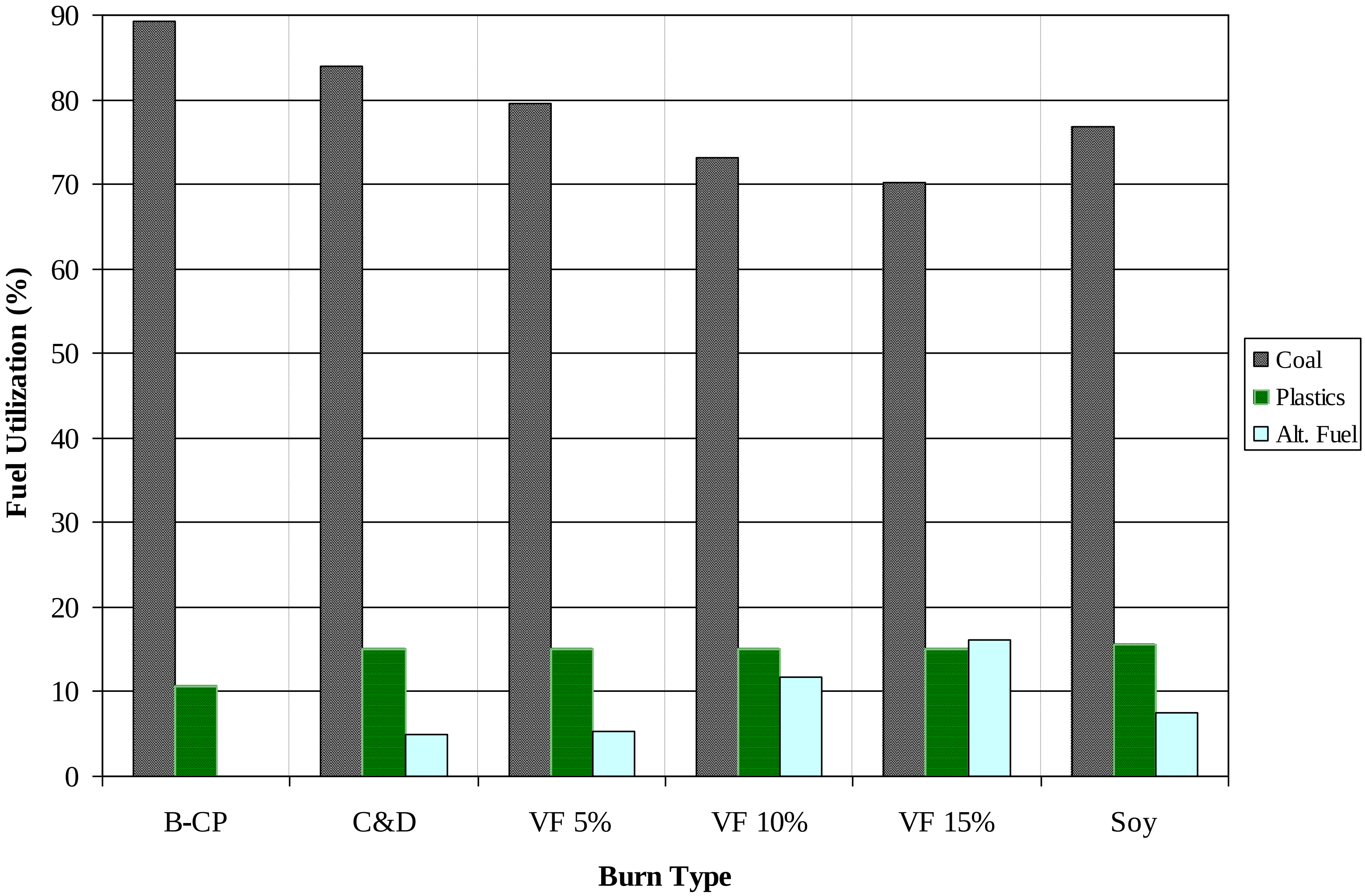

Figure 4.5: CPR – Fuel utilization for all burns

4.4.4.1 Coal

Pulverized coal was the most heavily utilized fuel throughout the study. Coal samples were taken twice daily during each burn period. Twenty-four-hour composite specimens were prepared for chemical analysis by the external laboratory. As previously stated, the external laboratory conducted proximate, ultimate, and combustion analyses as well as determined each fuel's standard parameters.

The results from the proximate, ultimate, and combustion analyses of coal are tabulated in Table 4.13. The proximate analysis of coal for all burns appeared to remain fairly consistent except for the moisture content, which possessed a relatively high percent difference for each trial burn compared to the baseline. The results from the ultimate analysis remained consistent for all parameters except for oxygen. Oxygen fluctuated significantly compared to the baseline for all burns. The oxygen content for coal in the construction and demolition waste was lower than the baseline and significantly higher for all three variable feed trials. Sulfur was also increased in the construction and demolition waste burn's coal, but remained fairly constant throughout the remainder of the trial burns compared to the baseline's results. The heating values for the coal remained with in 10 % of the baseline's heating values for all trial burns.

The results from the standard parameters analysis are shown in Table 4.14. The coal's P_2O_5 content increased for all burns compared to the baseline. The SO_3 content decreased for all burns compared to the baseline. The arsenic (As) concentration of the coal increased in the construction and demolition waste and soybean trials and decreased in all the variable feed trials. The Hg concentration of the coal was reduced in all trials except for the soybean burn in which it was significantly increased. The coal's Pb concentration also increased in the soybean trial compared to the baseline's results.

Table 4.13A: ELR – Proximate, ultimate, and combustion analysis of coal for all burns

Test	Parameter	B-CP	C&D		Soy	
		Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Proximate Analysis	Ash	19.5	20.8	6.6	22.5	16
	Fixed Carbon	50.8	50.5	-0.6	49.0	-3.7
	Moisture [1]	1.09	1.49	37	1.17	7.3
	Volatile Matter	29.7	28.7	-3.3	28.6	-3.8
Ultimate Analysis	Carbon	70.1	68.3	-2.6	66.8	-4.8
	Hydrogen	3.95	3.62	-8.4	3.48	-12
	Nitrogen	1.34	1.46	9.0	1.43	6.7
	Oxygen	1.52	0.89	-41	1.70	12
	Sulfur	3.58	4.96	39	4.10	15
Heat Value [2] (BTU/lb)		12,200	12,000	-1.5	11,600	-5.1

Notes: [1] As Received [2] Dry Basis

Table 4.13 B: ELR – Proximate, ultimate, and combustion analysis of coal for all burns

Test	Parameter	B-CP	VF 5%		VF 10%		VF 15%	
		Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Proximate Analysis	**Ash**	19.5	26.8	37.9	26.8	37.5	26.7	37.1
	Fixed Carbon	50.8	47.0	-7.5	47.4	-6.8	47.8	-6.0
	Moisture[1]	1.09	1.73	58.7	1.80	65.1	1.87	71.6
	Volatile Matter	29.7	26.2	-11.9	25.8	-13.0	25.5	-14.0
Ultimate Analysis	**Carbon**	70.1	61.7	-12.0	62.3	-11.2	62.9	-10.4
	Hydrogen	3.95	3.25	-17.7	3.23	-18.4	3.20	-19.0
	Nitrogen	1.34	1.32	-1.5	1.32	-1.5	1.32	-1.5
	Oxygen	1.52	3.33	119.1	3.07	102.0	2.81	84.9
	Sulfur	3.58	3.54	-1.1	3.32	-7.3	3.10	-13.4
Heat Value[2] **(BTU/lb)**		12,200	11,100	-9.5	11,000	-9.7	11,000	-9.8

Notes: [1] As Received [2] Dry Basis

Table 4.14 A: ELR – Standard Parameters of coal for all burns

Test	**Property**	**B-CP**	**C&D**		**Soy**	
		Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Standard Parameters	**Al_2O_3**	14.2	13.9	-2.1	16.9	19
	CaO	11.3	10.5	-6.9	7.77	-31
	Fe_2O_3	23.2	28.2	22	25.4	9.7
	K_2O	2.08	1.93	-7.5	2.29	10.0
	MgO	1.07	1.03	-3.9	1.05	-2.4
	Na_2O	0.24	0.23	-3.4	0.21	-12
	P_2O_5	0.07	0.15	116	0.13	86
	SiO_2	32.6	31.2	-4.0	35.2	8.3
	SO_3	14.3	11.8	-17	10.1	-29
	TiO_2	0.67	0.65	-3.7	0.68	1.9
	Property	**Value (ppm)**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**
	As	948	1,320	40	1,790	89
	Cd	6	6	0	6	0
	Cl	142	138	-3	145	2
	Co	62	61	-2	46	-26
	Cr	111	144	30	99	-11
	Cu	290	251	-13	223	-23
	Hg	0	0	-32	0	66
	Mo	68	82	21	55	-19
	Ni	118	144	22	112	-5
	Pb	73	62	-15	109	49
	Se	2	2	0	3	50
	V	266	249	-6	248	-7
	Zn	161	211	31	161	0

Table 4.14 B: ELR – Standard Parameters of coal for all burns

Test	**Property**	**B-CP**	**VF 5 %**		**VF 10 %**		**VF 15 %**	
		Value (wt. %)	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**	**Value (wt. %)**	**% Diff.**
Standard Parameters	**Al_2O_3**	14.2	17.7	25	17.6	24	17.4	23
	CaO	11.3	10.2	-9.7	9.75	-14	9.27	-18
	Fe_2O_3	23.2	16.3	-30	17.3	-25	18.4	-20
	K_2O	2.08	2.52	21	2.46	18	2.39	15
	MgO	1.07	1.30	21.1	1.26	17	1.22	13
	Na_2O	0.24	0.24	-1.9	0.23	-2.5	0.23	-3.2
	P_2O_5	0.07	0.14	99	0.14	97	0.14	96
	SiO_2	32.6	41.8	28	41.4	27	41.1	26
	SO_3	14.31	8.56	-40	8.54	-40	8.53	-40
	TiO_2	0.67	0.90	34	0.90	34	0.90	34
	Property	**Value (ppm)**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**	**Value (ppm)**	**% Diff.**
	As	948	482	-49	559	-41	635	-33
	Cd	6	6	0	6	0	6	0
	Cl	142	201	42	208	46	214	51
	Co	62	44	-29	47	-25	49	-21
	Cr	111	121	9	128	15	135	21
	Cu	290	188	-35	219	-25	249	-14
	Hg	0	0	-56	0	-51	0	-46
	Mo	68	38	-44	40	-42	41	-40
	Ni	118	94	-20	124	5	153	30
	Pb	73	70	-4	75	3	80	10
	Se	2	2	0	2	0	2	0
	V	266	246	-8	249	-7	251	-6
	Zn	161	142	-12	143	-11	144	-11

4.4.4.2 Waste Plastics

Waste plastics are typically considered alternative fuels when compared with traditional fuels such as coal, petroleum coke, and natural gas. For this study, however, the cement facility regularly co-fires waste plastics with coal. Therefore, the waste plastics are considered a traditional fuel. The waste plastics were sampled in accordance with the sampling plan shown in Table 3.1. Sampling of this fuel was conducted at a higher frequency in order to pinpoint local variations in the fuel's composition. Discrete specimens were prepared from the samples and analyzed by the external laboratory.

The results of the proximate, ultimate, and combustion analyses for waste plastics from the external laboratory are shown in Table 4.15. Overall, the waste plastic's proximate analysis remained fairly consistent over all burns. The moisture content was the only parameter that was significantly reduced in every trial burn when compared to the baseline's results. The ultimate analysis showed that the nitrogen concentration fluctuated significantly between all the trial burns. Sulfur showed increases between 18 to 169 % for all trial burns compared to the baseline's results. The heating values of the waste plastics remained within 20 % of the baseline for all burns. The plastics burnt during the construction and demolition waste trial burn possessed the lowest heating value for all the trial burns.

The external laboratory's results for the waste plastic's standard parameter analysis are tabulated in Table 4.16. Throughout all the trial burns, the majority of the standard parameters fluctuated significantly compared with the baseline's results. However, these fluctuations did not appear to substantially influence the final cement composition.

Table 4.15 A: ELR – Proximate, ultimate, and combustion analysis of plastics for all burns

Test	Parameter	B-CP	C&D		Soy	
		Avg. (wt. %)	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.
Proximate Analysis	**Ash**	6.82	5.83	-14.5	5.84	-14.4
	Fixed Carbon	10.2	10.1	-0.8	8.65	-15.1
	Moisture[1]	10.5	2.74	-73.8	2.39	-77.1
	Volatile Matter	83.0	84.1	1.3	85.5	3.0
Ultimate Analysis	**Carbon**	57.3	48.9	-14.7	60.7	6.1
	Hydrogen	5.92	5.34	-9.7	6.33	6.9
	Nitrogen	0.96	0.08	-91.7	1.16	20.7
	Oxygen	28.9	37.0	28.1	25.7	-10.9
	Sulfur	0.17	0.20	17.9	0.21	24.3
Heat Value[2] **(BTU/lb)**		11,300	9,100	-20	11,000	-3

Notes: [1] As Received [2] Dry Basis

Table 4.15 B: ELR – Proximate, ultimate, and combustion analysis of plastics for all burns

Test	Parameter	B-CP	VF 5%		VF 10%		VF 15%	
		Avg. (wt. %)	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.
Proximate Analysis	**Ash**	6.82	4.51	-33.8	6.61	-3.1	6.88	0.8
	Fixed Carbon	10.18	10.47	2.9	7.66	-24.8	8.28	-18.7
	Moisture[1]	10.45	3.55	-66.0	1.08	-89.7	0.92	-91.2
	Volatile Matter	83.00	85.01	2.4	85.73	3.3	84.85	2.2
Ultimate Analysis	**Carbon**	57.25	56.67	-1.0	57.81	1.0	57.80	1.0
	Hydrogen	5.92	5.62	-5.0	5.93	0.3	5.70	-3.7
	Nitrogen	0.96	1.10	14.5	1.70	77.0	1.32	37.3
	Oxygen	28.88	31.87	10.4	27.49	-4.8	27.99	-3.1
	Sulfur	0.17	0.22	31.3	0.46	169.0	0.31	84.1
Heat Value[2] **(BTU/lb)**		11,300	10,200	-10	10,500	-7	10,800	-5

Notes: [1] As Received [2] Dry Basis

Table 4.16 A: ELR – Standard parameters of plastics for all burns

Test	Parameter	B-CP	C&D		Soy	
		Avg. (wt. %)	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.
Standard Parameters	Al_2O_3	18.6	30.2	63	7.00	-62
	CaO	23.1	31.2	35	43.5	88
	Fe_2O_3	3.34	1.09	-68	1.01	-70
	K_2O	1.57	1.54	-2	2.57	64
	MgO	4.08	8.63	111	18.3	348
	Na_2O	3.06	2.23	-27	1.62	-47
	P_2O_5	0.54	0.58	7	1.86	245
	SiO_2	34.0	21.3	-37	17.0	-50
	SO_3	3.60	1.08	-70	1.20	-67
	TiO_2	3.09	1.67	-46	5.05	63
	Parameter	**Avg. (ppm)**	**Avg. (ppm)**	**% Diff.**	**Avg. (ppm)**	**% Diff.**
	As	42.8	12.0	-72	8.96	-79
	Cd	6.00	6.00	0	6.00	0
	Cl	1320	220	-83	351	-73
	Co	166	68.7	-59	120	-28
	Cr	968	214	-78	261	-73
	Cu	1340	427	-68	420	-69
	Hg	0.02	0.04	76	0.14	511
	Mo	38.9	21.0	-46	19.5	-50
	Ni	364	114	-69	120	-67
	Pb	1682	147	-91	78.3	-95
	Se	2.00	2.00	0	2.00	0
	V	167	80.9	-52	315	88
	Zn	15500	858	-94	2790	-82

Table 4.16 B: ELR – Standard parameters of plastics for all burns

Test	Parameter	B-CP	VF 5%		VF 10%		VF 15%	
		Avg. (wt. %)	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.
Standard Parameters	**Al_2O_3**	18.6	15.8	-15	18.2	-2	9.94	-46
	CaO	23.1	32.1	39	39.2	70	39.5	71
	Fe_2O_3	3.34	1.86	-44	2.44	-27	2.58	-23
	K_2O	1.57	0.51	-68	0.38	-76	0.32	-80
	MgO	4.08	8.70	113	12.6	209	19.6	381
	Na_2O	3.06	1.76	-42	0.84	-72	0.98	-68
	P_2O_5	0.54	0.56	4	0.31	-43	0.47	-12
	SiO_2	34.0	25.2	-26	87.7	158	16.6	-51
	SO_3	3.60	4.32	20	3.72	3	2.54	-30
	TiO_2	3.09	2.95	-5	3.09	0	4.08	32
	Parameter	**Avg. (ppm)**	**Avg. (ppm)**	**% Diff.**	**Avg. (ppm)**	**% Diff.**	**Avg. (ppm)**	**% Diff.**
	As	42.8	20.3	-53	8.00	-81	19.5	-54
	Cd	6.00	6.00	0	6.00	0	6.00	0
	Cl	1320	532	-60	228	-83	315	-76
	Co	166	95.7	-42	276	67	268	62
	Cr	968	239	-75	1320	36	879	-9
	Cu	1340	453	-66	445	-67	423	-68
	Hg	0.02	0.06	174	0.02	3	0.01	-34
	Mo	38.9	27.0	-31	48.9	26	33.2	-15
	Ni	364	69.7	-81	480	32	404	11
	Pb	1682	196	-88	123	-93	136	-92
	Se	2.00	2.00	0	2.00	0	2.00	0
	V	167	254	52	177	6	260	56
	Zn	15500	1090	-93	400	-97	1060	-93

4.4.4.3 Construction and Demolition (C&D) Waste Trial Burn

Coal, plastics, and construction and demolition waste were the fuels utilized during the C&D burn. The traditional fuel results were reported in the previous section, but are presented in this section with the alternative fuel results for comparison purposes. Chemical analyses of the construction and demolition waste specimens were conducted by the external laboratory and shown in Table 4.17 and Table 4.18.

The results of the proximate and ultimate analyses are tabulated in Table 4.17. The proximate analysis results show that the moisture content of the construction and demolition waste was significantly higher than the coal or the plastic results. This, however, is typical of biomass fuels. Conditioning practices such as drying and covered storage are necessary to control the moisture content in order to maximize the heating value of the fuel. The sulfur content should also be noted in the ultimate analysis results. The construction and demolition waste is primarily composed of biomass and therefore possesses significantly lower sulfur contents when compared to coal. The oxygen content of the construction and demolition waste is also significantly higher than that of the coal.

The standard parameters of all the fuels in the construction and demolition burn are listed in Table 4.18. The construction and demolition waste possessed the highest concentrations of P_2O_5, SiO_2, Cl, Cr, and Zn. In excess, these parameters can be problematic to both manufacture and performance of the cement.

Table 4.17: ELR – Proximate, ultimate, and combustion analysis of all fuels from C&D burn

Test	**Parameter**	**Coal**	**Plastics**	**C&D**
		Value (wt. %)	**Avg. (wt.%)**	**Avg. (wt.%)**
Proximate Analysis	**Ash**	20.8	5.83	14.5
	Fixed Carbon	50.5	10.1	16.1
	Moisture [1]	1.49	2.74	18.4
	Volatile Matter	28.7	84.1	69.4
Ultimate Analysis	**Carbon**	68.3	48.9	45.2
	Hydrogen	3.62	5.34	5.03
	Nitrogen	1.46	0.08	1.07
	Oxygen	0.89	37.0	34.1
	Sulfur	4.96	0.20	0.12
Heat Value [2] **(BTU/lb)**		12,000	9,100	7,400

Notes: [1] As Received [2] Dry Basis

Table 4.18: ELR – Standard parameters of all fuels from C&D burn

Test	Property	Coal	Plastics	C&D
		Value (wt. %)	Avg. (wt.%)	Avg. (wt.%)
Standard Parameters	**Al_2O_3 (wt. %)**	13.9	30.2	11.8
	CaO (wt. %)	10.5	31.2	13.4
	Fe_2O_3 (wt. %)	28.2	1.09	4.99
	K_2O (wt. %)	1.93	1.54	2.73
	MgO (wt. %)	1.03	8.63	1.90
	Na_2O (wt. %)	0.23	2.23	2.19
	P_2O_5 (wt. %)	0.15	0.58	0.68
	SiO_2 (wt. %)	31.2	21.3	57.9
	SO_3 (wt. %)	11.8	1.08	3.10
	TiO_2 (wt. %)	0.65	1.67	0.72
	As (ppm)	1320	12.00	43.0
	Cd (ppm)	6.00	6.00	6.00
	Cl (ppm)	138	220	776
	Co (ppm)	61.0	68.7	26.5
	Cr (ppm)	144	214	456
	Cu (ppm)	251	427	397
	Hg (ppm)	0.17	0.04	0.05
	Mo (ppm)	82.0	21.0	18.8
	Ni (ppm)	144	114	169
	Pb (ppm)	62.0	147	108
	Se (ppm)	2.00	2.00	2.00
	V (ppm)	249	80.9	72.3
	Zn (ppm)	211	858	2140

4.4.4.4 Variable Feed Woodchip Trial Burn (VF)

Coal, plastics, and woodchips were the fuels utilized during the VF 5%, 10%, and 15% burns. As previously mentioned, the traditional fuel results were reported in Section 4.4.4.1 and 4.4.4.2. However, they will be presented in this section with the alternative fuel results for comparison purposes. Chemical analyses of the variable feed specimens were conducted by the external laboratory and shown in Table 4.19 and 4.20.

The results of the proximate and ultimate analyses for each of the variable feed replacement rates are tabulated in Table 4.19. Since the sources of the fuels utilized during this burn did not change, the results of the proximate, ultimate, combustion, and standard parameter analyses fluctuate very little. Therefore, the results reported are 6-day averages.

The proximate analysis results show that the moisture content of the woodchips are significantly higher than the coal or the plastic results. This, however, is typical of biomass fuels. As with most bio-fuels, conditioning practices such as drying and covered storage are necessary to control the moisture content (Greco et al. 2004). The sulfur content should also be noted in the ultimate analysis results. Biomass fuels such as woodchips possess significantly lower sulfur contents than traditional fuel sources. Low sulfur fuels are advantageous because they can reduce sulfur emissions in the pyroprocess. The oxygen content of the woodchips is also significantly higher than the oxygen content observed in the coal.

The 6-day averages of the standard parameters of all the fuels in the variable feed woodchip burn are listed in Table 4.20. The woodchip waste possessed the greatest concentration of SiO_2 compared to the traditional fuels. On the other hand, the woodchip waste possessed the lowest concentrations of Al_2O_3, SO_3, and V.

Table 4.19: ELR – Average proximate, ultimate, and combustion analysis of all fuels from VF 5 – 15 % burns

Test	**Parameter**	**Coal**	**Plastics**	**VF Avg.**
		Value (wt. %)	**Avg. (wt.%)**	**Avg. (wt.%)**
Proximate Analysis	**Ash**	26.8	6.0	11.1
	Fixed Carbon	47.4	8.8	16.7
	Moisture [1]	1.80	1.85	38.10
	Volatile Matter	25.8	85.2	72.2
Ultimate Analysis	**Carbon**	62.3	57.4	47.9
	Hydrogen	3.23	5.75	5.15
	Nitrogen	1.32	1.37	0.29
	Oxygen	3.07	29.12	35.54
	Sulfur	3.32	0.33	0.02
Heat Value [2] **(BTU/lb)**		11,000	10,500	7,670

Notes: [1] As Received [2] Dry Basis

Table 4.20: ELR – Average standard parameters for all fuels from VF 5 – 15 % burns

Test	**Property**	**Coal**	**Plastics**	**VF Avg.**
		Value (wt. %)	**Avg. (wt.%)**	**Avg. (wt.%)**
Standard Parameters	**Al_2O_3 (wt. %)**	17.6	14.6	8.42
	CaO (wt. %)	9.7	36.9	13.1
	Fe_2O_3 (wt. %)	17.3	2.29	8.80
	K_2O (wt. %)	2.46	0.40	1.81
	MgO (wt. %)	1.26	13.7	2.97
	Na_2O (wt. %)	0.23	1.20	0.56
	P_2O_5 (wt. %)	0.14	0.45	0.22
	SiO_2 (wt. %)	41.4	43.2	62.4
	SO_3 (wt. %)	8.54	3.53	0.36
	TiO_2 (wt. %)	0.90	3.38	0.83
	As (ppm)	559	15.9	58.7
	Cd (ppm)	6.00	6.00	6.00
	Cl (ppm)	208	359	238
	Co (ppm)	46.5	213	72.1
	Cr (ppm)	128	812	792
	Cu (ppm)	219	441	219
	Hg (ppm)	0.12	0.03	0.03
	Mo (ppm)	39.5	36.4	27.6
	Ni (ppm)	124	318	294
	Pb (ppm)	75.0	152	110
	Se (ppm)	2.00	2.00	2.00
	V (ppm)	249	230	69.7
	Zn (ppm)	143	852	454

4.4.4.5 Soybean Trial Burn (Soy)

Coal, plastics, and soybean seeds were the fuels utilized during the soy trial burn. The traditional fuel results were reported in Sections 4.4.4.1 and 4.4.4.2. However, they will be presented in this section with the alternative fuel results for comparison purposes. Chemical analyses of the soybean seeds specimens were conducted by the external laboratory and shown in Table 4.21 and Table 4.22. The results from the proximate and ultimate analyses are tabulated in Table 4.21. From the proximate analysis results, the low ash and moisture content, and high volatile content should be noted. The carbon, nitrogen, and sulfur contents should also be noted in the ultimate analysis results. The heating value of the soybean seeds was within 10 percent of the energy output of the traditional fuels.

The standard parameters of all the fuels utilized in the soybean burn are listed in Table 4.22. The soybean seeds possessed the highest concentrations of K_2O, P_2O_5, and Mo. The soybean seeds possessed the lowest concentrations of Al_2O_3, Fe_2O_3, SiO_2, Cl, Co, Cr, Ni, Pb, and V.

4.4.5 Chemical Composition of Clinker

Clinker is the primary output of the pyroprocess. The cement plant collected approximately 8 samples per day. Composite specimens were analyzed by the cement plant and the external laboratory. The average clinker compositions, determined by the cement plant for each trial burn, are tabulated in Table 4.23 as well as their respective p-values and percent difference relative to the baseline. The p-values were obtained from the Wilcoxon rank-sum test. As discussed previously, this test does not depend on normality and determines if there is a significant difference between the average baseline and trial burn parameters.

Table 4.21: ELR – Proximate, ultimate, and combustion analysis of all fuels from the Soy burn

Test	**Parameter**	**Coal**	**Plastics**	**Soy**
		Value (wt. %)	**Avg. (wt.%)**	**Avg. (wt.%)**
Proximate Analysis	**Ash**	22.5	5.8	4.60
	Fixed Carbon	49.0	8.6	14.0
	Moisture ^{1}	1.17	2.39	10.41
	Volatile Matter	28.6	85.5	81.4
Ultimate Analysis	**Carbon**	66.8	60.7	57.1
	Hydrogen	3.48	6.33	6.83
	Nitrogen	1.43	1.16	6.60
	Oxygen	1.70	25.74	24.6
	Sulfur	4.10	0.21	0.22
Heat Value ^{2} **(BTU/lb)**		11,600	11,000	10,000

Notes: ^{1} As Received ^{2} Dry Basis

Parameter means that show a significant difference to the baseline are noted with a superscript. If the p-value indicates that the two samples populations are not equal (i.e. p-value < 0.1), the degree of difference should be noted and is represented by the trial burn's percent difference relative to the baseline burn. If, however, the p-value indicates that the two samples population means are equal, the degree of difference should disregarded.

From the data presented in Table 4.23 it can be concluded that the majority of trial burn parameter means are significantly different from the baseline mean data. Due to the small variation in each parameter's data set, the probability of a significant difference between means is increased. The data variation for each parameter is shown in Figure 4.6. Bars extending above and below the mean values denote the 5th and 95th percentiles.

Table 4.22: ELR – Standard parameters of all fuels from the Soy burn

Test	Property	Coal	Plastics	Soy
		Value (wt. %)	Avg. (wt.%)	Avg. (wt.%)
Standard Parameters	**Al_2O_3 (wt. %)**	16.9	7.00	0.27
	CaO (wt. %)	7.77	43.5	8.16
	Fe_2O_3 (wt. %)	25.4	1.01	0.33
	K_2O (wt. %)	2.29	2.57	50.8
	MgO (wt. %)	1.05	18.3	10.2
	Na_2O (wt. %)	0.21	1.62	0.36
	P_2O_5 (wt. %)	0.13	1.86	27.2
	SiO_2 (wt. %)	35.2	17.0	0.80
	SO_3 (wt. %)	10.1	1.20	1.34
	TiO_2 (wt. %)	0.68	5.05	0.12
	As (ppm)	1790	8.96	6.79
	Cd (ppm)	6.00	6.00	6.00
	Cl (ppm)	145	351	97.6
	Co (ppm)	46.0	120	21.13
	Cr (ppm)	98.7	261	28.20
	Cu (ppm)	223	420	101
	Hg (ppm)	0.42	0.14	0.17
	Mo (ppm)	55	20	153
	Ni (ppm)	112	120	68.0
	Pb (ppm)	109	78.3	59.3
	Se (ppm)	3.00	2.00	2.00
	V (ppm)	248	315	5.00
	Zn (ppm)	161	2790	1070

Almost all the primary oxides, such as Al_2O_3, CaO, Fe_2O_3, and SiO_2, in the trial burns possess significantly different means compared to the baseline's results for the trial burns conducted. The primary oxides in the trial burns possess percent differences relative to the baseline burn that are fairly low. The construction and demolition waste Al_2O_3 content increased 9 %, which was the greatest difference compared to the baseline's results.

The cement plant's Bogue compound results from the trial burns, in most cases, possessed significantly different means when compared to the baseline means. Similarly to the primary oxides, the degree of difference between trial and baseline means was fairly small. The belite content for the soybean trial possessed the largest difference with a decrease of 28 % compared to the baseline result.

Table 4.23 A: CPR – Statistical significance and percent difference of clinker relative to baseline medium

Parameter	**B-CP**	**C&D**			**Soy**		
	Avg. (wt. %)	**Avg. (wt. %)**	**P-value[1]**	**% Diff.[2]**	**Avg. (wt. %)**	**P-value[1]**	**% Diff.[2]**
Al_2O_3	4.65	5.05	<0.0001[3]	8.6	4.83	<0.0001[3]	4.0
CaO	64.5	64.9	0.1211	0.5	65.0	0.0075[3]	0.7
Fe_2O_3	3.31	3.30	0.4086	-0.1	3.43	0.0001[3]	3.7
K_2O	0.47	0.56	<0.0001[3]	17.3	0.49	0.0503[3]	4.3
MgO	3.55	3.06	<0.0001[3]	-13.7	3.50	0.1138[3]	-1.4
Na_2O	0.06	0.06	0.2035[3]	-3.7	0.05	0.0001[3]	-20.9
Na_2O_{eq}	0.37	0.42	0.0001[3]	13.9	0.37	0.7875	0.2
SiO_2	21.4	20.9	0.0001[3]	-2.2	21.0	0.0001[3]	-1.8
SO_3	0.99	1.15	0.375	15.7	1.24	0.0001[3]	25.2
Free CaO	1.30	1.73	0.0424[3]	33.5	1.04	0.1976	-20.0
C_3A	6.72	7.79	0.0001[3]	15.8	7.01	0.0001[3]	4.2
C_4AF	10.1	10.1	0.4139	-0.1	10.4	0.0001[3]	3.7
C_3S	64.5	66.8	0.0002[3]	3.5	67.8	0.0001[3]	5.1
C_2S	12.6	9.49	0.0001[3]	-24.6	9.03	0.0001[3]	-28.2

Notes:

[1] Wilcoxon Rank Sum Test

[2] Difference Relative to Baseline

[3] Data shows Significant Difference Between Means

Table 4.23 B: CPR – Statistical significance and percent difference of clinker relative to baseline

Parameter	**B-CP**	**VF 5%**			**VF 10%**			**VF 15%**		
	Avg. (wt. %)	**Avg. (wt. %)**	**P-value[1]**	**% Diff.[2]**	**Avg. (wt. %)**	**P-value[1]**	**% Diff.[2]**	**Avg. (wt. %)**	**P-value[1]**	**% Diff.[2]**
Al_2O_3	4.65	4.98	<0.0001[3]	7.2	4.87	<0.0001[3]	4.8	4.81	0.0024[3]	3.5
CaO	64.5	64.4	0.0356[3]	-0.3	64.5	0.0546[3]	0.0	64.2	0.0002[3]	-0.5
Fe_2O_3	3.31	3.44	0.0023[3]	4.1	3.30	0.8977	-0.2	3.37	0.0014[3]	1.8
K_2O	0.47	0.54	<0.0001[3]	14.0	0.52	<0.0001[3]	10.7	0.54	0.0002[3]	14.0
MgO	3.55	3.31	0.0001[3]	-6.9	3.43	0.0001[3]	-3.5	3.65	0.0143[3]	2.8
Na_2O	0.06	0.07	0.0006[3]	17.6	0.06	0.4778	3.7	0.07	0.0885[3]	10.6
Na_2O_{eq}	0.37	0.43	0.0001[3]	14.6	0.41	0.0001[3]	9.6	0.42	0.0001[3]	13.5
SiO_2	21.4	21.0	0.0001[3]	-1.6	21.2	0.0001[3]	-0.8	21.1	0.0003[3]	-1.2
SO_3	0.99	1.11	0.0002[3]	11.9	0.85	0.311	-14.5	1.06	0.0023[3]	7.0
Free CaO	1.30	1.32	0.793	1.3	1.46	0.3822	12.1	1.52	0.374	16.8
C_3A	6.72	7.39	0.0001[3]	9.9	7.33	0.0001[3]	9.0	7.05	0.0016[3]	4.9
C_4AF	10.1	10.5	0.0022[3]	4.1	10.0	0.8877	-0.2	10.2	0.0014[3]	1.8
C_3S	64.5	64.0	0.5556	-0.7	64.1	0.6263	-0.6	63.9	0.2884	-0.9
C_2S	12.6	11.9	0.8376	-5.0	12.4	0.5386	-1.2	12.3	0.8786	-2.6

Notes:

[1] Wilcoxon Rank Sum Test

[2] Difference Relative to Baseline

[3] Data shows Significant Difference Between Means

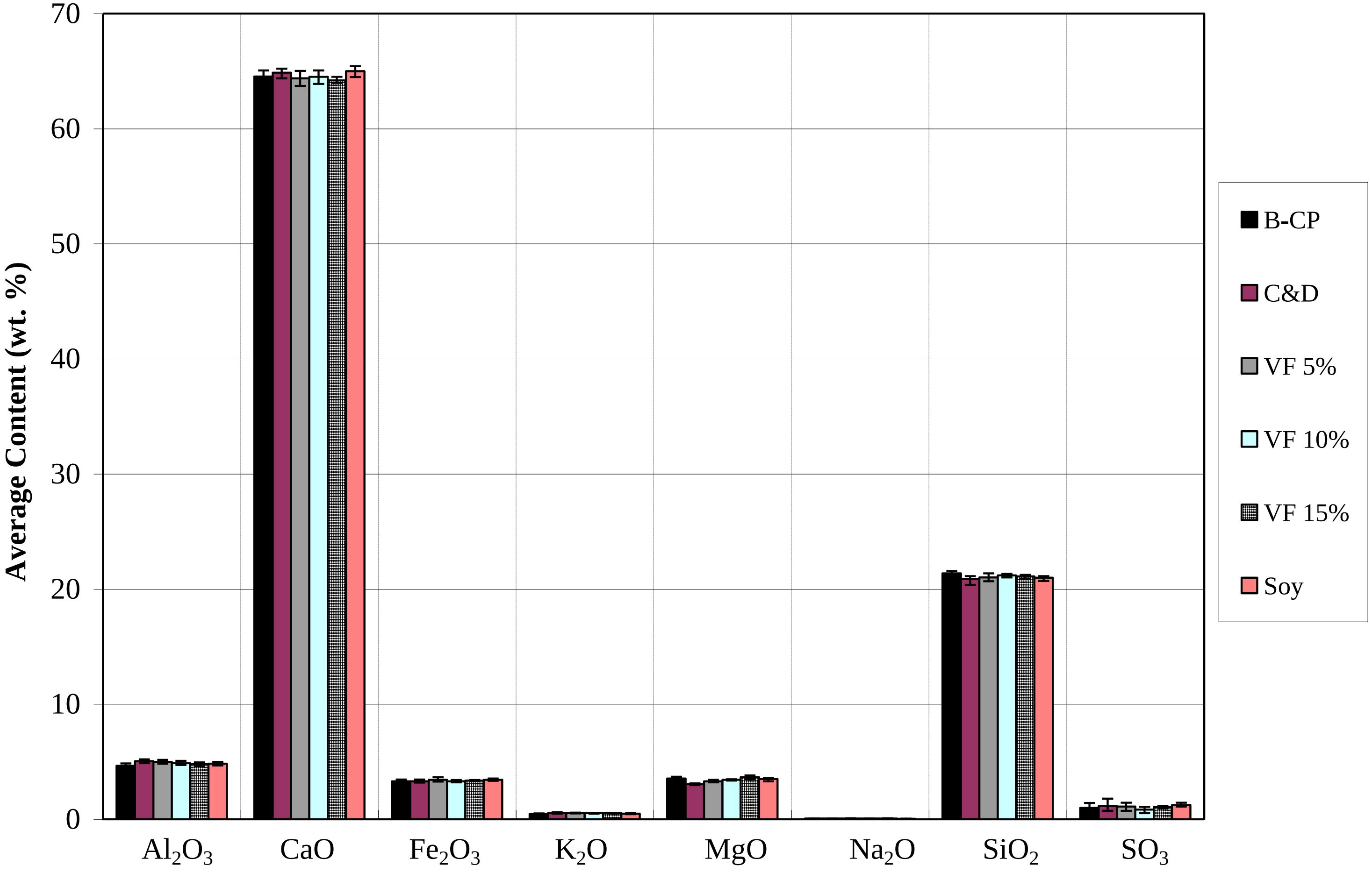

Figure 4.6: CPR – Average clinker composition with 5th and 95th percentiles

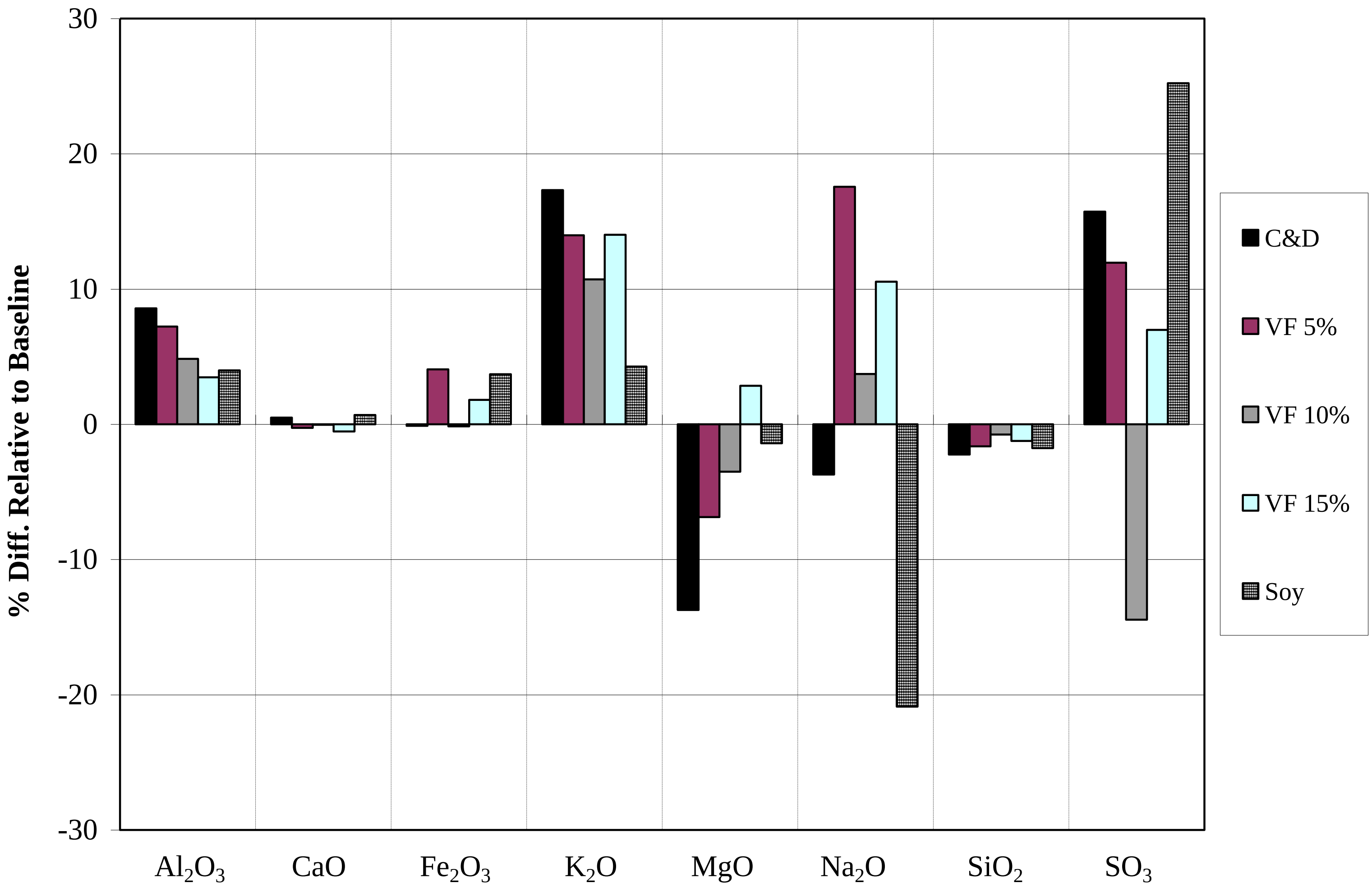

Figure 4.7: CPR – Percent difference in clinker composition relative to baseline

The external laboratory tested 24-hour composite specimens prepared from the clinker samples collected during each trial burn. The average chemical composition and the percent difference relative to the baseline for the standard parameters are tabulated in Table 4.24. Due to the limited number of tested specimens, statistical analysis is not presented for these data.

The external laboratory reported values that were similar to the cement plant parameter results in all trials except the baseline burn. In Table 4.24, a significant number of the percent difference values seem extreme; however, these values depend on the baseline results. Observing the similarity between the trial burn results from the external lab and the cement plant results suggests the possibility of error in the external lab baseline chemical analysis results.

Composite clinker specimens were also tested by the cement plant's specialty laboratory. A Rietveld analysis was conducted by the specialty laboratory in order to determine the Bogue compounds. The test results and their percent difference relative to the baseline are tabulated in Table 4.25. The alite content of the variable feed 15 % trial burn cement decreased 24 % compared to the baseline's results. The belite content increased 19 and 42 % for the variable feed 5 and 15 % trial burns, respectively, compared to the baseline. The specialty laboratory also found that belite decreased 18% in the soybean trial. Recall from the clinker chemical composition from the cement plant's results, the belite decreased around 28 %. Ferrite and Aluminate levels were also significantly increased for the construction and demolition waste and variable feed trial burns compared to the baseline's results. The physical properties of the cement will dictate any practical significance and are discussed in the following section.

Table 4.24: ELR – Chemical composition of clinker and percent difference relative to baseline for all burns

Parameter	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Avg. (wt. %)	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.	Avg. (wt. %)	% Diff.
Al_2O_3 (wt. %)	11.8	5.20	-56.0	5.35	-54.8	5.09	-57.0	5.03	-57.5	21.2	79.1
CaO (wt. %)	48.2	64.5	33.8	63.3	31.4	63.5	31.9	63.6	32.0	63.9	32.6
Fe_2O_3 (wt. %)	2.78	3.36	20.9	3.32	19.5	3.12	12.3	3.29	18.7	3.40	22.3
K_2O (wt. %)	0.78	0.52	-34.1	0.44	-43.7	0.50	-35.9	0.41	-47.8	0.44	-43.1
MgO (wt. %)	2.84	3.22	13.2	3.59	26.1	3.67	29.1	3.98	39.8	3.84	34.9
Na_2O (wt. %)	0.10	0.07	-29.0	0.07	-26.6	0.05	-44.0	0.04	-58.3	0.04	-54.1
P_2O_5 (wt. %)	0.04	0.06	43.5	0.07	56.0	0.07	48.9	0.06	44.2	0.07	59.4
SiO_2 (wt. %)	32.1	20.9	-35.0	22.1	-31.0	22.4	-30.2	21.6	-32.6	21.2	-34.0
SO_3 (wt. %)	0.71	1.06	49.0	1.15	61.9	1.10	54.7	1.22	72.1	1.21	71.4
TiO_2 (wt. %)	0.34	0.23	-31.0	0.25	-26.1	0.24	-29.0	0.24	-27.9	0.27	-20.7
Moisture (wt. %)	0.02	0.01	-63.9	0.01	-73.1	0.00	-94.7	0.00	-93.8	0.00	-88.1
LOI (wt. %)	0.21	0.84	303	0.22	7.22	0.12	-42.6	0.41	96.2	0.15	-26.5
As (ppm)	41.5	30.7	-26.1	41.0	-1.20	43.0	3.61	44.5	7.23	61.0	47.0
Cd (ppm)	< 6	< 6	NA	< 6	NA	< 6	NA	< 6	NA	< 6	NA
Cl (ppm)	182	140	-22.9	494	172	691	280	379	108	54.4	-70.1
Co (ppm)	12.3	10.7	-12.9	10.0	-18.4	13.3	8.84	11.5	-6.12	8.60	-29.8
Cr (ppm)	48.5	69.3	43.0	72.2	48.8	65.0	34.0	57.1	17.8	69.8	43.9
Cu (ppm)	51.5	16.0	-68.9	43.0	-16.5	29.7	-42.4	23.0	-55.3	42.8	-16.9
Hg (ppm)	0.14	0.06	-54.9	0.06	-55.2	0.01	-91.4	0.01	-94.5	0.04	-67.3
Mo (ppm)	11.0	< 5	NA	10.0	-9.09	9.33	-15.2	8.50	-22.7	< 5	-54.6
Ni (ppm)	14.8	19.3	31.1	94.0	537	15.0	1.7	11.5	-22.0	29.2	98.0
Pb (ppm)	31.3	47.3	51.1	57.5	83.5	22.3	-28.7	20.0	-36.2	45.6	45.5
Se (ppm)	< 2	< 2	NA	< 2	NA	< 2	NA	< 2	NA	< 2	NA
V (ppm)	54.0	45.7	-15.4	63.7	17.9	59.7	10.5	56.0	3.7	40.4	-25.2
Zn (ppm)	83.3	77.3	-7.1	65.0	-21.9	36.0	-56.8	48.5	-41.7	88.4	6.19

Table 4.25: SLR – Rietveld anlaysis of clinker and percent difference relative to baseline

Property	**B-CP**	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Value	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**
Alite (C_3S) (wt. %)	59.2	55.6	-6.08	53.4	-9.92	55.5	-6.30	44.9	-24.2	62.4	5.31
Belite (C_2S) (wt. %)	22.9	24.8	8.23	27.4	19.4	25.3	10.3	32.5	41.9	18.6	-18.8
Aluminate (C_3A) (wt. %)	3.03	4.12	36.2	3.55	17.4	3.94	30.2	3.81	25.9	3.41	12.6
Ferrite (C_4AF) (wt. %)	10.4	11.0	6.01	11.1	6.92	10.7	3.68	10.9	5.06	10.8	4.02

4.4.6 Chemical Composition of Cement

The final product of the manufacturing process is portland cement. All of the cement produced during the trial burns by the cement plant was indented to meet ASTM C 150 specifications for Type I/II cement. Samples were gathered by the cement plant during each burn period. Composite specimens were prepared and tested by the cement plant and sent to the external laboratory for analysis. Sample sizes were not large enough in order to perform Wilcoxon rank-sum tests for each parameter. Therefore, only the average values and percent difference relative to the baseline test results are presented.

The cement chemical composition data obtained from the cement plant are shown in Table 4.26 and Figure 4.8. Most parameters are fairly consistent throughout trial burns. The average content as well as the 5th and 95th percentiles of the data collected are shown in Table 4.26 and Figure 4.8. Since the data from the trials have a small variance, the percentile bars are nearly equal to the mean value.

All the primary oxides decreased slightly from the reported values from the clinker. The SO_3 contents increased from the clinker results which is due to the addition of gypsum or other sources of sulfates during grinding. The SO_3 contents in the baseline and soybean burn cements slightly exceeded the allowable 3 % maximum to be considered Type I and II cement. A slight excess is permissible, however, if the cement is in compliance with ASTM C 563 and 1038. Overall, the parameter values from the cement plant stayed fairly consistent between the clinker and cement results. The percent difference relative to the baseline, depicted in Figure 4.9, shows that the parameters for all the trial burns stayed fairly consistent. The greatest fluctuation was found in the K_2O

and Na_2O contents. The K_2O content for the construction and demolition waste trial burn differed by 19 % from the baseline burn. The Na_2O content increased by 14 % and 17 % for the variable feed 5 % and 10 % burns, respectively. The Na_2O content decreased by 12 % in the soy trial burn.

Composite cement specimens were prepared for testing by the external laboratory for every 24-hour period during each burn. The external laboratory results are shown in Table 4.27. The results of each parameter between the external and cement plant laboratories are similar. This provides a high level of confidence in precision of the results.

In the external laboratory results, the primary oxides stayed fairly consistent compared to the baseline. Due to the addition of sulfate during grinding, the SO_3 content in the cement increased from the clinker composition just as it did in the cement plant results. The external laboratory reported that the P_2O_5 content increased over the variable feed 5 and 10 % and soybean seed trial burns compared to the control results. Excessive P_2O_5 concentrations can inhibit the formation of C_3S. However, the external laboratory reported that the C_3S content of the variable feed 5 and 10 % trial burns decreased 17 and 14 %, respectively, compared to the baseline's results. The C_3A concentrations were increased in the construction and demolition waste and variable feed 10 % trial burns compared to the baseline's results.

Table 4.26: CPR – Average cement composition and percent difference relative to baseline results

Parameter	**B-CP**	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Average (wt. %)	**Average (wt. %)**	**% Diff.**	**Average (wt. %)**	**% Diff.**	**Average (wt. %)**	**% Diff.**	**Average (wt. %)**	**% Diff.**	**Average (wt. %)**	**% Diff.**
Al_2O_3	4.51	4.95	9.63	4.76	5.58	4.73	4.75	4.73	4.84	4.54	0.55
CaO	62.8	63.1	0.60	62.9	0.24	62.9	0.17	62.6	-0.31	63.4	1.06
CO_2	1.30	1.30	0.00	1.30	0.00	1.30	0.00	1.30	0.00	1.55	19.2
Fe_2O_3	3.11	3.08	-0.90	3.21	3.22	3.11	-0.11	3.18	2.35	3.18	2.43
K_2O	0.44	0.52	19.4	0.48	9.89	0.48	10.3	0.46	5.67	0.45	2.53
MgO	3.44	3.13	-8.91	3.26	-5.38	3.33	-3.36	3.53	2.70	3.40	-1.04
Na_2O	0.07	0.07	0.00	0.08	14.3	0.08	17.0	0.07	0.39	0.06	-12.28
Na_2Oeq	0.35	0.41	15.7	0.39	10.7	0.40	11.4	0.37	4.65	0.35	-0.33
SiO_2	19.9	19.6	-1.66	19.3	-3.32	19.6	-1.63	19.6	-1.49	19.4	-2.71
SO_3	3.18	2.78	-12.6	2.97	-6.73	2.75	-13.7	2.82	-11.27	3.23	1.46
Free CaO	1.20	1.51	25.7	1.03	-14.4	1.02	-15.2	0.78	-35.18	1.16	-3.88
LOI	2.50	2.08	-16.9	2.46	-1.92	2.53	1.04	2.42	-3.55	2.51	0.11
C_3A	6.70	7.90	17.9	7.20	7.43	7.28	8.58	7.16	6.80	6.64	-0.92
C_4AF	9.46	9.37	-0.90	9.76	3.22	9.45	-0.15	9.68	2.35	9.69	2.43
C_3S	53.4	55.7	4.32	57.8	8.26	56.1	5.08	54.3	1.69	58.5	9.57
C_2S	16.8	14.1	-16.0	11.6	-31.0	13.9	-17.7	15.3	-9.10	11.4	-32.1
Blaine SSA (m^2/kg)	387	374	-3.3	379	-2.1	369	-4.7	367	-5.2	385	-0.5

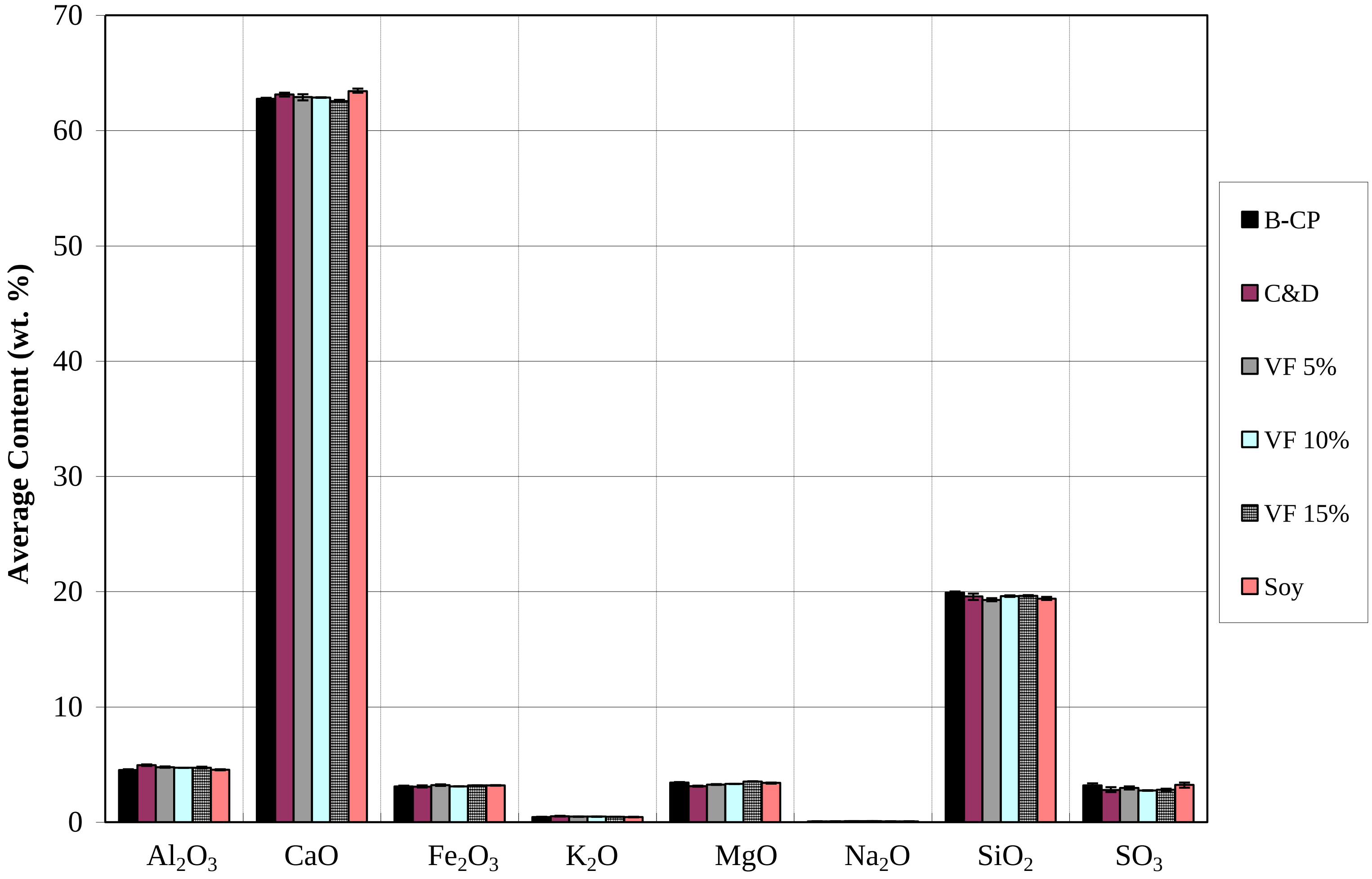

Figure 4.8: CPR – Average cement composition with 5th and 95th percentiles

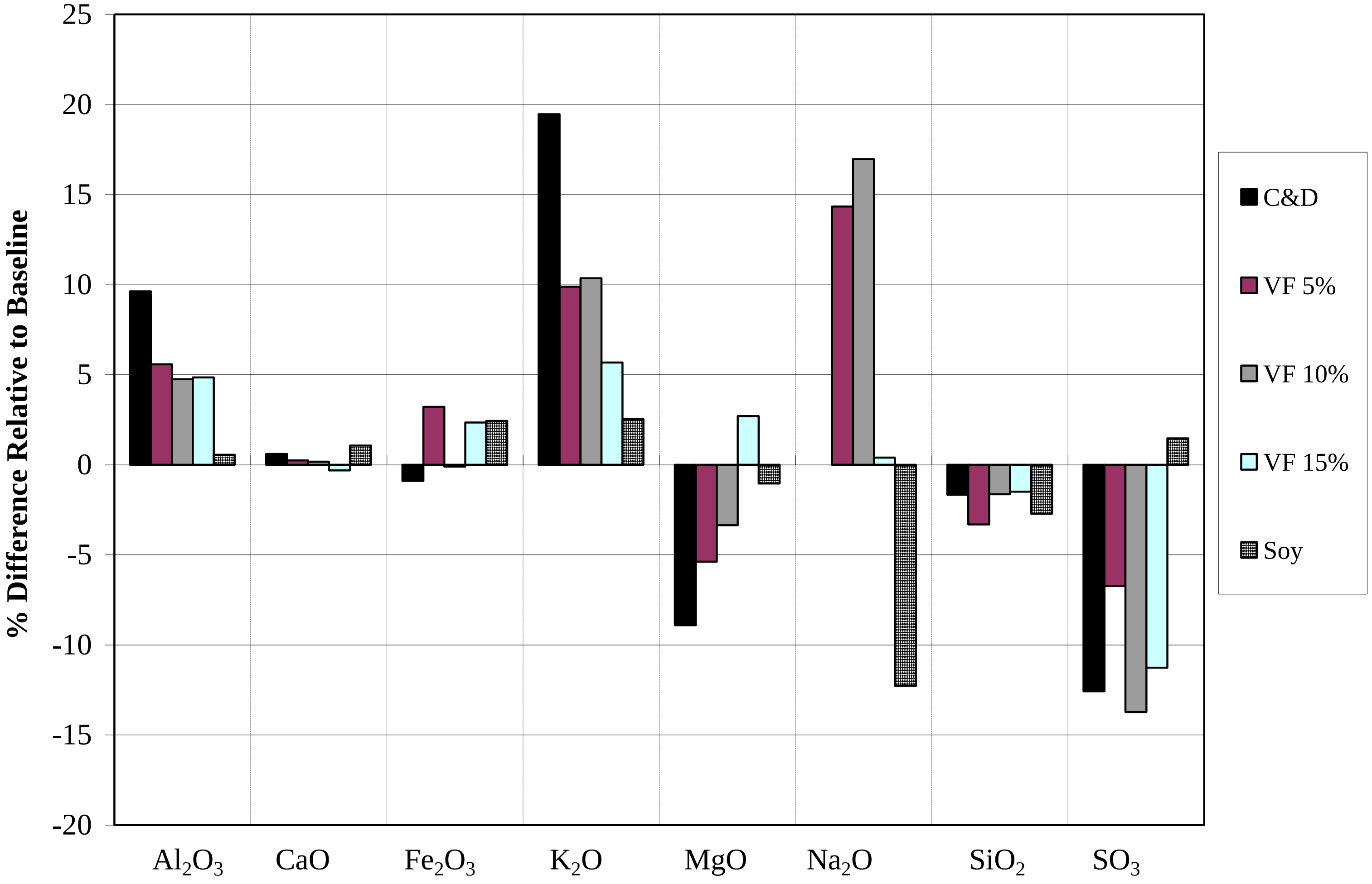

Figure 4.9: CPR – Percent difference of cement composition relative to baseline

The trace elements were only tested by the external laboratory and are presented in Table 4.27. The arsenic (As) concentrations decreased for the construction and demolition waste trial burn, stayed relatively the same for the variable feed trial burns, and increased for the soybean seed trial burn compared to the baseline values. The chlorine (Cl) and zinc (Zn) contents were significantly lower in the construction and demolition waste and variable feed trial burns when compared to the baseline. The soybean seed trial burn also had a significantly reduced chlorine content compared to the baseline burn's chlorine content.

The cement plant's specialty laboratory also received cement samples in order to perform a Reitveld analysis. The Reitveld analysis results and their percent difference relative to the baseline are tabulated in Table 4.28. The alite and belite content of the cement remained fairly constant for the construction and demolition waste and variable feed 5 % and 10% trial burns. The soybean seed trial burn cement had the greatest increase in alite of 17 % and the greatest decrease in belite of 20 % when compared to the baseline burn results. The variable feed 15 % trial burn showed a 14% increase in belite compared to the baseline results. The aluminate increased 33 % in the construction and demolition waste trial burn and 24 % in the variable feed 10 % trial burn compared to the baseline results. The remaining trial burn's aluminate levels were comparable to the baseline results. All the aluminate levels were within allowable limits for Type I and II cement according to ASTM C 150. The ferrite level in the soybean seed trial burn had an increase of 6 % over the baseline results, which was the greatest difference in ferrite for all the trial burns. The Bogue compounds in the variable feed 5 % trial burn cement had the lowest percent differences compared to the baseline cement composition. Therefore, the cement from the variable feed 5 % trial burn has the greatest resemblance to the baseline cement. The results from the physical property tests of the trial burn cements will dictate any practical significance between the trial and baseline cements and are discussed in the following section.

Table 4.27: ELR – Average cement composition and percent difference relative to baseline results

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Al2O3 (wt. %)	4.64	5.23	12.8	5.00	7.79	5.01	8.01	4.97	7.23	4.88	5.36
CaO (wt. %)	62.4	62.5	0.25	62.0	-0.66	61.9	-0.81	61.6	-1.22	62.4	0.04
Fe2O3 (wt. %)	3.08	3.12	1.35	3.19	3.68	3.07	-0.20	3.13	1.56	3.18	3.06
K2O (wt. %)	0.38	0.47	26.4	0.33	-11.25	0.39	4.01	0.42	11.7	0.33	-13.3
MgO (wt. %)	3.45	3.15	-8.65	3.34	-3.19	3.46	0.11	3.67	6.19	3.65	5.64
Na2O (wt. %)	0.05	0.06	23.0	0.06	20.6	0.05	0.13	0.06	20.0	0.05	-0.39
P2O5 (wt. %)	0.05	0.06	11.8	0.07	27.9	0.07	27.4	0.06	9.08	0.08	44.8
SiO2 (wt. %)	20.1	20.2	0.62	20.4	1.72	20.4	1.77	20.4	1.83	19.6	-2.46
SO3 (wt. %)	3.03	2.91	-3.82	3.07	1.31	2.77	-8.43	2.92	-3.40	3.23	6.81
TiO2 (wt. %)	0.21	0.21	0.13	0.23	5.07	0.23	9.22	0.23	9.07	0.25	17.70
Moisture (wt. %)	0.12	0.19	64.4	0.25	114	0.35	205	0.34	196	0.53	360
LOI (wt. %)	2.55	1.93	-24.1	2.22	-12.61	2.54	-0.19	2.39	-6.17	2.25	-11.77
C3S (wt. %)	49.0	44.8	-8.71	40.8	-16.8	42.0	-14.2	40.6	-17.3	50.9	3.77
C2S (wt. %)	20.5	24.1	17.4	27.7	35.2	26.8	30.6	28.0	36.2	17.7	-13.7
C3A (wt. %)	7.07	8.58	21.3	7.84	10.8	8.07	14.1	7.88	11.4	7.57	7.05
C4AF (wt. %)	9.38	9.50	1.35	9.72	3.68	9.36	-0.20	9.52	1.56	9.66	3.06
TOC (wt. %)	0.08	1.84	2350	1.50	1900	1.48	1870.0	1.88	2400	0.03	-66.7
As (ppm)	42.5	27.0	-36.5	40.0	-5.88	47.0	10.6	40.0	-5.88	62.5	47.1
Cd (ppm)	6.00	6.00	0.00	6.00	0.00	6.00	0.00	6.00	0.00	6.00	0.00
Cl (ppm)	423	200	-52.8	200	-52.7	163.0	-61.5	135	-68.1	121	-71.4
Co (ppm)	10.0	11.5	15.0	12.0	20.0	6.0	-40.0	17.0	70.0	6.00	-40.0
Cr (ppm)	57.0	64.0	12.3	61.0	7.00	66.7	16.9	84.6	48.4	95.8	68.0
Cu (ppm)	28.0	13.0	-53.6	27.0	-3.57	43.0	53.6	26.0	-7.14	56.5	102
Hg (ppm)	0.01	0.02	250	0.01	0.00	0.01	20.0	0.01	20.0	0.14	2640
Mo (ppm)	5.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00	0.00	5.00	0.00
Ni (ppm)	13.0	19.5	50.0	13.0	0.00	18.0	38.5	12.0	-7.69	27.5	111.5
Pb (ppm)	5.00	51.5	930	102	1940	5.00	0.00	5.00	0.00	15.5	210.0
Se (ppm)	2.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00	2.00	0.00
V (ppm)	58.0	40.5	-30.2	58.00	0.00	51.0	-12.1	60.0	3.45	37.0	-36.2
Zn (ppm)	95.0	73.5	-22.6	62.0	-34.7	41.0	-56.8	66.0	-30.5	87.0	-8.42

Table 4.28: SLR – Rietveld analysis and percent difference of trial burn cement relative to baseline results

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Value (wt. %)	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.	Value (wt. %)	% Diff.
Alite (C_3S)	53.6	51.6	-3.8	51.5	-4.0	51.1	-4.8	50.5	-5.8	62.9	17.3
Belite (C_2S)	23.0	24.3	5.7	25.0	8.7	25.2	9.5	26.1	13.6	18.5	-19.8
Aluminate (C_3A)	3.0	4.0	32.8	3.1	4.8	3.7	23.6	3.0	2.0	3.3	10.3
Ferrite (C_4AF)	10.1	10.2	1.1	10.4	3.3	10.1	0.3	10.2	1.5	10.6	5.9

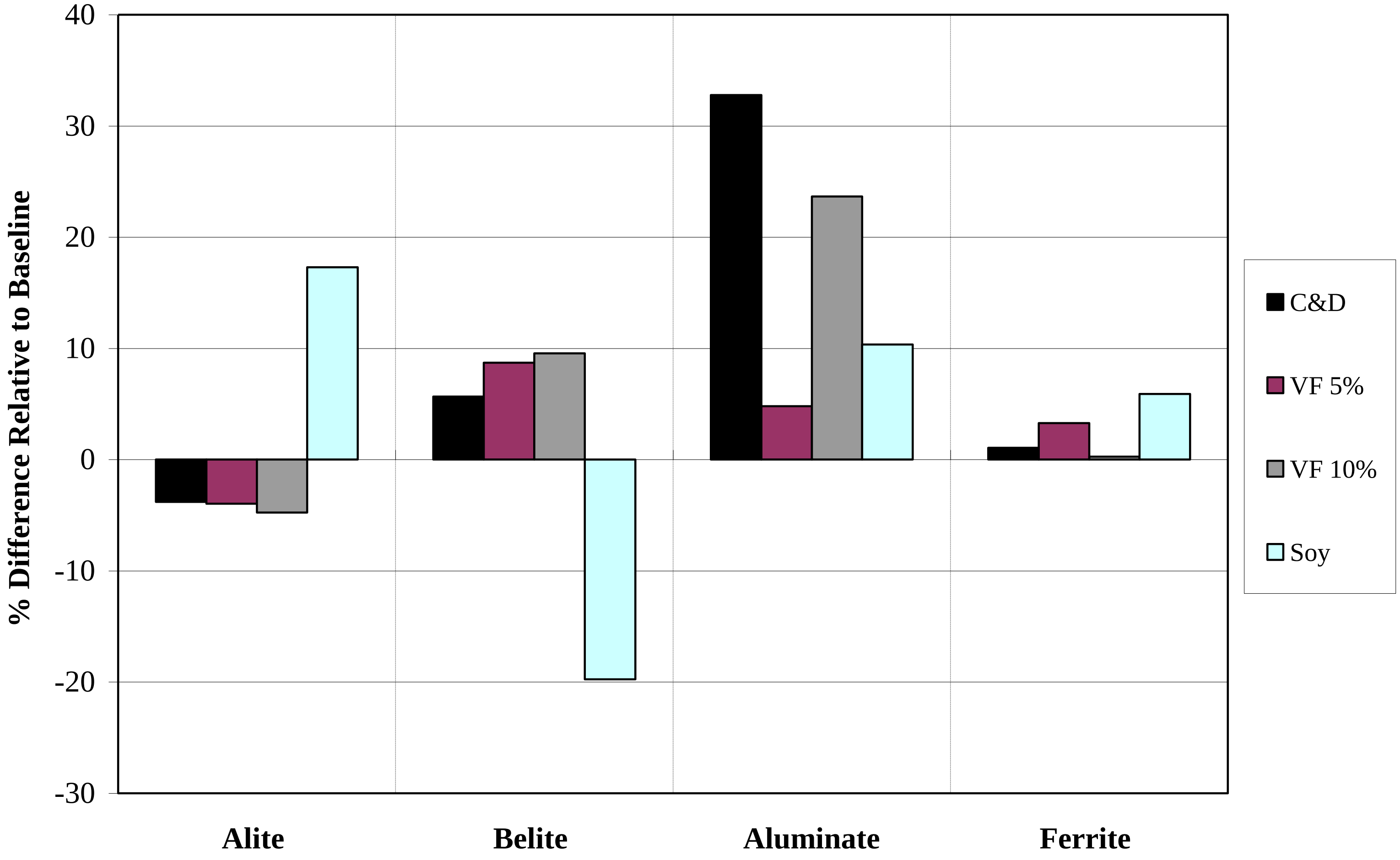

Figure 4.10: SLR – Percent difference of Bogue compounds relative to baseline

4.4.7 Physical Properties of Cement

On the completion of each burn, cement was tested by the cement plant and Auburn University. The cement plant tested cement specimens for the same properties as Auburn University, except for the additional tests of mortar air content and Blaine specific surface area. Auburn University also tested paste prisms for drying shrinkage development.

The precision requirements for several of the cement properties tested are tabulated in Table 4.29. If results from trial tests fall within the allowable limits set forth by the ASTM specifications, the trial tests results are comparable to the baseline's results. When comparing results between the cement plant and Auburn University, the multi-lab precision limits must be met to be considered similar. Single lab precision limits must be met for specimens tested at Auburn University in order to be considered similar. The percent difference between a trial burn result relative to the baseline burn result will be compared to both single-lab and multi-lab precision limits to determine the level of practical significance. It should be noted that the precision limits for mortar cube strengths are calculated using the d2s%, which is defined as the difference between trial and baseline results divided by their average.

Portland cement results obtained by the cement plant and Auburn University are tabulated in Table 4.30 and 4.31 and Figure 4.11 through 4.12. The average values and the percent difference relative to the baseline's results for each test are presented in these tables and figures. It should be noted that the percent difference between a trial and a baseline may appear large due to a small baseline value. The percent differences of testing conducted by both the cement plant and Auburn University are plotted in Figure 4.11 and Figure 4.12

Table 4.29: Precision requirements for single and multiple laboratories for cement physical properties

Property	ASTM Specification	Single-lab	Multi-lab
Autoclave Expansion	C 151 (2005)	0.07%[1]	0.09%[1]
Mortar flow	C 1437 (2007)	11%[1]	31%[1]
Cube strength	C 109 (2007)	10.7%[2]	18.7%[2]
Dry shrinkage	C 596 (2007)	70με[1]	25.0%[1]

Notes: [1] Difference between two results
[2] Represents d2s% limits as prescribed in Practice C 670

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The majority of results from the properties expressed in Table 4.30 and Table 4.31 fall within precision requirements for single and multiple laboratories. The tests that fall out of the precision range will be highlighted in this section.

To meet single-laboratory precision requirements for mortar cube flow, the allowable percent difference relative to the baseline burn result is 10 %. The mortar cube flow results from the cement plant for the variable feed 15 % and soybean seed trial burns exceeded the allowable precision limit for single-lab results. The mortar cube flow results from Auburn University for the construction and demolition waste and variable feed 5 % trial burns fell below the allowable precision limit for the single-lab results and therefore the single-lab precision results were not satisfied. The multi-laboratory precision limit for mortar cube flow was satisfied for all burns.

To meet single-laboratory precision limits for mortar cube strengths, the allowable percent difference relative to the baseline burn is 11 %. The allowable percent difference relative to the baseline was calculated from the d2s%. The mortar cube strength results from the cement plant that exceeded the precision limit for 1-day strengths occurred for the construction and demolition waste, variable feed 15 %, and soybean seed trial burns. The cement plant results of mortar cube strength results at later ages did meet the single-laboratory precision limit. The mortar cube strength results from Auburn University all met the single-laboratory precision limit except for the cubes made from the soybean seed trial burn cement. The mortar cubes made from the soybean seed trial burn cement fell significantly below the allowable single-laboratory precision limits over early- and late-age testing. Since the cement plant results showed that the mortar cube prepared from the soybean seed trial cement resembled the baseline strengths, the differences found by Auburn University could be due to error during the preparation or testing these cubes. Therefore, the Auburn University results pertaining to the mortar cube strengths prepared from the soybean seed trial cement will not be presented. All the mortar cube strength results between the cement plant and Auburn University fell within the allowable precision limit for multiple-laboratories except the soybean seed trial burn results. Graphical representations of mortar cube strengths are shown in Figure 4.13 and Figure 4.14.

All the drying shrinkage falls within the single laboratory precision limits except for the prisms prepared with the variable feed 15% cement. The drying shrinkage of the prisms are tabulated in Table 4.31 and graphically represented in Figure 4.15 The dry shrinkage percentage is the strain of the prism recorded in percent. The maximum allowable strains for 14, 21, and 28 days are 730, 850, and 920 με, respectively. The prisms made with the variable feed 15% possessed strains of 740, 870, and 1020 με. The drying shrinkage from the concrete specimens will have to be evaluated to determine if the drying shrinkage of the variable feed 15 % trial burn cement is elevated.

A paste setting test from each cement was conducted by the cement plant and Auburn University. ASTM C 191 (2008) reported that when using the manual vicat test method, the allowable single-laboratory precision for the initial and final setting times can vary by 34 and 56 minutes, respectively, and be considered similar. For multiple laboratory precision, the initial and final setting time can vary by 45 and 122 minutes, respectively, and be considered similar. The initial and final setting results from the cement plant can be considered similar to the baseline cement for each trial burn cement. All setting results from Auburn University fell within precision limits. A graphical representation of the cement properties percent difference relative to the baseline for the cement plant and Auburn University results are shown in Figure 4.11 and Figure 4.12.

The particle size distribution of each cement produced in this study was determined by laser diffraction at the cement plant's specialty laboratory. The particle size distribution of each cement is shown in Figure 4.16. The graph shows that all the cements in the study were ground to nearly the same size distribution. Thus, differences in cement behavior cannot be attributed to different particle size distributions.

Table 4.30: CPR – Physical properties of cement and percent difference relative to baseline for all burns

Property	**B-CP**	**C&D**		**VF (5%)**		**VF (10%)**		**VF (15%)**		**Soy**	
	Value	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**	**Value**	**% Diff.**
Air in Mortar (%)	5.1	6.3	23.5	5.3	3.9	5.3	3.9	5.80	13.7	6.10	19.6
Blaine Specific Surface Area (m^2/kg)	374	372	-0.5	371	-0.8	357	-4.5	374	0.0	376	0.5
Autoclave Expansion (% Exp.)	0.07	0.12	79.7	0.07	-4.3	0.11	65.9	0.08	15.9	0.09	26.1
Mortar flow (%)	106	96.0	-9.4	101	-4.7	105	-0.9	127	19.8	126	18.6
Compressive Strength (MPa)											
1	12.9	15.0	16.3	NR	-	12.6	-2.3	15.0	16.3	16.0	24.3
3	25.8	23.8	-7.8	24.4	-5.6	25.7	-0.6	21.7	-15.9	25.9	0.3
7	29.4	31.4	6.8	31.7	7.7	29.9	1.7	29.3	-0.3	32.3	9.8
28	42.1	40.6	-3.6	44.7	6.1	45.5	8.1	43.2	2.6	44.0	4.5
Normal Consistency (%)	25.4	25.5	0.4	25.7	1.2	25.3	-0.6	25.3	-0.4	25.1	-1.0
Gillmore Initial Set (Min.)	NR	NR	-	NR	-	NR	-	NR	-	NR	-
Gillmore Final Set (Min.)	NR	NR	-	NR	-	NR	-	NR	-	NR	-
Vicat Initial Set (Min.)	122	95	-22.1	121	-0.8	138	12.7	150	23.0	117	-4.4
Vicat Final Set (Min.)	210	195	-7.1	248	17.9	240	14.3	260	23.8	228	8.7

Notes: NR- Not Reported

Table 4.31: AUR – Physical properties of cement and percent difference relative to baseline for all burns

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Value	Value	% Diff.	Value	% Diff.	Value	% Diff.	Value	% Diff.	Value	% Diff.
Autoclave Expansion (% Exp.)	0.06	0.07	16.7	0.05	-16.7	0.06	0.00	0.08	33.3	0.05	-16.7
Mortar flow (%)	102	89.5	-12.1	74.8	-26.5	102	0.20	104	1.67	96.5	-5.21
Compressive Strength (MPa)											
1	14.2	14.3	0.7	15.3	7.75	13.6	-4.23	13.2	-7.04	11.8	-16.9
3	23.2	24.6	6.0	24.5	5.60	24.3	4.74	22.9	-1.29	19.2	-17.2
7	30.4	31.5	3.6	32.5	6.91	32	5.26	31.2	2.63	26.2	-13.8
28	40.9	45.1	10.3	42.9	4.89	43.4	6.11	44.7	9.29	31.8	-22.2
Normal Consistency (%)	24.5	25.2	2.9	25.0	2.04	24.5	0.00	24.5	0.00	25.0	2.04
Gillmore Initial Set (Min.)	132	190	43.9	137	3.79	145	9.85	134	1.52	200	51.5
Gillmore Final Set (Min.)	222	243	9.5	227	2.25	265	19.4	254	14.4	275	23.9
Vicat Initial Set (Min.)	109	144	32.1	122	11.9	130	19.3	121	11.0	185	69.7
Vicat Final Set (Min.)	207	242	16.9	197	-4.83	220	6.28	209	0.97	250	20.8
Drying Shrinkage (%)											
7	-0.045	-0.045	1.1	-0.047	5.62	-0.049	8.99	-0.050	12.9	-0.048	6.74
14	-0.066	-0.071	6.4	-0.069	4.53	-0.072	8.68	-0.074	12.1	-0.070	4.91
21	-0.078	-0.083	6.1	-0.082	4.49	-0.085	9.29	-0.087	11.5	-0.081	3.85
28	-0.085	-0.090	5.3	-0.090	5.87	-0.096	12.6	-0.102	19.4	-0.089	4.40

Note: NA – Not Available

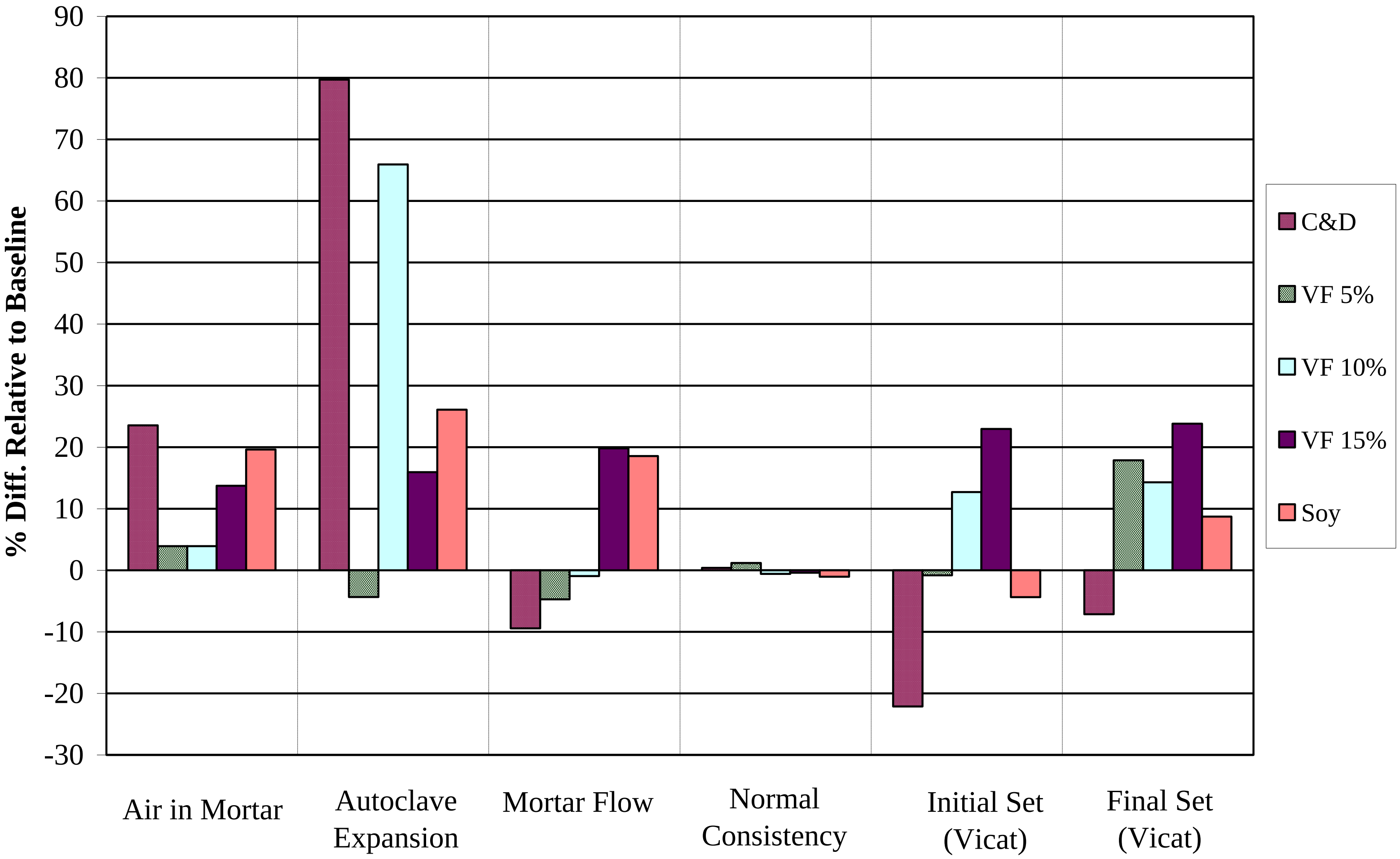

Figure 4.11: CPR – Percent difference in cement properties relative to baseline

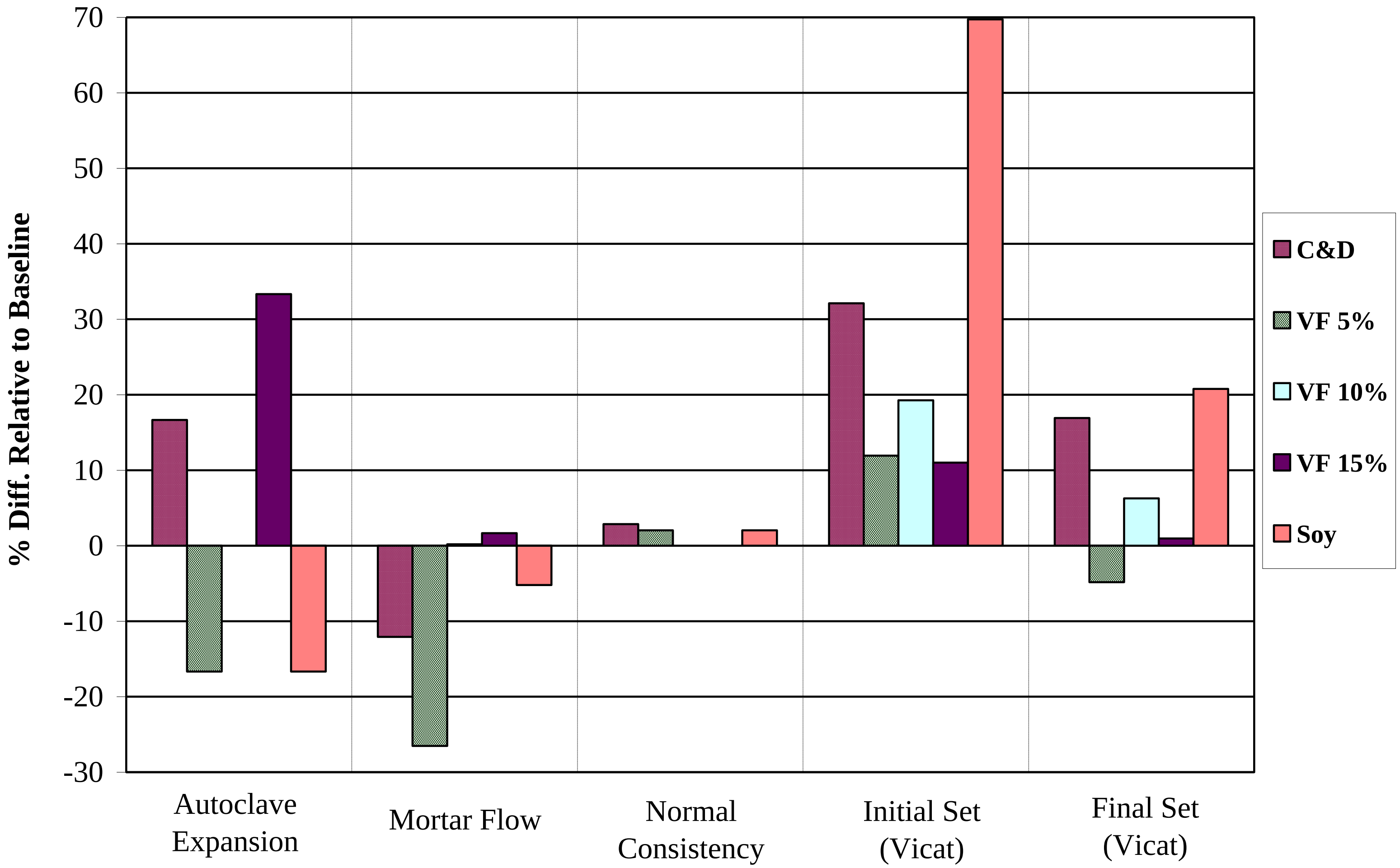

Figure 4.12: AUR – Percent difference in cement properties relative to baseline

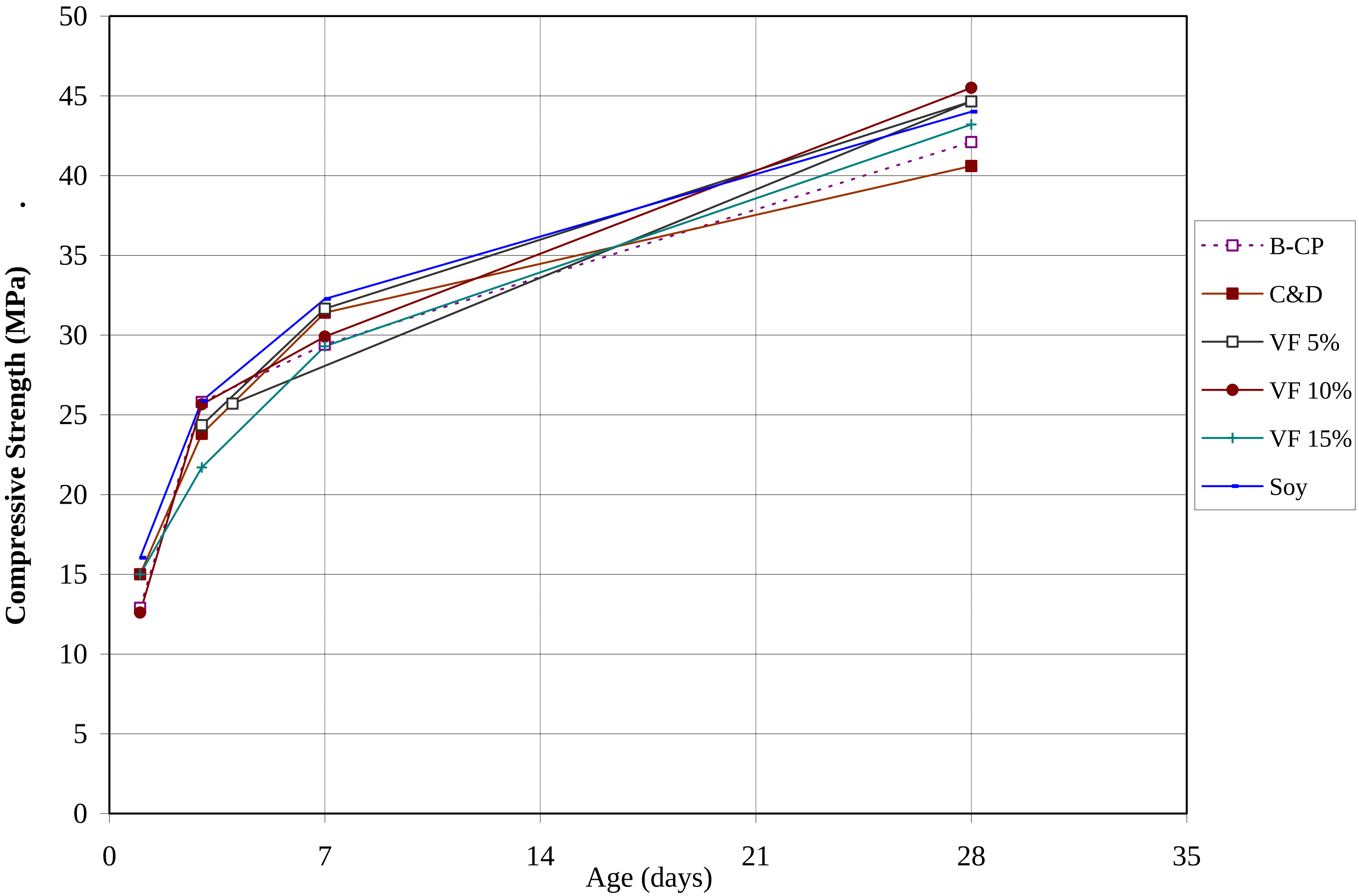

Figure 4.13 : CPR – Mortar cube compressive strengths for all burns

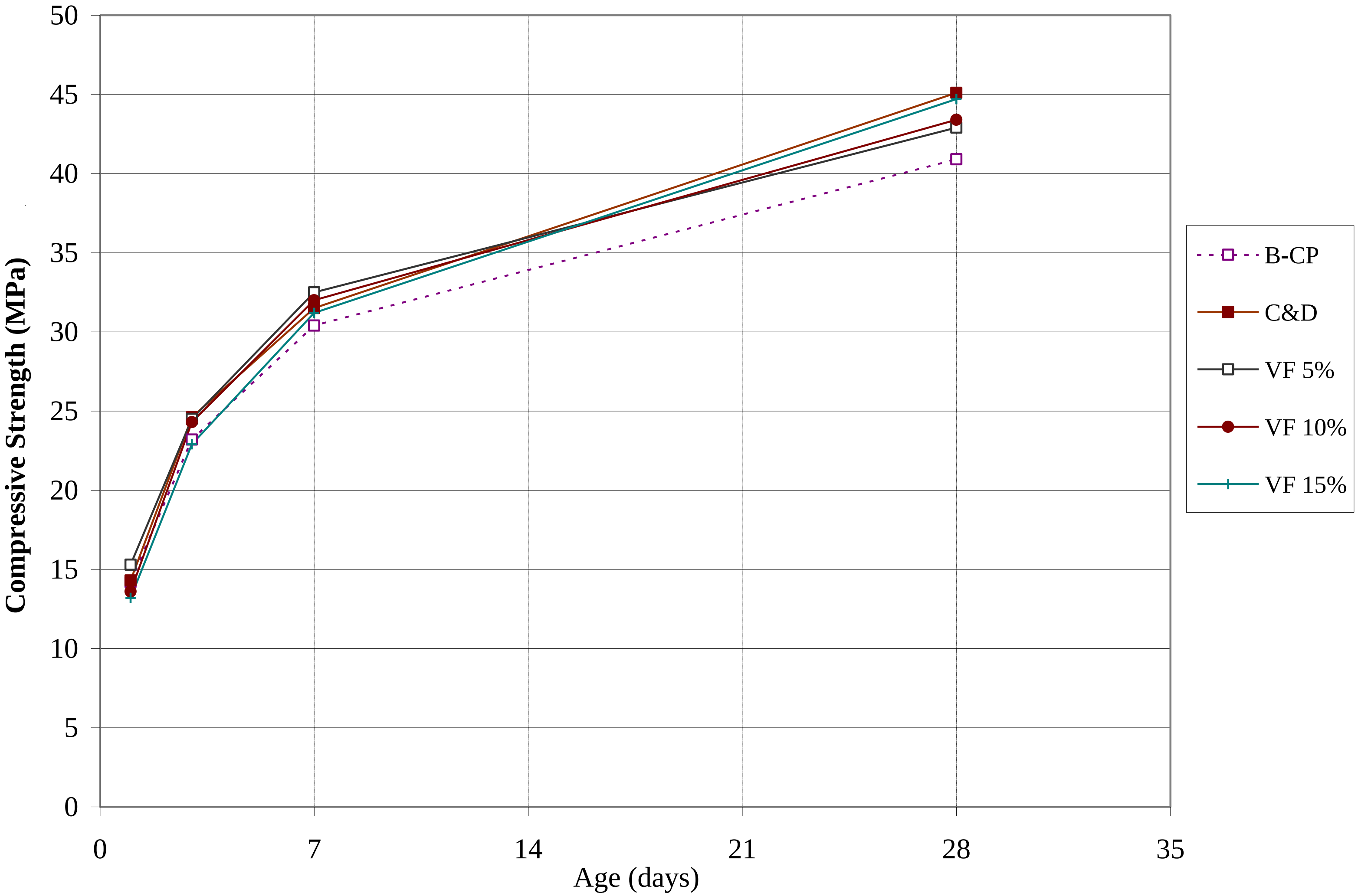

Figure 4.14: AUR – Mortar cube compressive strengths for all burns

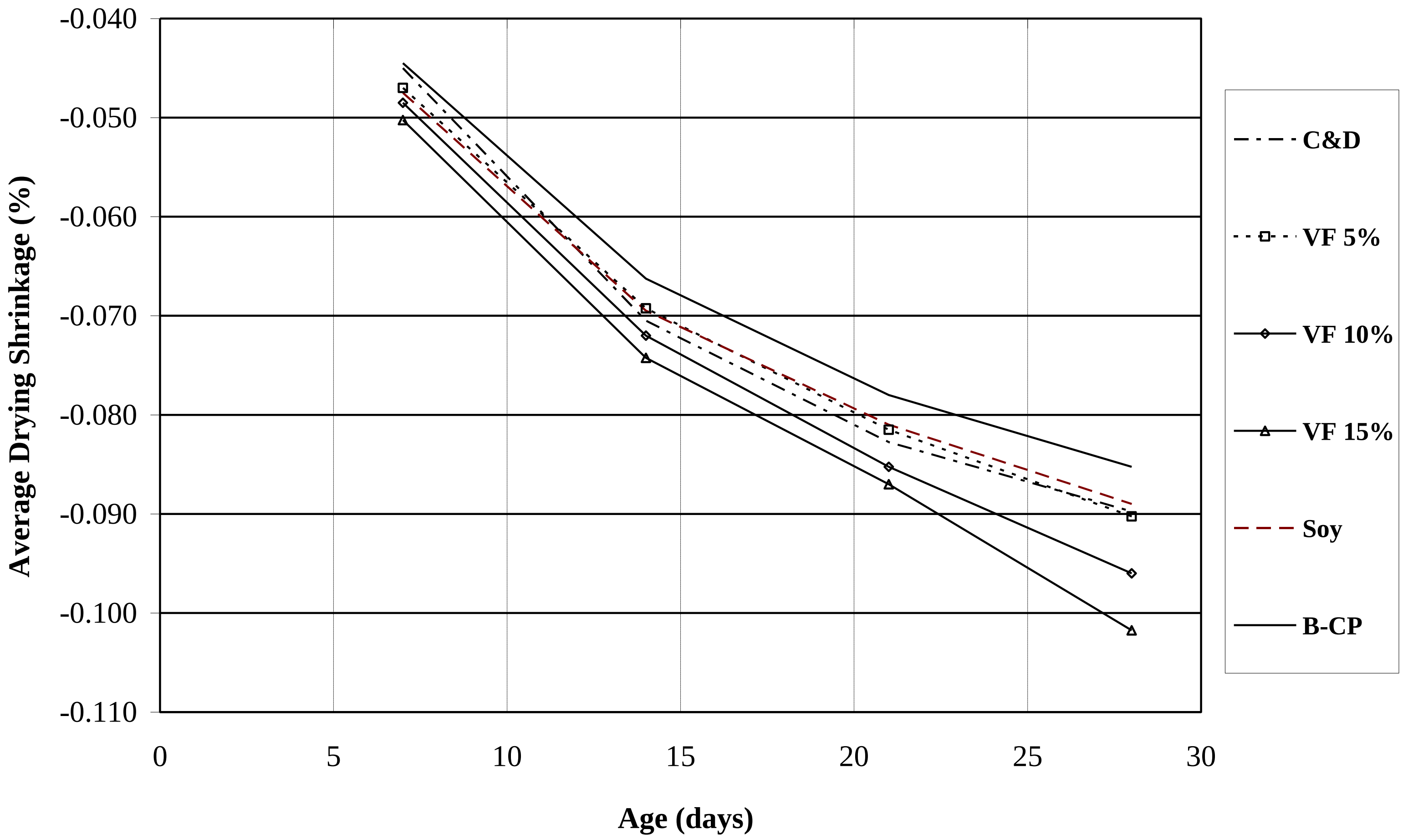

Figure 4.15: AUR – Average drying shrinkage of mortar prisms for all burns

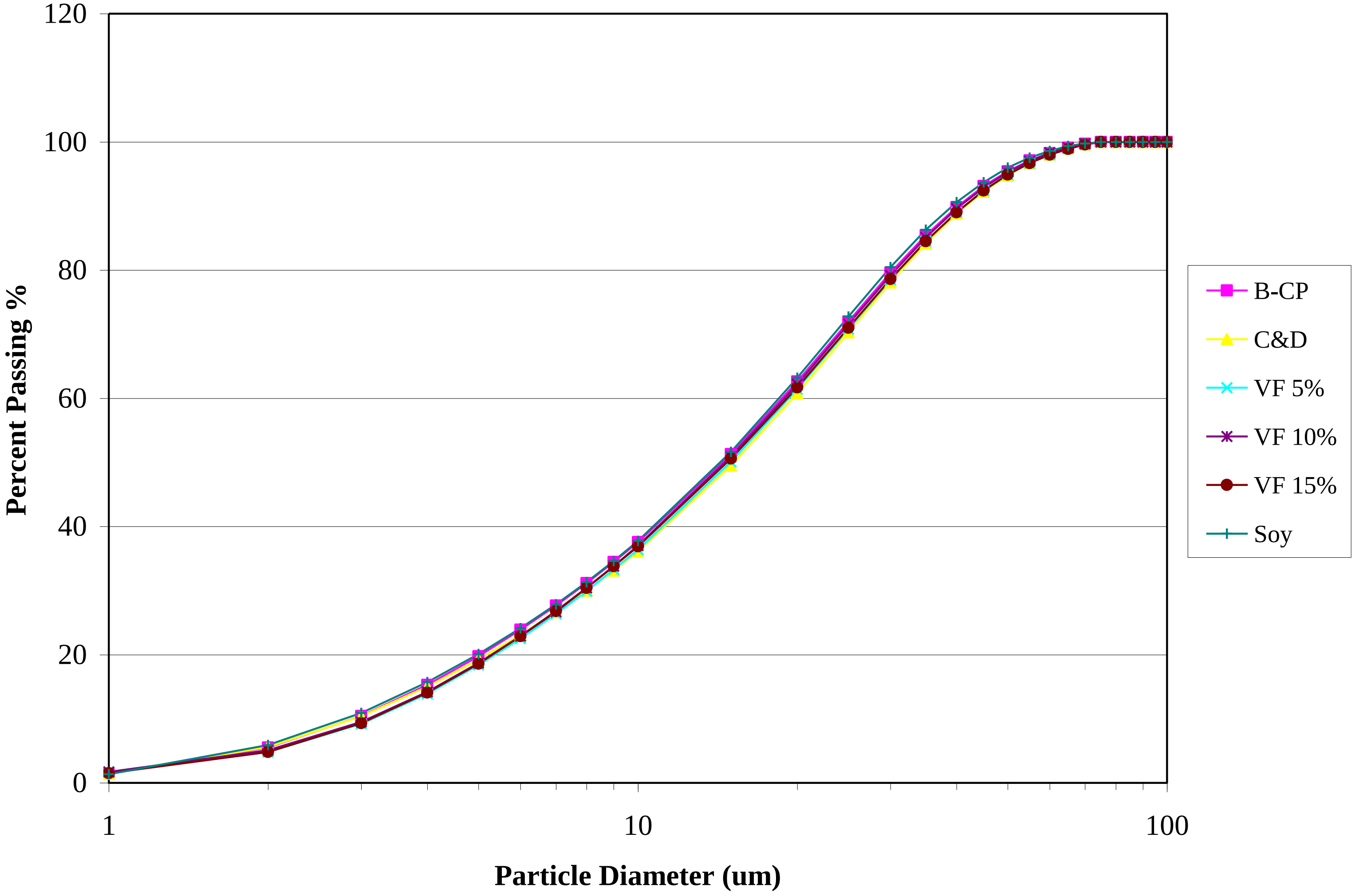

Figure 4.16: SLR – Particle size distribution of cement for all burns

4.4.8 Properties of Concrete

As previously discussed in Chapter three, Auburn University tested properties of concrete prepared from the cement produced during each burn of this study. Two mix designs were utilized. Mix 0.44 and Mix 0.37 have unique water-cement ratios and therefore cannot be directly compared. Trends that are consistent through both mixtures could establish practical significance in the effect that a specific cement has on a specific property. The data from the results will be presented for both mixtures before they are discussed.

Similarly to the cement tests discussed earlier, precision statements acquired from ASTM specifications allow for a specific range of results to be considered comparable when multiple tests are preformed. The testing property, ASTM specification, and precision for both single and multiple laboratories are presented in Table 4.32. To assess the practical significance of the trial burn results, the ASTM precision limits are applied to the baseline results. If the test results from a trial burn fall within the baseline burn result's allowable value range, the trial burn and baseline burn results are considered similar. Precision statements from ASTM specifications are given for all concrete tests except setting time. ASTM C 403 (2008) provides precision in terms of difference in setting times. Weakley (2009) conducted a study and reported setting precision in terms of percent difference, which is thought to be more appropriate.

Table 4.32: 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/m3 (2.5 lb/ft^3)[1]	64.1 kg/m3 (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)	6.6%[2]	7.8%[2]
Splitting tensile strength	C 496 (2004)	14%[2]	NA
Permeability	C 1202 (2007)	42%[2]	51%[2]
Drying shrinkage	C157 (2006)	0.0137%[1]	

Notes:
[1] Difference in the average of two results
[2] Acceptable range of values (d2s%) as described in ASTM C 670
[3] Percent difference relative to baseline

4.4.8.6 Concrete Mix 0.44

All physical concrete properties were determined by Auburn University. Concrete Mix 0.44 was a normal-strength mixture possessing a water-cement ratio of 0.44. The mix design proportions for Mix 0.44 are detailed in Section 3.4.3. The average results and percent difference of each trial burn relative to the baseline results from Mix 0.44 are shown in Table 4.33. A graphical representation of the fresh property results of each trial burn's cement relative to the baseline cement's results are shown in Figure 4.17.

Due to the volume of concrete required to conduct the necessary tests and the volume limitations of available mixing equipment, each mixture was divided roughly in half to ensure adequate blending of all materials. The air content, slump, and unit weight recorded in Table 4.33 are the average of two batches of concrete mixed for each trial.

Table 4.33: AUR – Physical properties and percent difference relative to baseline for Mix 0.44 concrete for all burns

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	AUR	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**
Total Air Content (%)	3.9	4.0	2.6	3.8	-2.6	4.8	21.8	4.1	5.1	4.3	10.3
Slump (in)	2.9	2.0	-31.0	2.3	-20.7	3.3	12.1	2.0	-31.0	2.3	-20.7
Unit Weight (lb/ft^3)	150	151	0.5	151	0.2	148	-1.6	150	-0.3	150	-0.4
Initial Set (Min.)	239	238	-0.4	264	10.5	333	39.3	262	9.6	266	11.3
Final Set (Min.)	311	326	4.8	352	13.2	430	38.3	352	13.2	353	13.5
Compressive Strength (MPa)											
1 day	17.2	15.2	-11.6	15.0	-12.8	12.5	-27.3	12.3	-28.5	15.5	-9.9
3 days	25.1	21.5	-14.3	22.7	-9.6	23.0	-8.4	22.1	-12.0	22.8	-9.2
7 days	27.4	27.7	1.1	28.7	4.7	28.3	3.3	28.0	2.2	28.8	5.1
28 days	37.5	35.9	-4.3	37.3	-0.5	39.6	5.6	40.7	8.5	36.1	-3.7
91 days	41.8	40.1	-4.1	42.7	2.2	42.3	1.2	41.7	-0.2	38.5	-7.9
Splitting Tensile Strength (MPa)											
1 day	2.1	1.9	-9.5	1.9	-9.5	1.9	-9.5	1.7	-19.0	1.9	-9.5
3 days	2.7	2.2	-18.5	2.8	3.7	2.8	3.7	2.3	-14.8	2.5	-7.4
7 days	3.0	3.0	0.0	3.2	6.7	3.4	13.3	3.1	3.3	3.0	0.0
28 days	3.5	3.6	2.9	3.7	5.7	4.2	20.0	4.1	17.1	3.6	2.9
91 days	4.1	4.0	-2.4	4.1	0.0	4.2	2.4	4.1	0.0	3.8	-7.3
Permeability @ 91 days (Coulombs)	2047	2051	0.2	2449	19.6	2369	15.7	2067	1.0	2449	19.6

Notes: [1]Relative to B-CP

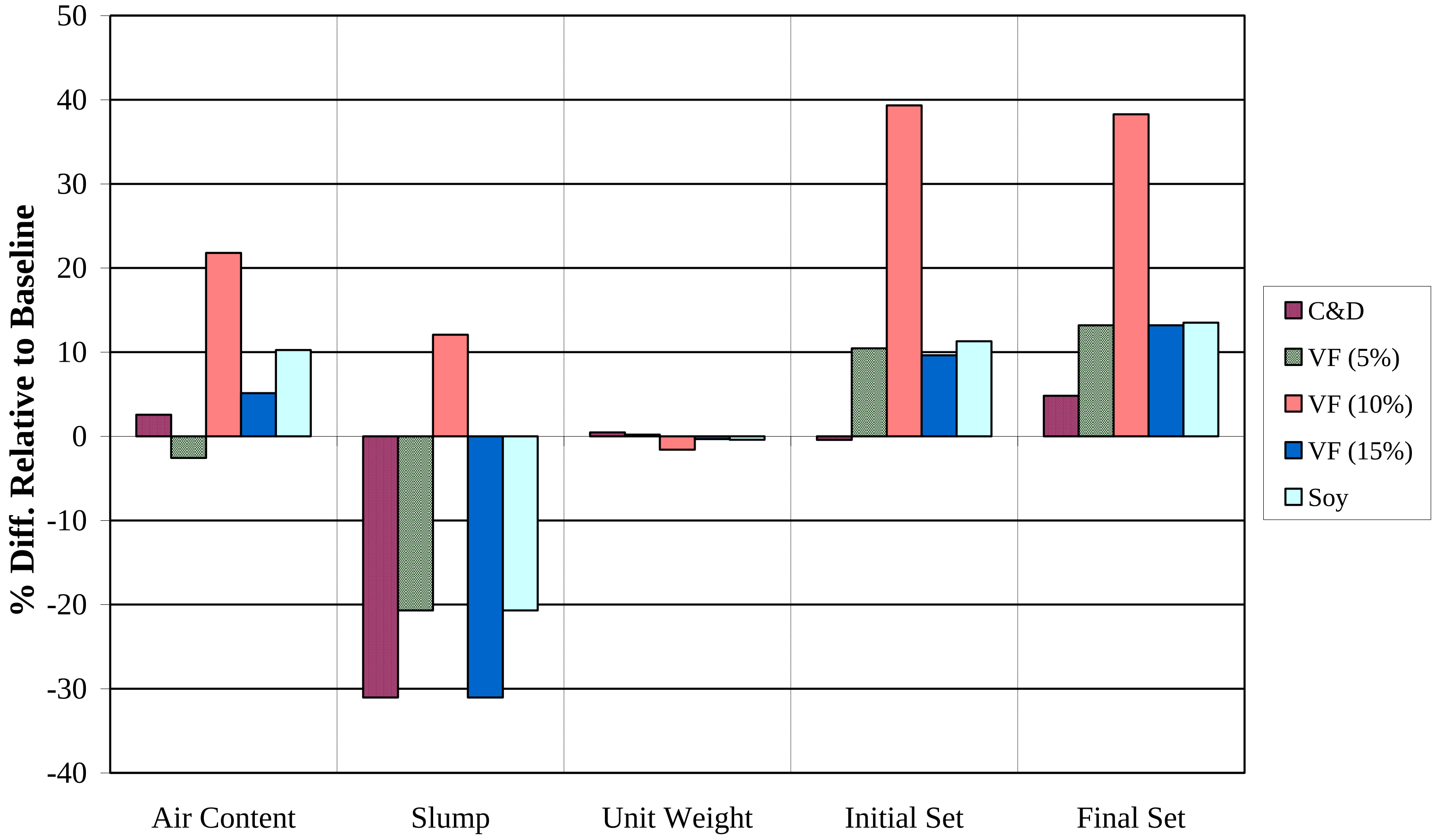

Figure 4.17: AUR – Percent difference in physical properties relative to baseline for Mix 0.44 concrete for trial burns

All single-lab precision requirements were met between the individual batches prepared with the cement sampled from each trial.

The air content for Mix 0.44 remained within baseline precision limits for all trial mixtures except VF 10 %, which exceeded allowable limits by 0.1 %. The target air content for each mix was 4.0%. All the trial mixes were within single-lab precision limits if compared to the target air content.

All of the trial concrete slump results were within 1 inch of the baseline mixture and therefore met baseline precision limits. The plot of percent difference, however, is deceiving due to the small baseline slump.

The unit weights of all the trial mixtures were within the allowable ± 2.5 lb difference to the baseline unit weight. The minimal percent differences relative to the baseline for the unit weights of the trial mixtures are shown in Figure 4.17.

Many factors including temperature, water-cement ratio, cement chemistry, and admixtures can affect setting (Odler 1998). Mix 0.44 concrete made with all the trial burn cements failed the baseline concrete setting precision limits except the initial setting time from the construction and demolition waste trial burn concrete. It can be seen in Figure 4.17 that the cement from the variable feed and soybean seed trial burns produced concrete setting times that were significantly retarded, or extended, compared to the baseline concrete setting results. The setting results from the concrete made with the variable feed 10 % trial cement showed between 10 and 39 % longer initial and final setting times than the baseline setting results. To ensure the variable feed 10 % setting results were not erroneous, the tests for this mixture were repeated by making new concrete. Almost identical setting results were found to occur again.

The compressive strength of concrete is significantly affected by the mixture's air content. ACI (1992) reported, "Incorporation of entrained air may reduce strength at a ratio of 5 to 7 percent for each percent of air." To account for the fluctuation of air between each concrete mixture, the trial air content was normalized to the baseline's air content. The actual compressive strengths for each trial mixture were decreased 5% for every 1% increase in air content that the trial mixture exceeded the baseline's air content. This provides an adjusted strength for the trial concrete if the baseline and trial mixtures had the same air content. The unadjusted compressive strengths for each trial burn and their percent difference relative to the baseline results are presented in Table 4.33. The air-corrected compressive strengths and their percent difference relative to the baseline results are presented in Table 4.34. The air-corrected compressive strength development results are shown in Figure 4.18. The allowable percent difference relative to the baseline results for trial burns to meet the baseline's compressive strength precision limit is 7 %.

The air-corrected concrete compressive strength results for the trial burn cements indicate that at early ages, there is a strength loss compared to the baseline strength results. However, the air-corrected compressive strengths for 7 to 91 days for the construction and demolition waste and variable feed trials had similar compressive strengths compared to the results from the baseline trial burn cement. The variable feed 10 and 15 % trial burn strength results decreased between 12 and 30 % at early ages compared to the baseline strength results, which was the largest decrease in strength for any of the trial burns compared to the baseline burn. The air-corrected compressive strengths from the soybean seed trial burn were decreased between 10 and 12 % for 1, 3, and 91-day tests compared to the baseline results.

Similarly to the compressive strengths, air corrections were also performed on the splitting tensile results. The air correction factor used for compressive strength estimations is not valid for splitting tensile strengths. An extensive research effort by Raphael (1984) resulted in the estimation of concrete splitting tensile strength expressed as a function of the compressive strength. Rachael (1984) recommended the use of Equation 4.1.

$$f_t = 1.7 f_c^{2/3} \text{ (psi)} \qquad \text{(Equation 4.1)}$$

where

$f_t =$ concrete splitting tensile estimation (MPa), and

$f_c =$ concrete compressive strength (MPa).

In order to calculate air corrected splitting tensile strengths, the original compressive and air-corrected compressive strengths were converted to their respective splitting tensile strengths utilizing Raphael's formula. The difference between these values provides the change in splitting tensile strength due differences in air content. Adding this change in strength to the experimental splitting tensile results provides an estimated air-corrected splitting tensile strength. The air-corrected splitting tensile strengths and their percent difference relative to the baseline results are presented in Table 4.35. The air-corrected splitting tensile strength development results are shown in Figure 4.19. The allowable percent difference relative to the baseline results for trial burns to meet the baseline's compressive strength precision limit is 15 %.

The splitting tensile strengths for the variable feed 5 and 10 % and the soybean seed trial burns resulted in early-age strengths that are similar to the baseline's results. The variable feed 15 % trial burn showed a decrease in splitting tensile of 20 and 15 % for the 1- and 3-day tests, respectively. The construction and demolition waste trial burn also showed a 19 % decrease in splitting tensile strength for the 3-day test. The variable feed 10 and 15 % trial burn splitting tensile strength results showed an increase of over 16 % compared to the baseline results. For the 28- and 91-day strengths, cement from the construction and demolition waste, variable feed 5 %, and soybean seed trial burns produced concrete splitting tensile strengths that were similar to the baseline splitting tensile results. The cement produced in the variable feed 5 % and soybean seed trial burns resulted in air-corrected concrete splitting strengths that were similar to the baseline's results over all testing ages.

The drying shrinkage results of concrete prisms from Mix 0.44 are shown in Table 4.36. The average drying shrinkage strain of the concrete prisms and their percent difference relative to the baseline's results are presented. A plot of the average drying shrinkage strain development over 112 days for all the trial cement's concrete prisms are shown in Figure 4.20. To meet the allowable precision limit for drying shrinkage, the difference between the trial and baseline results can not exceed 0.0137 %. The concrete prisms with the greatest strain development were made with the baseline burn's cement. All the trial burn cements used for Mix 0.44 concrete prisms showed average strains that met the precision limits set by the baseline's drying shrinkage results. Therefore, drying shrinkage is minimally affected by the use of alternative fuels such as construction and demolition waste, woodchips, and soybean seeds to produce portland cement.

Concrete permeability results from Mix 0.44 are shown in Table 4.33. At 91days, the test results show that the concrete has a moderate permeability. The levels of chloride ion penetration are defined in ASTM 1202 (2007). The concrete made using the soybean seed trial burn cement showed the greatest increase (20 %) of all the trial burns compared to the baseline results. This increase seems significant, but it is within the baseline permeability result's precision limits and is therefore considered similar.

Table 4.34: AUR – Air-corrected compressive strength and percent difference relative to baseline for Mix 0.44 concrete

Concrete Age	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Avg. (MPa)	**% Diff [1]**	**Avg. (MPa)**	**% Diff [1]**	**Avg. (MPa)**	**% Diff [1]**	**Avg. (MPa)**	**% Diff [1]**	**Avg. (MPa)**	**% Diff [1]**
1 day	15.1	-12.1	15.1	-12.4	12.0	-30.4	12.2	-29.2	15.2	-11.7
3 days	21.4	-14.8	22.8	-9.1	22.0	-12.3	21.9	-12.8	22.3	-11.0
7 days	27.6	0.6	28.8	5.3	27.1	-1.1	27.7	1.2	28.2	3.0
28 days	35.7	-4.7	37.5	0.0	37.9	1.1	40.3	7.4	35.4	-5.7
91 days	39.9	-4.5	42.9	2.7	40.5	-3.1	41.3	-1.2	37.7	-9.7

Notes: [1]Relaive to B-CP

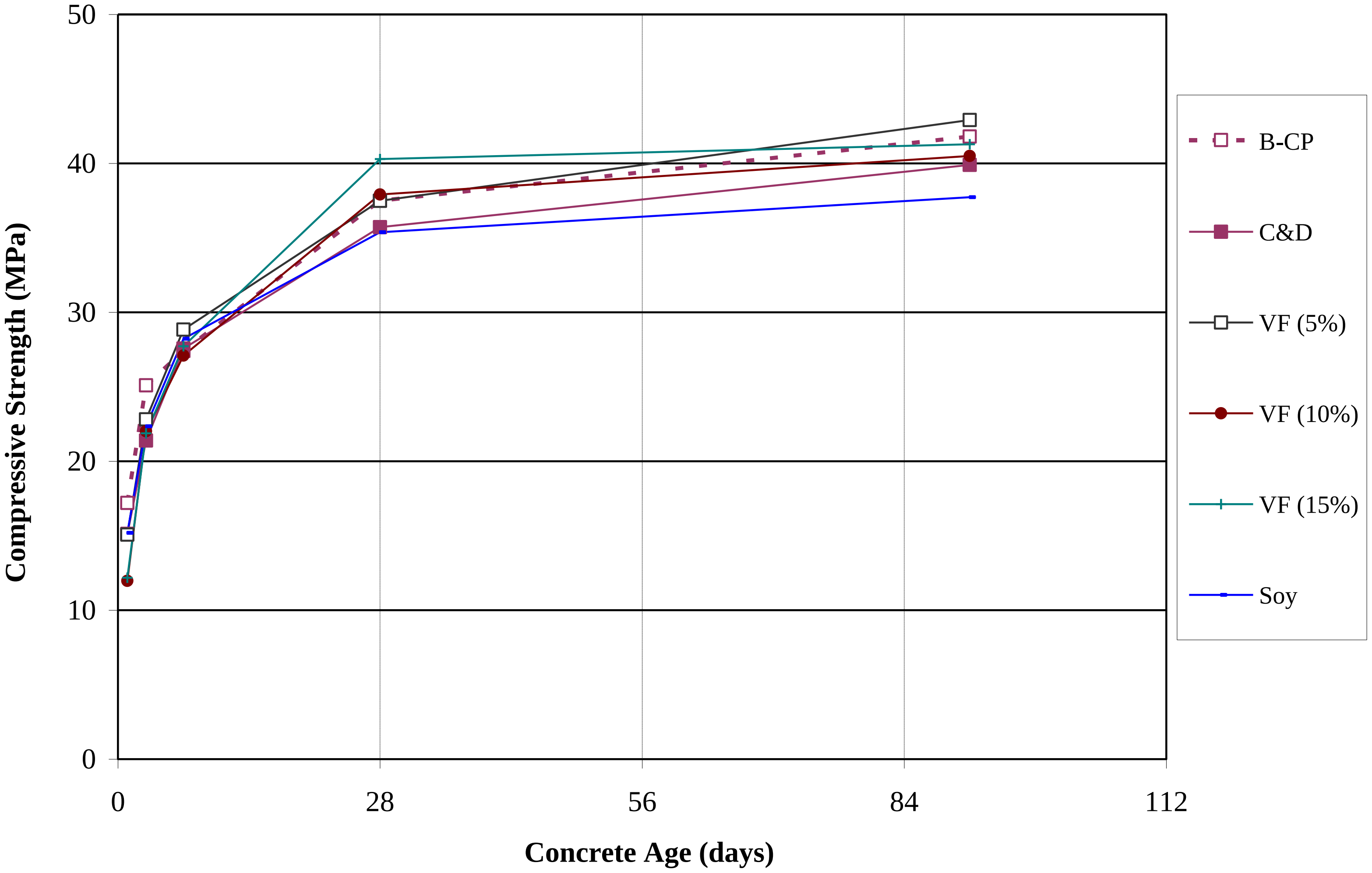

Figure 4.18: AUR – Air-corrected compressive strengths for Mix 0.44 for all burns

Table 4.35: AUR – Air-corrected splitting tensile strengths and percent difference relative to baseline for Mix 0.44 concrete

Concrete Age	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Avg. (MPa)	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**
1 day	1.9	-9.8	1.9	-9.2	1.9	-11.9	1.7	-19.6	1.9	-10.8
3 days	2.2	-18.8	2.8	4.0	2.7	0.9	2.3	-15.4	2.5	-8.7
7 days	3.0	-0.3	3.2	7.0	3.3	10.5	3.1	2.7	3.0	-1.4
28 days	3.6	2.5	3.7	6.1	4.1	16.9	4.1	16.4	3.6	1.5
91 days	4.0	-2.7	4.1	0.3	4.1	-0.3	4.1	-0.6	3.8	-8.5

Notes: % Diff. relative to baseline

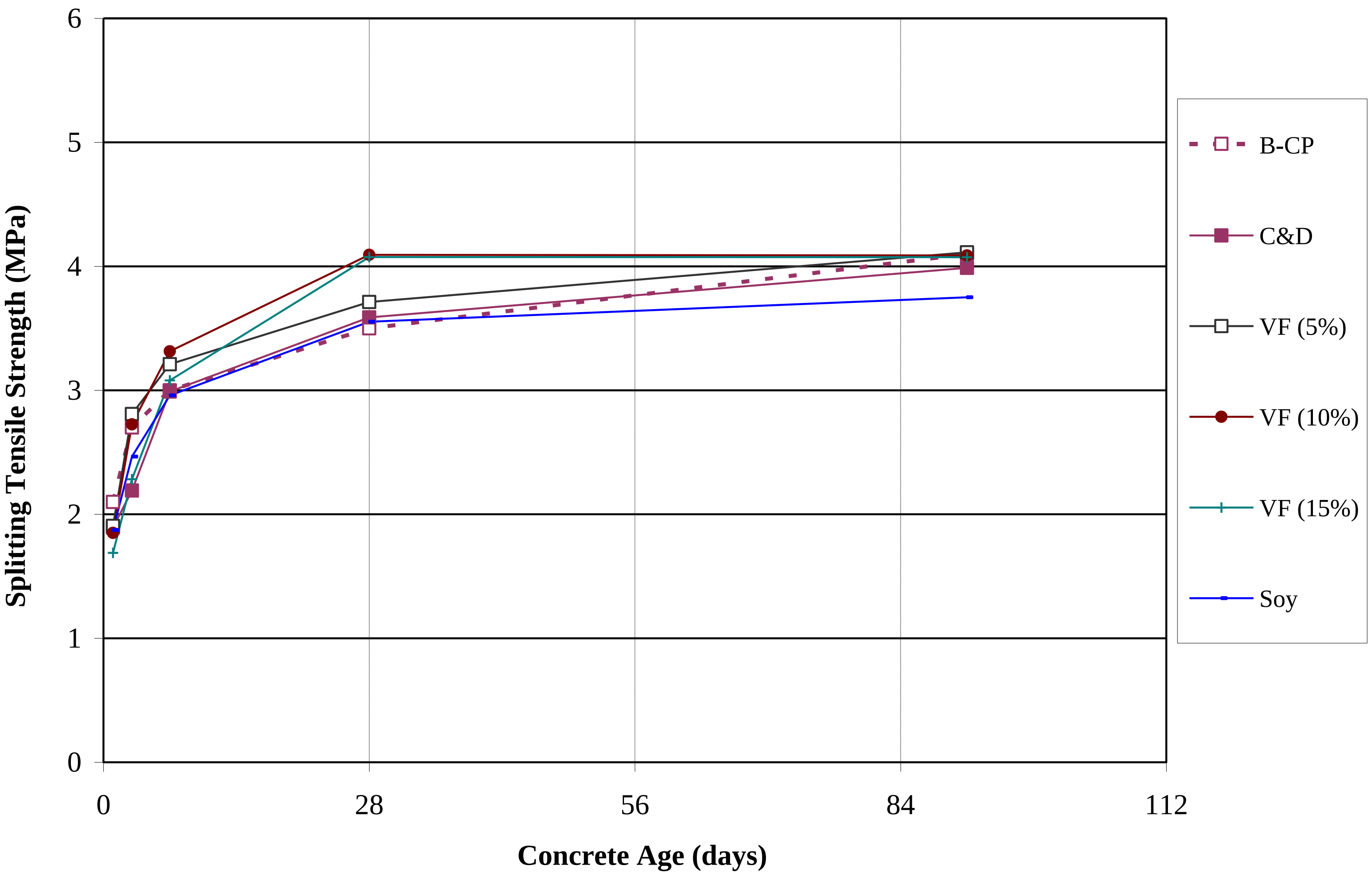

Figure 4.19: AUR – Air-corrected splitting tensile strengths for Mix 0.44 for all burns

Table 4.36: AUR – Drying shrinkage development and percent difference relative to baseline for Mix 0.44 concrete for all burns

Drying Age (days)	**B - CP**	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Avg. Strain (%)	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**
4	-0.010	-0.015	46.7	-0.014	43.3	-0.015	46.7	-0.014	40.0	-0.011	6.7
7	-0.013	-0.019	52.6	-0.020	57.9	-0.017	31.6	-0.022	76.3	-0.018	42.1
14	-0.023	-0.025	8.8	-0.027	19.1	-0.023	0.0	-0.027	17.6	-0.025	10.3
28	-0.030	-0.036	18.9	-0.033	8.9	-0.030	0.0	-0.037	23.3	-0.033	10.0
56	-0.038	-0.040	7.1	-0.039	4.4	-0.041	8.0	-0.041	8.0	-0.043	13.3
112	-0.048	-0.046	-4.2	-0.046	-4.2	-0.040	-16.1	-0.045	-4.9	-0.045	-4.9
224	-0.050	-0.047	-5.3	CIP	-	CIP	-	CIP	-	CIP	-

Notes: CIP - Collection in Process

[1] Relative to B-CP

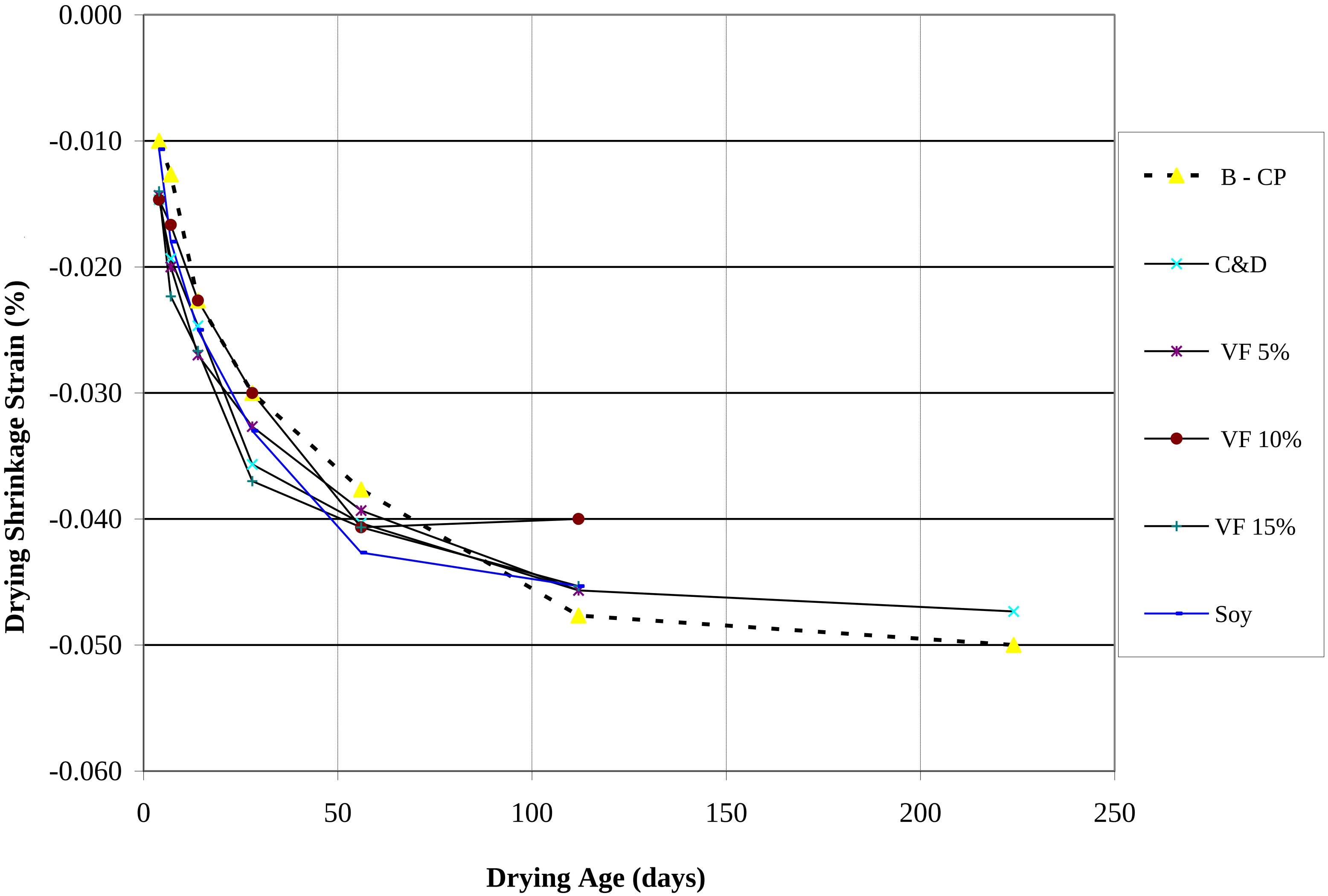

Figure 4.20: AUR – Drying shrinkage development of concrete prisms for Mix 0.44 concrete

4.4.8.7 Concrete Mix 0.37

All physical concrete properties were determined by Auburn University. Concrete Mix 0.37 was a high-strength mixture possessing a water-cement ratio of 0.37. Specifics for Mix 0.37 are detailed in Section 3.4.3. The average results and percent difference of each trial burn relative to the baseline results from Mix 0.37 are shown in Table 4.37. A graphical representation of the fresh property results relative to the baseline is shown in Figure 4.21.

This is a high-performance concrete, and its fresh properties are highly dependent on the functionality of chemical admixtures. Therefore, the results are more variable for the mixture than Mix 0.44.

Due to the volume of concrete required to conduct the necessary tests and the volume limitations of available mixing equipment, each mixture was divided roughly in half to ensure adequate blending of all materials. The air content, slump, and unit weight shown in Table 4.37 are the average of two batches of concrete mixed for each trial. All single lab precision requirements were met between the individual batches prepared for each trial.

The air content for Mix 0.37 decreased significantly over all trials and are outside the allowable precision limits for the baseline concrete. Interactions between the high-range water-reducing admixture and the cement and/or the air-entraining admixture used in each 0.37 concrete mixture could be the cause for the fluctuation in air content. The target air content for each mix was 4.0 %. The trial mixture made with the construction and demolition waste trial burn cement was 0.2 % outside the baseline's allowable precision limit of 0.8 % and was the only trial mixture to fall outside the precision limits.

The Mix 0.37 trial mixtures failed to meet slump precision requirements when compared to the baseline. The slump test results showed a significant decrease in slump for all trial burn mixtures. The low air content for each trial mixture is one of the possible causes for the low slump in each trial. If the precision statement for concrete slump is converted into an allowable percentage relative to the baseline, the limiting value is ± 42.6%. From Figure 4.21, VF 5 % shows the largest decrease in slump relative to the baseline. This concrete mixture was repeated in order to rule out possible human error that may have occurred during the initial mixture. The results from the repeated concrete tests were within precision limits when compared to all the original results obtained.

The unit weight results of the variable feed trials and the soy trial slightly exceeded the allowable limits to be deemed similar to the baseline. The small percent differences relative to the baseline for all the trial mixtures unit weight are presented in Figure 4.21. The increase in unit weight can be attributed to the lower air contents of the trial mixtures relative to the baseline mixture.

Many factors including temperature, water-cement ratio, cement chemistry, and admixtures control setting (Odler 1998). The concrete produced from the variable feed 5 % trial burn cement was the only trial concrete that met the setting precision limits when compared to the baseline setting results. From Figure 4.21, it can be seen that the setting times for concrete made with the construction and demolition waste, variable feed 15 %, and soybean seed trial burn cement's were reduced compared to the baseline setting results. The concrete produced from the variable feed 10 % trial burn cement significantly increased for initial and final setting times compared to the baseline burn setting results.

The air-corrected compressive strengths were calculated in the same manner as described for Mix 0.44. The unadjusted compressive strengths for each trial burn and their percent difference relative to the baseline results are presented in Table 4.37. The air-corrected compressive strengths and their percent difference relative to the baseline results are presented in Table 4.38. The air-corrected compressive strength development data for Mix 0.37 are shown in Figure 4.22. The allowable percent difference relative to the baseline results for trial burns to meet the baseline's compressive strength precision limit is 7 %.

The compressive strengths from the concrete prepared with the construction and demolition waste burn cement was the most comparable to the baseline. One-day compressive strength results from concrete made using cement from the variable feed 10 and 15 % trial burns showed reductions of 20 and 18 %, respectively, compared to the baseline compressive strength results. Seven to 91-day day compressive strength results from concrete made using cement from the variable feed 5 and 15 % and the soybean seed trial burns increased 8 to 20 % compared to the baseline results. The late-age compressive strength results from the variable feed 10 % trial burn are similar to the baseline strength results. Compressive strength results from concrete made using cement produced during the soybean trial burn exhibited slightly higher strengths over the majority of testing ages compared to the baseline.

Table 4.37: AUR – Physical properties and percent difference relative to baseline for Mix 0.37 concrete for all burns

Property	B-CP	C&D		VF 5%		VF 10%		VF 15%		Soy	
	AUR	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**	**AUR**	**% Diff.**
Total Air Content (%)	5.8	5.0	-14	3.5	-40	4.7	-20	4.5	-22	3.5	-40
Slump (in)	4.7	3.4	-28	0.5	-89	2.5	-47	2.3	-52	1.5	-68
Unit Weight (lb/ft^3)	146	147	1.0	150	2.9	148	1.2	149	2.1	150	2.9
Initial Set (Min.)	224	205	-8.5	217	-3.1	266	18.8	208	-7.1	187	-16.5
Final Set (Min.)	301	282	-6.3	301	0.0	351	16.6	282	-6.3	254	-15.6
Compressive Strength (MPa)											
1 day	24.2	22.7	-6.2	23.6	-2.5	18.3	-24.4	18.7	-22.7	23.6	-2.5
3 days	32.8	31.3	-4.6	31.3	-4.6	27.9	-14.9	29.4	-10.4	29.8	-9.1
7 days	36.6	36.5	-0.3	39.3	7.4	34.3	-6.3	37.3	1.9	36.4	-0.5
28 days	45.0	44.5	-1.1	48.3	7.3	44.5	-1.1	47.9	6.4	44.7	-0.7
91 days	50.6	50.1	-1.0	53.4	5.5	49.2	-2.8	51.2	1.2	49.4	-2.4
Splitting Tensile Strength (MPa)											
1 day	2.8	2.5	-10.7	2.6	-7.1	2.1	-25.0	2.1	-25.0	2.6	-7.1
3 days	3.6	3.2	-11.1	3.7	2.8	3.4	-5.6	3.4	-5.6	3.2	-11.1
7 days	3.4	3.6	5.9	3.9	14.7	3.8	11.8	3.7	8.8	3.6	5.9
28 days	4.0	4.0	0.0	4.3	7.5	4.6	15.0	4.6	15.0	4.1	2.5
91 days	4.3	4.1	-4.7	4.8	11.6	4.7	9.3	4.8	11.6	4.3	0.0
Permeability @ 91 days (Coulombs)	1762	1846	4.8	1717	-2.6	1939	10.0	1715	-2.7	2100	19.2

Notes:

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

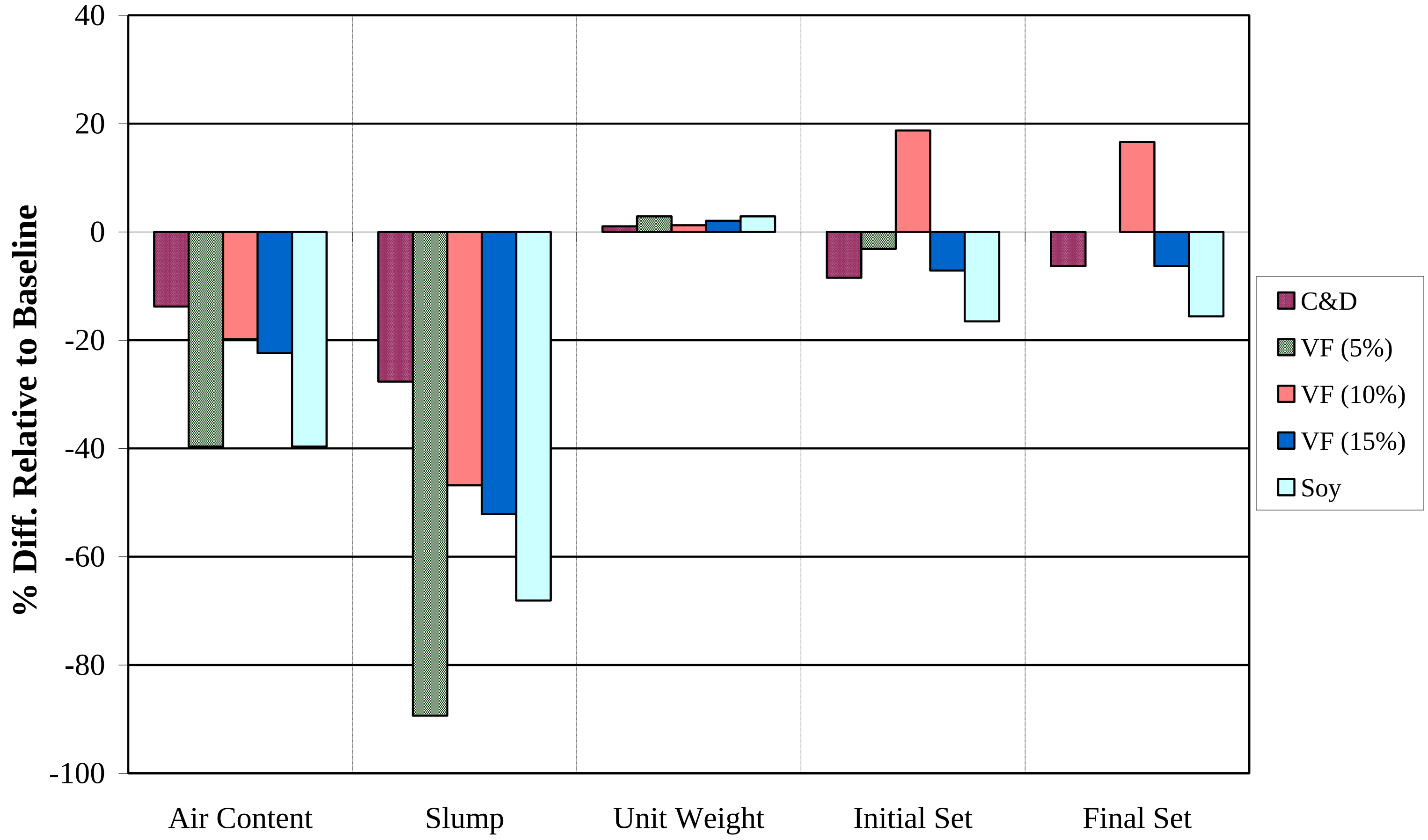

Figure 4.21: AUR – Percent difference in physical properties relative to baseline for Mix 0.37 concrete for trial burns

Air-corrected splitting tensile strengths were calculated in the same manner as described for Mix 0.44. The air-corrected splitting tensile strengths and the percent difference relative to the baseline results are presented in Table 4.39. A graph of the strength development results for the air-corrected splitting tensile strengths are shown in Figure 4.23. The allowable percent difference relative to the baseline results for trial burns to meet the baseline's splitting tensile strength precision limit is 15 %.

The splitting tensile strength results for the cement from the construction and demolition waste and soybean seed trial burns were similar to the baseline results. The splitting tensile strength results for cement from the variable feed 10 and 15 % trial burns showed a 22 % decrease in strength for the 1-day strength compared to the baseline result. Cement from all the variable feed trial burns showed late-age splitting tensile strengths that ranged from similar to a 23 % increase compared to the baseline splitting tensile results.

Drying shrinkage results of concrete prisms from Mix 0.37 are shown in Table 4.40. The average drying shrinkage strain of the concrete prisms and their percent difference relative to the baseline's results are presented. A plot of the average drying shrinkage strain development over 112 days for all the trial cement's concrete prisms are shown in Figure 4.24. To meet the allowable precision limit for drying shrinkage, the difference between the trial and baseline results can not exceed 0.0137 %. The concrete prisms with the greatest drying shrinkage strain development were made with the baseline burn's cement. The concrete prisms made with the soybean seed trial burn cement fell below the allowable precision limit for the 112-day test. All the other the trial burn cements used for Mix 0.37 concrete prisms showed average strains that met the precision limits set by the baseline's drying shrinkage results. Therefore, overall drying shrinkage is minimally affected by the utilization of alternative fuel cements.

Concrete permeability results from Mix 0.37 are shown in Table 4.37. At 91 days, the test results show that the concrete has a low permeability. The levels of chloride ion penetration are defined in ASTM 1202 (2007). The concrete made using the soybean seed trial burn cement showed the greatest increase (19 %) of all the trial burns compared to the baseline results. The concrete permeability that was made from the soybean seed cement is within the baseline permeability result's precision limit and is therefore considered similar.

Table 4.38: AUR – Air-corrected compressive strength and percent difference relative to baseline for Mix 0.37 concrete

Concrete Age	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Avg. (MPa)	% Diff [1]	Avg. (MPa)	% Diff [1]	Avg. (MPa)	% Diff [1]	Avg. (MPa)	% Diff [1]	Avg. (MPa)	% Diff [1]
1 day	23.6	-2.4	26.3	8.7	19.4	-20.0	19.9	-17.7	26.3	8.7
3 days	32.6	-0.8	34.9	6.4	29.5	-10.0	31.3	-4.5	33.2	1.3
7 days	38.0	3.7	43.8	19.7	36.3	-0.9	39.7	8.5	40.6	10.9
28 days	46.3	2.8	53.9	19.7	47.1	4.6	51.0	13.4	49.8	10.8
91 days	52.1	3.0	59.5	17.7	52.0	2.8	54.5	7.8	55.1	8.9

Notes: [1]Relaive to B-CP

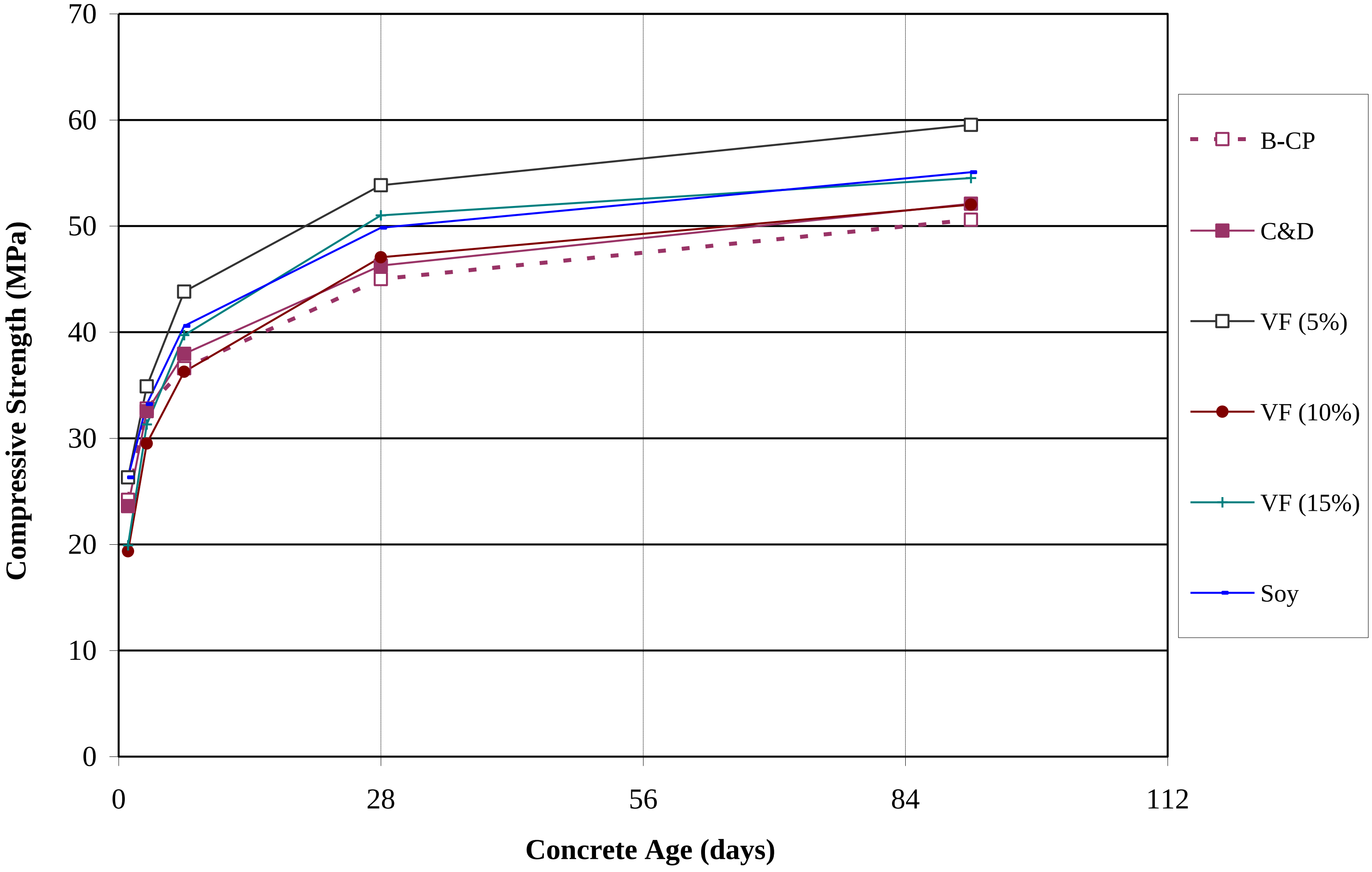

Figure 4.22: AUR – Air-corrected compressive strengths for Mix 0.37 for all burns

Table 4.39: AUR – Air-corrected splitting tensile strengths and percent difference relative to baseline for Mix 0.37 concrete

Concrete Age	C&D		VF 5%		VF 10%		VF 15%		Soy	
	Avg. (MPa)	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**	**Avg. (MPa)**	**% Diff.**
1 day	2.6	-8.3	2.8	0.0	2.2	-22.0	2.2	-21.5	2.8	0.0
3 days	3.3	-8.7	3.9	9.5	3.5	-2.4	3.5	-1.9	3.4	-4.6
7 days	3.7	8.7	4.2	23.0	3.9	15.6	3.9	13.4	3.9	13.7
28 days	4.1	2.7	4.6	15.6	4.8	18.9	4.8	19.6	4.4	10.2
91 days	4.2	-1.9	5.1	19.7	4.9	13.1	5.0	16.1	4.6	7.6

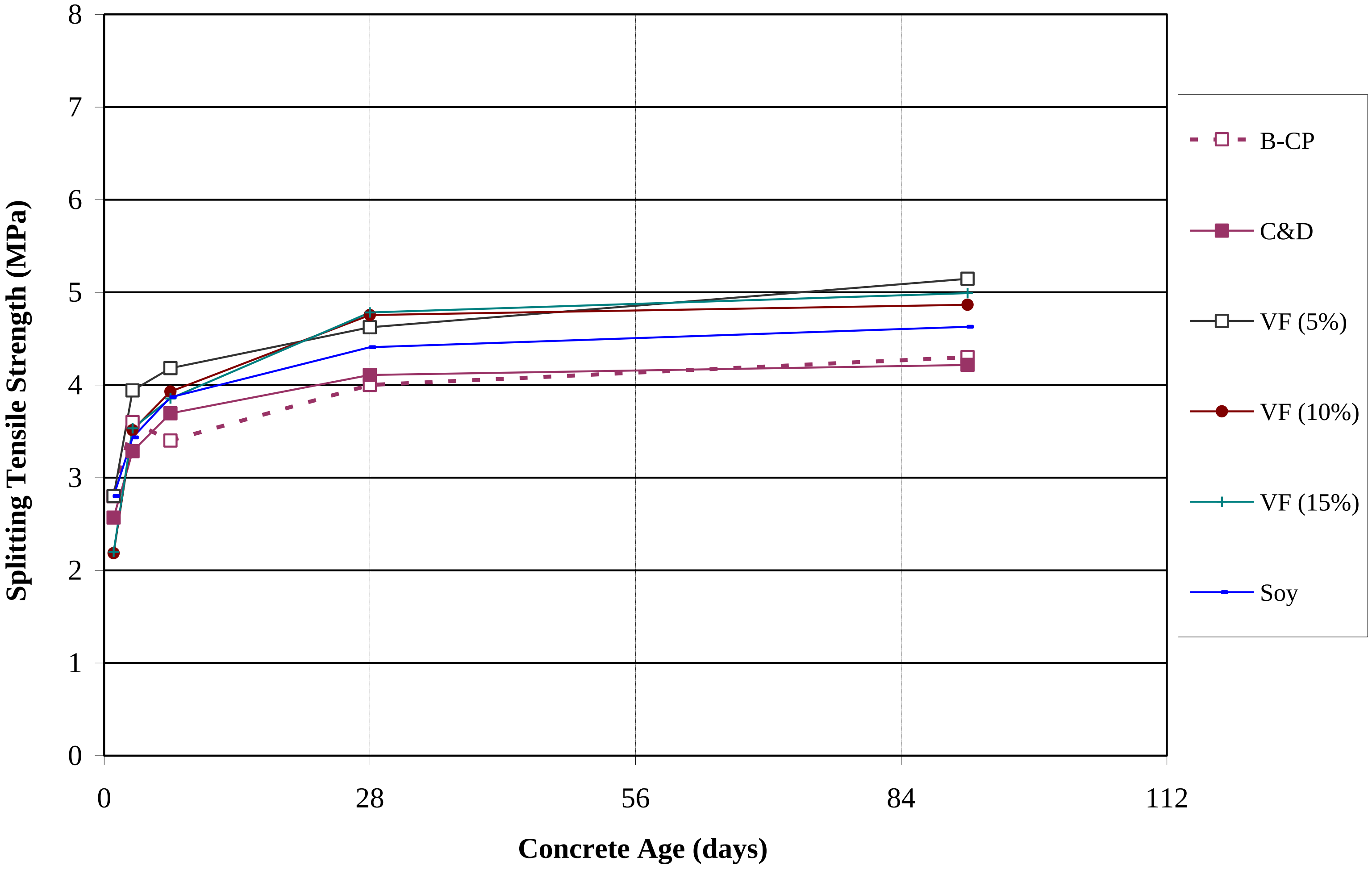

Figure 4.23: AUR – Air-corrected splitting tensile strengths for Mix 0.37 for all burns

Table 4.40: AUR – Drying shrinkage development and percent difference relative to baseline for Mix 0.37 concrete for all burns

Drying Age (days)	**B - CP**	**C&D**		**VF 5%**		**VF 10%**		**VF 15%**		**Soy**	
	Avg. Strain (%)	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**	**Avg. Strain (%)**	**% Diff [1]**
4	-0.015	-0.018	17.8	-0.017	15.6	-0.013	-15.6	-0.014	-8.9	-0.015	2.2
7	-0.021	-0.022	8.1	-0.020	-1.6	-0.017	-16.1	-0.018	-12.9	-0.021	0.0
14	-0.029	-0.029	1.2	-0.030	5.8	-0.026	-10.5	-0.026	-8.1	-0.027	-5.8
28	-0.038	-0.036	-4.4	-0.040	4.4	-0.034	-10.5	-0.032	-14.9	-0.036	-6.1
56	-0.048	-0.046	-4.2	-0.046	-3.5	-0.042	-11.8	-0.040	-17.4	-0.040	-17.4
112	-0.058	-0.053	-8.7	-0.050	-12.7	-0.049	-15.6	-0.045	-22.5	-0.043	-25.4
224	-0.058	CIP	-	CIP	-	CIP	-	CIP	-	CIP	-

Notes: CIP - Collection in Process

[1] Relative to B-CP

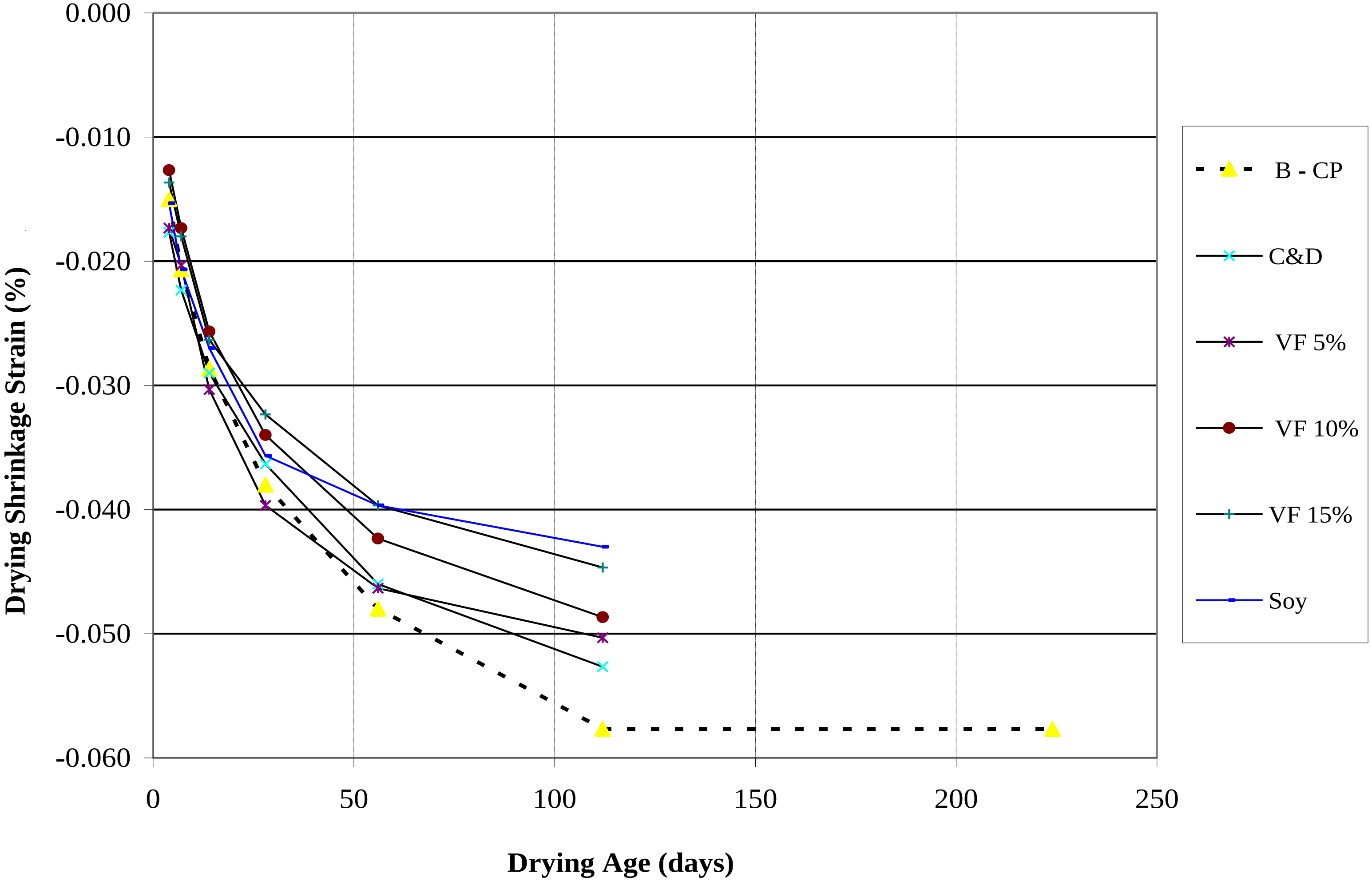

Figure 4.24: AUR – Drying shrinkage development of concrete prisms for Mix 0.37 concrete

4.4.9 Comparison of Paste, Mortar, and Concrete Properties

The properties of paste, mortar, and concrete that were made with the cement of each trial burn are compared in this section. A brief review of the test results is presented followed by a discussion of any trends that are consistent between the paste, mortar, and concrete results.

The physical changes observed from the cement and concrete testing are presented in Tables 4.41 through 4.45. The number of tests conducted for a particular property as well as the medium of the observed effect (paste, mortar, or concrete) are presented in order to add perspective to the observed effects. Each arrow indicates a significant change in an individual test compared to the baseline's results. A trial test result is considered significantly different from the baseline result if the trial's result falls outside the baseline's allowable range of values. These values are specified by the test's ASTM precision statement. The results that are not significantly different are not reported unless all the test results for a particular property show similarities to the baseline result.

The physical properties of the paste, mortar, and concrete made with the construction and demolition waste trial burn cement are presented in Table 4.41. The concrete setting time and mortar cube flow are the only properties that did not show similarities to the baseline's results. Both mortar setting results for initial and final setting tests were comparable to the baseline's results. The chemical admixtures used in each concrete mixture could have caused the fluctuations observed in the setting times.

The physical properties of the paste, mortar, and concrete made with the variable feed 5 % trial burn cement are presented in Table 4.42. The decreased slump and increased unit weight compared to the baseline could be caused by the decrease in air content observed in the Mix 0.37 concrete mixture. Since the mortar setting times were comparable to the baseline's results, the concrete's chemical admixtures could be the cause of the concrete's retarded setting times. Two concrete 28-day strength results showed strength increases compared to the baseline's results. Both the mortar cube 28-day strength results were comparable to the baseline's results.

Table 4.41: Summary of physical properties of cement and concrete from the C&D trial burn

Property	**# of Tests**	**Trend or Effect Relative to B-CP**	**Medium of Observed Effect**	**Likely Cause**
Air Content	3	CTB	NA	NA
Slump	2	CTB	NA	NA
Unit Weight	2	CTB	NA	NA
Initial Set (↓ = accelerated)	4	↓↑	Concrete	Chemical Admixtures
Final Set (↓ = accelerated)	4	↓↑	Concrete	Chemical Admixtures
Strength (28-day)	6	CTB	NA	NA
Autoclave Exp.	2	CTB	NA	NA
Mortar Flow	2	↓	Mortar	Unknown
Normal Consistency	2	CTB	NA	NA
Drying Shrinkage	3	CTB	NA	NA
Permeability	2	CTB	NA	NA
Blaine SSA	1	CTB	NA	NA

Notes:
CTB – All tests are comparable to baseline's results
NA - Not Applicable

Table 4.42: Summary of physical properties of cement and concrete from the VF 5 % trial burn

Property	# of Tests	Trend or Effect Relative to B-CP	Medium of Observed Effect	Likely Cause
Air Content	3	↓	Concrete	Unknown
Slump	2	↓	Concrete	Low Air Content
Unit Weight	2	↑	Concrete	Low Air Content
Initial Set (↓ = accelerated)	4	↑	Concrete	Chemical Admixtures
Final Set (↓ = accelerated)	4	↑	Concrete	Chemical Admixtures
Strength (28-day)	6	↑↑	Concrete	Chemical Admixtures
Autoclave Exp.	2	CTB	NA	NA
Mortar Flow	2	↓	Mortar	Unknown
Normal Consistency	2	CTB	NA	NA
Drying Shrinkage	3	CTB	NA	NA
Permeability	2	CTB	NA	NA
Blaine SSA	1	CTB	NA	NA

Notes:
CTB – All tests are comparable to baseline's results   NA - Applicable

The physical properties of the paste, mortar, and concrete made with the variable feed 10 % trial burn cement are presented in Table 4.43. The air content tests did not produce any trends that were consistent over the mortar and concrete testing. The concrete setting and 28-day strengths showed increases in two tests. Since increases in the mortar setting and 28-day strength tests did not show increases, the increases seen in the concrete tests could have been caused by admixture-cement interactions.

Table 4.43: Summary of physical properties of cement and concrete from the VF 10 % trial burn

Property	# of Tests	Trend or Effect Relative to B-CP	Medium of Observed Effect	Likely Cause
Air Content	3	↓↑	Concrete	Unknown
Slump	2	↓	Concrete	Low Air Content
Unit Weight	2	CTB	NA	NA
Initial Set (↓ = accelerated)	4	↑↑	Concrete	Chemical Admixtures
Final Set (↓ = accelerated)	4	↑↑	Concrete	Chemical Admixtures
Strength (28-day)	6	↑↑	Concrete	Chemical Admixtures
Autoclave Exp.	2	CTB	NA	NA
Mortar Flow	2	CTB	NA	NA
Normal Consistency	2	CTB	NA	NA
Drying Shrinkage	3	CTB	NA	NA
Permeability	2	CTB	NA	NA
Blaine SSA	1	↓	NA	NA

Notes:

CTB – All tests are comparable to baseline's results
NA - Not Applicable

The physical properties of the paste, mortar, and concrete made with the variable feed 15 % trial burn cement are presented in Table 4.44. The air content tests did not produce any trends that were consistent over the mortar and concrete testing. The initial and final setting times for the concrete mixtures were not consistent with each other or the mortar setting results. Three of the four 28-day concrete strength results showed increases. This increase could be an effect of the chemical admixtures since the mortar 28-day results were comparable to the baseline’s strength results. The increased drying shrinkage of the mortar specimens relative to the baseline’s results could be caused by the increased cube flow. The drying shrinkage of the concrete specimens, however, did not significantly fluctuate from the baseline’s results.

Table 4.44: Summary of physical properties of cement and concrete from the VF 15 % trial burn

Property	# of Tests	Trend or Effect Relative to B-CP	Medium of Observed Effect	Likely Cause
Air Content	3	↓	Concrete	Unknown
Slump	2	↓	Concrete	Low Air Content
Unit Weight	2	↑	Concrete	Low Air Content
Initial Set (↓ = accelerated)	4	↓↑	Concrete	Chemical Admixtures
Final Set (↓ = accelerated)	4	↓↑	Concrete	Chemical Admixtures
Strength (28-day)	6	↑↑↑	Concrete	Chemical Admixtures
Autoclave Exp.	2	CTB	NA	NA
Mortar Flow	2	↑	Mortar	Unknown
Normal Consistency	2	CTB	NA	NA
Drying Shrinkage	3	↑	Mortar	Increased Cube Flow
Permeability	2	CTB	NA	NA
Blaine SSA	1	CTB	NA	NA

Notes:

CTB – All tests are comparable to baseline's results
NA - Not Applicable

The physical properties of the paste, mortar, and concrete made with the soybean seed trial burn cement are presented in Table 4.45. The decrease air content observed in the Mix 0.37 concrete mixture could be the cause of the observed decrease slump and increase in unit weight. There were no defined trends that were observed in the mortar or concrete setting times. One of the two mortar setting tests showed acceleration compared to the baseline's mortar setting results. Both the final mortar setting time tests, however, were comparable to the baseline's mortar setting results. The 28-day mortar and concrete strength results were comparable to the baseline's strength results for 5 of 6 tests. The mortar cube flow was increased in one of two tests. The mortar drying shrinkage, however, was not affected by the increased cube flow.

Table 4.45: Summary of physical properties of cement and concrete from the Soy trial burn

Property	**# of Tests**	**Trend or Effect Relative to B-CP**	**Medium of Observed Effect**	**Likely Cause**
Air Content	3	↓	Concrete	Unknown
Slump	2	↓	Concrete	Low Air Content
Unit Weight	2	↑	Concrete	Low Air Content
Initial Set (↓ = accelerated)	4	↓ ↑↑	Paste and Concrete	Chemical Admixtures
Final Set (↓ = accelerated)	4	↓↑	Concrete	Chemical Admixtures
Strength (28-day)	6	↑	Concrete	Chemical Admixtures
Autoclave Exp.	2	CTB	NA	NA
Mortar Flow	2	↑	Mortar	Unknown
Normal Consistency	2	CTB	NA	NA
Drying Shrinkage	3	CTB	NA	NA
Permeability	2	CTB	NA	NA
Blaine SSA	1	CTB	NA	NA

Notes:

CTB – All tests are comparable to baseline's results

NA - Not Applicable

4.4.9.8 Workability

The cement plant and Auburn University conducted several tests to determine the workability of each trial cement. The cement plant and Auburn University determined each trial cement's normal consistency and mortar flow. Auburn University also measured the slump of each concrete mixture made with the trial cements.

The results from the cement plant and Auburn University showed that all trial burn cement's normal consistency were similar to the baseline cement's results. The cement plant's results for mortar flow showed increases with the mortar made from the variable feed 15 % and soybean seed trial burn cements. Auburn University's mortar flow test results did not indicate increases for the variable feed 15 % and soybean seed trial burn cements. Auburn University found mortar flow decreases of 12 and 27 % with mortar made with the construction and demolition waste and variable feed 5 % trial burn cements, respectively. The concrete slumps measured for all Mix 0.44 trial mixtures were similar to the baseline's slump results. The concrete Mix 0.37 slumps made from the variable feed and soybean seed trial burn cements showed decreases between 47 and 89 %, respectively, compared to the baseline's slump results. The air contents of the Mix 0.37 concrete mixtures were significantly decreased compared to the baseline. The reduced air contents in the trial mixtures are thought to have reduced the slump of the Mix 0.37 concrete. There were no consistent trends in the tests defining workability that were found in the paste, mortar and concrete results. Therefore, the workability of paste, mortar and concrete are minimally affected by the use of the trial burn cements.

4.4.9.9 Setting

The cement plant and Auburn University conducted paste setting tests on all the cements produced during the trial burns. Auburn University also tested Mix 0.44 and Mix 0.37 concrete setting times that were made with the trial burn cements. The Vicat paste setting tests were conducted using ASTM C 191, and the concrete setting tests were conducted using ASTM C 403.

Both the cement plant and Auburn University results showed that the Vicat paste setting times for all the trial cements were similar to the baseline's paste setting results. The Mix 0.44 concrete setting results showed 10 to 39 % retardation compared to the baseline results for the concretes made with the variable feed trial burn cements. The

Mix 0.37 concrete setting results made with the variable feed 10 and 15 % trial burn cements showed retardation and slight acceleration compared to the baseline burn's concrete setting results, respectively. The setting times for the Mix 0.37 concrete made with the construction and demolition waste and soybean seed trial burn cements were accelerated compared to the baseline's results.

The aluminate content of the construction and demolition waste and the variable feed 10 % trial burn cements increased 33 and 24 %, respectively, compared to the baseline's aluminate content. However, the Vicat paste setting times for the construction and demolition waste and variable feed 10 % trial burns did not seem to be affected by the aluminate increase and were similar to the baseline's results. The behavior of the concrete setting times are also not fully described by the aluminate content found in the trial burn cements. Other factors such as admixture-cement interaction, temperature, and the water-cement ratio can influence concrete setting times. There were no consistent trends that appeared in both the paste and concrete setting results. Since all the trial paste setting tests were similar to the baseline's paste setting results and the paste setting results were not influenced by the addition of admixtures, the effects of the trial fuel cements had minimal impact on setting results.

4.4.9.10 Strength

The cement plant and Auburn University conducted compressive strength tests on mortar cube specimens in order to determine the strength properties of the trial burn cements. Auburn University tested the compressive and splitting tensile strengths of the concrete made with cement produced during the trial burns. Since air content directly affects concrete strength, each concrete trial mixture's air content was normalized to the baseline’s air content. The compressive and splitting tensile cylinder strengths made with each trial’s cement were adjusted accordingly.

One-day Mix 0.44 compressive and splitting tensile strength for the variable feed 15 % trial burn cements were reduced 29 and 20 %, respectively, compared to the baseline’s compressive and splitting tensile strength results. Since the mortar cube results made with the variable feed 15 % cement did not show 1-day reductions in strength, no trend could be established. Concrete Mix 0.37 compressive strengths made from variable feed 10 and 15 % trial cements showed reductions of 20 and 17 % in strength compared to the baseline’s results for tests, respectively. Here again, the mortar cubes made from variable feed 10 and 15 % trial burn cement did not show 1-day reductions in strength and therefore trends cannot be established.

The cement plant and Auburn University found that the 28-day mortar cube compressive strength results were similar to the baseline’s results at this age. Twenty-eight-day Mix 0.44 concrete compressive strengths made with all the trial burn cements were similar to the baseline’s 28-day compressive strength. Mix 0.37 concrete compressive strengths made with variable feed 5 and 15 % and soybean seed trial burn cements showed increases in strength between 10 and 20 % compared to the baseline’s results for 28-day tests. The strength differences between the concrete and mortar results could be influenced by admixture-cement interactions and differences in air content. Since chemical admixtures were not used in the mortar specimens, their strength results are more representative of the trial cement’s strength attributes than the concrete strength results. Given that the majority of trial mortar cube compressive strengths were similar to the baseline's results, the effect that the trial fuels had on the cement is concluded to be minimal.

In an earlier phase of this project woodchips were used as an alternative fuel and co-fired with coal and tires. The mortar cube strengths from the earlier trial and the cubes made with the variable feed 10 % trial burn cement all fell within 12 % of each other. The 28-day strength difference between the two trial's mortar cube strength was 5 %. The Mix 0.44 concrete compressive strengths made from the previous woodchip trial burn and the variable feed 10 % trial burn were also compared. The 1- and 28-day strengths showed a 16 % and 7 % difference, respectively. The 1-day strength showed the largest difference in strengths over all the testing dates.

4.4.9.11 Drying Shrinkage

Auburn University prepared mortar and concrete specimens with the cement produced during the trial burns in order to measure the drying shrinkage characteristics of the cement. The mortar specimens that were made with the cement produced in the variable feed 15 % trial burn showed the largest drying shrinkage strains compared to the baseline's strains. The remaining trial cements produced mortar strains that were similar to the baseline results. The concrete specimens that were made with the variable feed 15 % trial burn cement were similar to the baseline's concrete strains for both Mix 0.44 and 0.37. There were no consistent trends for drying shrinkage that were found in both the mortar and concrete testing results. Therefore, mortar and concrete drying shrinkage are minimally affected by the trial burn cements.

4.4.9.12 Permeability

Auburn University conducted rapid chloride ion penetration tests to measure the permeability of concrete specimens that were made with the cement produced during the trial burns. Mix 0.44 produced moderate permeability concrete at 91-days of curing with each the trial cement tested. Mix 0.37 produced low permeability concrete at 91-days of curing with each trial cement tested. A lower permeability was expected from Mix 0.37 because it was a lower water-cement ratio concrete than Mix 0.44. The fluctuation between trial and the baseline specimen results were minimal for Mix 0.44 and 0.37 permeability tests. The permeability of the concrete specimens tests do not appear to be affected by the trial burn cements.

4.4.10 Plant Emissions

Pollutants emitted from cement manufacturing facilities during production have raised environmental concerns about the sustainability of the cement manufacturing process. Emissions during this study were closely monitored by a Continuous Emission Monitoring System (CEMS) that recorded data in five-minute intervals. The emissions of the cement plant used are regulated by emission limits set by the Alabama Department of Environment Management (ADEM).

Emission data from the cement plant were reported in tons of emissions per hour. Auburn University normalized the emission data to account for variations in production rate of clinker. Therefore, the emission data are presented in tons per ton of clinker. Results are presented in Table 4.46. The percent differences between the emissions from trial burns and the emissions from the baseline burn are shown in Figure 4.25.

Similar to the clinker data, the emission results were statistically analyzed using the Wilcoxon rank-sum test. If the Wilcoxon test showed a difference between the trial and baseline means, the percent difference relative to the baseline's result establishes the degree of difference. If the statistical analysis does not show a difference between the baseline and trial means, the percent difference is not meaningful.

The p-values calculated for the nitrogen oxides showed that all the trial burns except for the soybean seed trial burn have significantly different means compared to the baseline's NO_x mean. The nitrogen emissions were reduced for the construction and demolition waste and the variable feed burns compared to the baseline burn.

Thermal nitrogen oxides constitute around 70% of the the total NO_x emissions and are created when atmospheric nitrogen begins to oxidize (Hendrik and Padovani 2003). Thermal NO_x is controlled by the amount of available oxygen during the pyroprocess (Greer et al. 2004). The type of alternative fuels utilized has not been shown to alter the overall nitrogen oxide emission. The decrease in NO_x, therefore cannot be attributed to any of the trial fuels due to not knowing the oxygen levels in the kiln during each burn.

The p-values calculated for sulfur dioxide show that all the burn means are significantly different compared to the baseline mean. As shown in Figure 4.25, the SO_2 emission levels for the construction and demolition waste and soybean seed trials increased compared to the baseline SO_2 level. Conversely, the SO_2 emission levels decreased for the variable feed 5 and 10 % woodchip trial burns. Sulfur dioxides are formed from raw materials and fuels (Hendrik and Padovani 2003). The concentrations of sulfur within the alternative fuels are small compared to the traditional fuels and the raw materials. Therefore, the trial alternative fuels seem to have little effect on the SO_2 emissions. In the previous woodchip trial, the SO_2 level fell between the variable feed 5 and 10 % trial burn SO_2 values. This is notable because the woodchip replacement rate during the previous woodchip trial was 7 %. The kiln feed for the construction and demolition waste trial burn had a 43% increase in sulfur relative to the baseline. The coal used for the construction and demolition waste trial burn also had a 38 % increase in sulfur. The kiln feed and coal sulfur contents were also elevated for the soybean seed trial burn. The increase in sulfur content in the kiln feed and coal could be the cause of the elevated SO_2 content shown in Figure 4.25 for the construction and demolition waste and soybean seed trial burns. The sulfur content in the kiln feed and coal was slightly elevated and decreased, respectively for the variable feed trial burns.

Table 4.46: CPR – Emission wilcoxon rank sum results and percent difference relative to baseline

Emissions		**NO$_x$ (10^{-3}) (tons/ton clinker)**	**SO$_2$ (10^{-5}) (tons/ton clinker)**	**VOC (10^{-5}) (tons/ton clinker)**	**CO (10^{-4}) (tons/ton clinker)**
B-CP	**Avg.**	0.95	1.0	4.26	3.85
C&D	**Avg.**	0.81	1.55	1.44	3.68
	P-value[1]	0.0001[2]	0.0001[2]	0.0001[2]	0.0075[2]
	%Diff	-14.65	63.43	-66.29	-4.45
VF 5%	**Avg.**	0.76	0.25	1.34	3.93
	P-value[1]	0.0001[2]	0.0001[2]	0.0001[2]	0.1729
	%Diff	-20.34	-73.72	-68.45	2.17
VF 10%	**Avg.**	0.83	0.42	0.85	3.89
	P-value[1]	0.0001[2]	0.0001[2]	0.0001[2]	0.5137
	%Diff	-13.03	-55.50	-80.04	1.15
VF 15%	**Avg.**	0.87	1.11	1.67	3.13
	P-value[1]	0.0077[2]	0.0074[2]	0.0001[2]	0.0001[2]
	%Diff	-8.53	17.15	-60.79	-18.74
Soy	**Avg.**	1.15	1.68	3.33	3.86
	P-value[1]	0.7471	0.001[2]	0.0001[2]	0.4990
	%Diff	20.83	76.58	-21.79	0.20

Notes:

[1] Based on Wilcoxon rank-sum

[2] Significantly different means

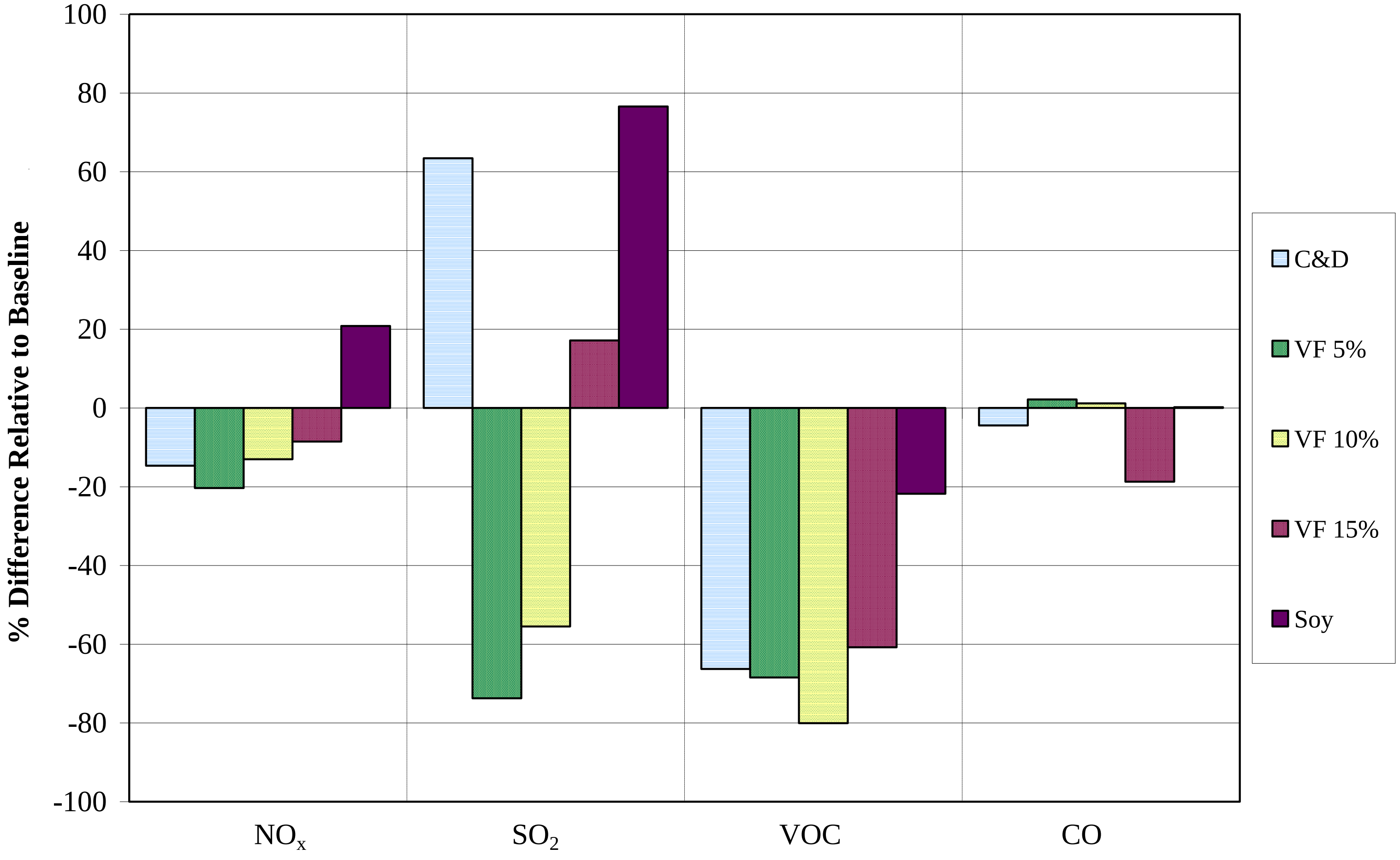

Figure 4.25: Percent difference relative to baseline emissions for all burns

The p-values calculated for the volatile organic compounds (VOC) show that all the burn means are significantly different. The percent difference relative to the baseline of the volatile organic compound emissions for all the trial burns are shown in Figure 4.25. The volatile organic emissions were significantly reduced throughout all the trials compared to the baseline. Compared to the previous woodchip trial burn VOC level, the variable feed 5 and 10 % trial burn CO levels were reduced 48 and 67 %, respectively. Volatile organic compounds are formed from combustion of organic material within the raw materials and fuels. Research has shown that system design and control, such as the number of stages in the preheater and the exiting flu-gas temperatures, dictate the formation of dioxin and furan formations more so than the fuels utilized (Bech and Mishulovich 2004; Loo 2008).

The p-values calculated for the carbon monoxide (CO) show that the construction and demolition waste and variable feed 15 % woodchip trial burns are significantly different. The variable feed 5 and 10 % and the soybean seed trial burns have statistically similar means to the baseline, and therefore their percent differences relative to the baseline are negligible. The carbon monoxide content in the variable feed 15 % trial burn was decreased by 19 % compared to the baseline, which was the greatest difference for all the trial burns. Compared to the previous woodchip trial burn CO level, the variable feed 5 and 10 % trial burn CO levels were each reduced 34 %.

CO emissions remained within -19 to 2 % of the baseline CO emissions. Research has shown that carbon monoxide develops from the incomplete combustion of carbon rich fuels due to insufficient oxygen at the combustion site (Greer et al. 2004). Coal has the highest carbon content of all the fuels used. The ultimate analysis showed that the carbon content of the coal fluctuated more than the carbon contents of the plastic blend and trial fuels. Since coal was the most utilized fuel during all the trial burns, the effects from changes in the coal's chemical composition are more likely to influence emission results than the plastic blend or the trial fuels. As previously mentioned, the carbon monoxide emitted from the construction and demolition waste and the variable feed 15 % burns were the two trials with differing means compared to the baseline. Although the coal composition for the construction and demolition waste possessed a negligible percent difference to the baseline, the variable feed 15 % showed a decrease of about 10 % in carbon content. This could explain a portion of the overall decrease in carbon monoxide within the variable feed 15 % trial burn.

The ADEM limits pertaining to each emission monitored by the cement plant are tabulated in Table 4.47. The emission limits are reported in tons per 30 days or tons per hour. Utilizing the cement plant's production rates from each trial, the emission limits were converted to ton of emission per ton of clinker. The average of each emission for all the burns is presented at the bottom of Table 4.47 and shown in Figure 4.26.

The average, 5th and 95th percentiles of each emission for all burns are shown in Figure 4.26. All the emissions remained within limits except for the volatile organic compounds within the baseline and soybean seed burns. As previously stated, controlling the VOC emissions relies more on system control than fuel utilization and this apparent non-compliance cannot be attributed to the use of the trial fuels.

Table 4.47: ADEM emission limits and normalized limits for each burn

ADEM Limits (2007-2010)					
Emission		**NO_X**	**SO_2**	**VOC**	**CO**
Limit (tons/30 days)		221	202	4.8	NA
Limit (tons/hr)		0.307	0.282	0.007	0.36
B-CP	**tons clinker/hr[1]**	198.3			
	Limit (tons/ton clinker)	1.55E-03	1.42E-03	3.53E-05	1.82E-03
C&D	**tons clinker/hr[1]**	218.6			
	Limit (tons/ton clinker)	1.40E-03	1.29E-03	3.20E-05	1.65E-03
VF	**tons clinker/hr[1]**	219.9			
	Limit (tons/ton clinker)	1.40E-03	1.28E-03	3.18E-05	1.64E-03
Soy	**tons clinker/hr[1]**	225.4			
	Limit (tons/ton clinker)	1.36E-03	1.25E-03	3.11E-05	1.60E-03
Average Limit (tons/ton clinker)[1]		1.43E-03	1.31E-03	3.26E-05	1.67E-03

Notes: [1] Based on Average Production Data

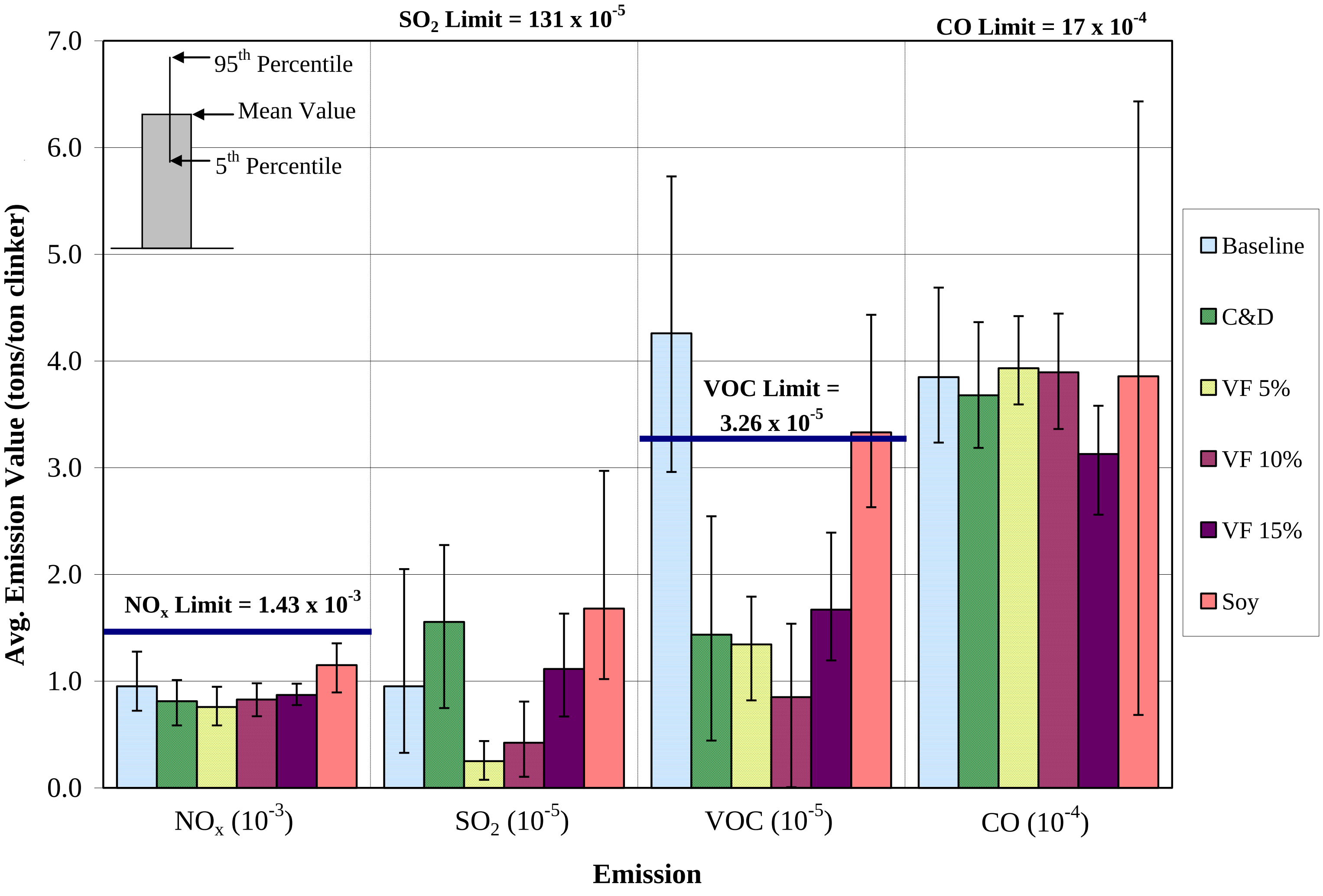

Figure 4.26: Average normalized plant emissions with ADEM limits for all burns

4.5 Concluding Remarks

The complex nature of cement manufacturing and inherent variability in the chemical composition of raw materials and fuels create challenges attributing the effects of one process input to the overall production and performance of the cement. However, multiple conclusions have been formed regarding the utilization of alternative fuels in the manufacture of portland cement.

The ability of the cement plant to maintain production rates and efficiently process and dose the trial fuels were the initial objectives of this study. The processing ability of the available equipment is one factor that limits substitution rates. The construction and demolition waste and woodchip burns did not cause any feed problems. Several cement plant personnel experienced allergic reactions due to handling and de-dusting the soybean seeds. This was most likely due to the herbicide on the soybean seed. This problem, however, was eliminated with the use of proper personal protective equipment.

The energy value associated with each fuel was also an important aspect in determining the viability of the alternative fuel source. The energy values of the fuels utilized during all the trials of this study were less than those of the traditional fuels. The as-received energy values for each fuel utilized during this study were as follows:

1. Coal: 10,820 to 12,090 with an average of 11,320 BTU/lb,
2. Plastics: 8,855 to 10,780 with an average of 10,130 BTU/lb,
3. Construction and Demolition waste: 3,370 to 8,180 with an average of 6,050 BTU/lb,
4. Woodchips: 3,355 to 6,996 with an average of 4,736 BTU/lb, and

5. Soybean seeds: 8,977 to 9,375 with an average of 9,150 BTU/lb.

The coal had the highest energy content followed by the plastic waste and alternative fuels. The high energy content of the plastic waste is one reason it has been utilized for a number of years and is considered a traditional fuel for this study. The soybean seeds possessed the highest energy values for the alternative fuels followed by the construction and demolition waste and woodchips. The minimum and maximum heating values are expressed to show the fluctuation in energy values associated with each fuel. Moisture content greatly affects the energy content of a fuel. Coal, plastics, and soybean seeds all possessed fairly stable moisture contents and thus the ranges of energy values are significantly lower than the construction and demolition waste and the woodchip fuels heating ranges.

The second goal of this study was to determine if the utilization of alternative fuels had a direct impact on the chemical composition of the portland cement. The kiln feed and the cement kiln dust, reported in Sections 4.4.1 and 4.4.2, respectively, were compared to their respective baseline values and found to be consistent with the exception of an elevated SO_3 content found in all the trial burns kiln feed. A probable cause for the increase in SO_3 was the elevated SO_3 contents found in the of cement kiln dust, which is recycled into the kiln feed.

The statistical analysis performed on the clinker data in Section 4.4.4 showed that the majority of parameter means were significantly different than the parameter means of the baseline burn. This was expected because of the narrow range of values surrounding the mean of each parameter. Of the parameter means that showed significant differences, however, the percent difference between the trial and baseline parameter means were small for most parameters. This indicates a fair amount of consistency throughout the trial burns. An example of the consistency that was maintained over all the trial burns can be seen in the chemical composition of the cement's primary oxides levels, Al_2O_3, CaO, Fe_2O_3, and SiO_2 compared to the baseline cement. All of the primary oxide levels are within 10 % of the baseline's results. There were minimal fluctuations found in the cement Bogue compounds. The alite content increased 17 % in the cement produced during the soybean seed trial burn and the aluminate content of the construction and demolition waste and variable feed 10 % trial cements also increased compared to the baseline alite content. The Bogue compounds are influenced by multiple variables such as process inputs, kiln temperature, and clinker cooling rates. Because of the inherent variability throughout portland cement production, changes in cement chemistry are difficult to link to the utilization of a particular fuel.

The third and fourth objectives of this study were to evaluate the effects of alternative fuel on the physical properties of cement and concrete. For comparison purposes, several physical properties of the trial cements were determined by experiments conducted by the cement plant and Auburn University. Precision statements for the repeatability of individual tests developed by ASTM were used in order to determine if results between a trial and its baseline showed practical significance. A comparison of the paste, mortar, and concrete test results are provided in Section 4.4.9.

The physical property results from the cement plant and Auburn University were compared. If consistent changes were observed between a trial and the baseline result throughout paste, mortar, and concrete testing, the property change could be verified and attributed to the trial cement. The majority of paste and mortar physical properties tested were similar to the baseline's paste and mortar results. Since the paste and mortar testing did not use the admixtures found in the concrete mixtures, the paste and mortar tests were thought to better represent the actual behavior of the trial cements. Overall, it was found that the trial burn cements had minimal effects on workability, setting time, strength, drying shrinkage, and permeability compared to the baseline cement.

The emissions results were reported in Section 4.4.8. The statistical analysis conducted for the NO_x emission showed significant differences between the trial and baseline means for all burns except the soybean seed trial. The NO_x, however, were reduced for the construction and demolition waste and variable feed trails. Since the majority of NO_x develops from the oxidation of atmospheric nitrogen, conclusions about the effects of alternative fuels cannot be drawn without reports of oxygen levels in the kiln during the pyroprocess.

Statistical analysis also showed significant differences between the baseline and trial means for SO_2. The increase of SO_2 in the construction and demolition waste and soybean seed trials was thought to be caused by the elevated sulfur contents found in the kiln feed and coal. Because of the low sulfur content of woodchips, the increase in SO_2 from the variable feed 5 % to the 15 % trial burn is probably not due to the increase in woodchip substitution. The kiln feed of the variable feed burns, however, showed progressively increasing SO_3 levels compared to the baseline.

All the trials showed significantly different means for the volatile organic compound emissions. The VOC's were reduced for all burns compared to the baseline's VOC levels. Research has proven that control of volatile organic emissions depend more on system design and control than fuels utilized.

Statistical analysis of the carbon monoxide results for all burns showed that only the construction and demolition waste and variable feed 15 % possessed significantly different means compared to the baseline. The degree of difference between the construction and demolition waste and the baseline, however, was almost a negligible. The decrease seen in the variable feed 15 % trial is thought to be partially caused by a 10 % decrease in the carbon content of the coal utilized during that trial.

Throughout this chapter, several physical changes in the cement could be attributed to changes in chemical composition. It is, however, unfortunate that the variability in the production of portland cement makes connecting changes in cement chemistry or physical properties directly to the utilization of alternative fuels a difficult task. This study did not find conclusive evidence that the changes in cement chemistry and performance were solely due to the utilized alternative fuels. The implementation of trial fuels in this study successfully decreased the quantity of the traditional fuels required and produced cement with equal if not slightly improved properties.

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Chapter 5
Summary, Conclusions, and Recommendations

5.1 Summary

Portland cement is produced from several raw materials mined from the earth. When mixed in the proper proportions, and exposed to gas temperatures in excess of 1800 °C, the raw materials fuse together to form a product known as clinker. The clinker is then ground with an addition of sulfate to a specific fineness to produce portland cement. In order to reach these high kiln temperatures, fossil fuels such as coal, petroleum coke, and natural gas are regularly used. Due to the rising costs of fossil fuels, cement manufacturers have investigated the utilization of alternative fuels for partial replacements to traditional fuels. Over the years, the utilization of alternative fuels has proven to be both beneficial to the cement industry and the environment. It is, however, imperative to fully understand the effects of each new fuel to determine its viability as a fuel source.

Many of today's alternative fuels are industrial waste by-products and are typically disposed of in land-fills. Utilizing industrial waste as fuel not only frees diminishing landfill space, but produces an end product. Waste incineration, which also requires large quantities of fossil fuels, is routinely performed at landfills in order to free space and accommodate additional material. Waste incineration typically does not harness the heat generated from the combustion process. Unlike traditional fuels, waste fuel supplies are steadily increasing, widely available, and are a fraction of the cost.

Alternative fuels included in this study are construction and demolition waste, woodchips, and soybean seeds. Each of these fuels was utilized in order to partially replace and therefore lessen the demand for traditional fuels. Each trial fuel and was co-fired with coal and a plastic blend. In this study, the plastic bend is considered a traditional fuel since it is used during normal operation at the cement plant.

The first alternative utilized over a 3-day burn period was construction and demolition waste (C&D). The construction and demolition waste consisted of wood, paper, and plastics. The second trial utilized woodchips (VF) and was conducted over a 6 -day period. This burn was unique to this study due to the progressively increasing substitution rate of woodchips. The third and final burn, which utilized soybean seeds, was also conducted over a 3-day burn period. Although this burn took place several months after the baseline, the conditions at the cement plant were maintained to the best of the staffs' ability. A baseline or control burn consisting of just coal and the waste plastic blend occurred prior to the trial burns. Additional information on each fuel is provided in Section 2.3.4.

During each trial burn, samples of process inputs and outputs were sampled by the cement plant. The chemical compositions of the samples were determined by two testing agencies. The chemistry of the process inputs and outputs for each trial burn were compared to the baseline's burn results. Since chemical changes in clinker can be caused by the incorporation of noncombustible materials, an attempt was made to establish connections between the clinker chemistry and the alternative fuel. Cement physical properties were determined by two agencies. Fresh and hardened concrete properties were determined by one party. Finally, emissions were monitored by the cement plant during each trial burn. These emissions were compared to the baseline's emissions in order to determine if any correlations could be established between the alternative fuels and their emission profiles.

5.2 Conclusions

The ability of the cement plant to maintain production rates and efficiently process and dose alternative fuels was the initial objective of this study. The processing ability of the available equipment is one factor that limits substitution rates. The construction and demolition waste and woodchip burns did not cause any feed problems. Several cement plant personnel experienced minor allergic reactions due to handling and de-dusting the soybean seeds. This problem, however, was eliminated with the use of proper personal protective equipment.

The energy value associated with each fuel was also an important aspect in determining the viability of the fuel. The energy values of the alternative fuels utilized during this study were less than those of traditional fuels. The as-received energy values for each fuel utilized during this study were presented in Section 4.5.

When assessing the feasibility of the alternative fuel, the unit cost of the fuel is an important parameter. Although some of the alternative fuels possess energy values that are roughly half that of the traditional fuels, the price for traditional fuels is typically significantly more than alternative fuels. Due to fuel cost data being proprietary knowledge, the feasibility of the trial alternative fuels based on price could not be evaluated or compared.

The utilization of each fuel remained fairly consistent over the burn periods. Coal accounted for almost 90 percent of the required energy during the baseline burn, but was reduced to 70 percent during the variable feed 15 percent trial burn. The plastic blend accounted for roughly 15 percent of the required energy for all trial burns. Alternative fuels accounted for 5, 5.4, 11.8, 16, and 7.5 percent of the total energy for the construction and demolition waste, variable feed 5, 10, and 15 percent, and soybean seed burns, respectively. Since the alternative fuels and waste plastic blend only accounted for 20-30 percent of the total fuel energy, only parameters possessing significant differences to the baseline have the possibility to affect the cement and concrete properties.

The second goal of this study was to determine if the utilization of alternative fuels had a direct impact on the chemical composition of the portland cement. The kiln feed and the cement kiln dust results were reported in Sections 4.4.1 and 4.4.2, respectively. These results were compared to their respective baseline values and found to be consistent over all trials with the exceptions of elevated SO_3 and P_2O_5 concentrations. A probable cause for the increase in SO_3 was significantly elevated SO_3 contents found in the cement kiln dust. Cement kiln dust is routinely recycled into the kiln feed because it contains many of the same chemical properties that are found in the kiln feed. Since none of the raw materials possessed elevated SO_3 concentrations, the cement kiln dust SO_3 content was more than likely increased by the utilized fuels. It was, however, determined from the standard parameters that the SO_3 content for the coal and plastics decreased over all the trials compared to the baseline. Also, the alternative fuels did not possess excessive SO_3 concentrations. Therefore, the source of increase in the cement kiln dust was not determined.

The external laboratory reported significant increases in P_2O_5 for all trial burns. Slightly increased P_2O_5 levels were also found in the cement kiln dust. In the trial burns, coal possessed significantly elevated levels of P_2O_5 compared to the baseline's coal level. The construction demolition waste contained approximately 3 and 2 times the P_2O_5 content compared to the woodchip and soybean seed trials, respectively. Though the construction and demolition waste fuel possessed the highest P_2O_5 content for the alternative fuels tested, their contribution to the overall P_2O_5 content of the clinker and cement was minimal. The combination of materials and fuel led to the increased P_2O_5 levels found in the clinker and cement.

The statistical analysis performed on the clinker data in Section 4.4.4 showed that the majority of data from the trial burns had significantly different means. This was expected because of the narrow range of values surrounding the mean of each parameter. However, the percent differences calculated for the data showing significantly different means were small for most parameters. This indicates a fair amount of consistency throughout the trial burns. The primary oxides such as Al_2O_3, CaO, Fe_2O_3, and SiO_2 remained consistent throughout the trial burns. The Bogue compounds calculated by the cement specialty laboratory for the cement, however, showed significant fluctuations in the alite and aluminate contents compared to the baseline's results. The alite content increased 17 % in the soybean seed trial burn cement compared to the baseline's results. Significant increases were also found in the aluminate content of the construction and demolition waste and variable feed 10 % trial burn cements compared to the baseline's results. The Bogue compounds are influenced by multiple variables such as all process inputs, kiln temperature, and clinker cooling rates. Because of the inherent variability throughout portland cement production, changes in cement chemistry are difficult to link to the utilization of a particular fuel.

The third and fourth objectives of this study were to evaluate if the utilization of the trial fuels directly impacted the physical properties of the portland cement or the concrete that was prepared with the trial burn cements. Cement chemistry ultimately defines performance, and therefore, an attempt was made to pair performance and chemistry fluctuations. The physical properties of cement and concrete were analyzed in Sections 4.4.7 and 4.4.8, respectively. A comparison of the paste, mortar, and concrete test results are provided in Section 4.4.9.

The majority of paste and mortar physical properties tested were similar to the baseline's paste and mortar results. Since the paste and mortar testing did not use the admixtures found in the concrete mixtures, the paste and mortar test results were thought to better represent the actual behavior of the trial cement. Overall, it was found that the trial burn cements had minimally different effects on workability, setting time, strength, drying shrinkage, and permeability compared to the baseline cement. A summary of the physical changes observed from the cement and concrete testing are presented in Tables 4.41 through 4.45.

The fifth and final objective of this study was to assess the impact of alternative fuels on emissions produced by the cement plant. The emission results were reported in Section 4.4.8. The emission data was collected by the cement plant using a continuous emission monitoring system (CEMS). Nitrogen Oxides (NO_x), sulfur dioxide (SO_2), volatile organic compounds (VOC), and carbon monoxide (CO) were the monitored emissions. All emission data was normalized and expressed in units of tons of emission per ton of clinker produced. The emission limits were calculated according to cement plant production rates and reported in Table 4.48. All emissions were within acceptable emission limits except for the volatile organic compounds produced during the baseline and soybean seed trial burns. The production of volatile organic compounds is more dependent on system design and control than the type of fuel used. The trial fuels utilized were not found to greatly effect the quantity of emission produced A graphical representation of the average emission values are shown in Figure 4.26.

The nitrogen oxides emitted from the cement plant remained fairly consistent throughout all trial burns. The baseline and soybean seed burns possessed statistically similar means. The construction and demolition waste and variable feed trials showed reductions in NO_x compared to the baseline. Since the majority of NO_x develops from the oxidation of atmospheric nitrogen, conclusions regarding the effects of alternative fuels cannot be drawn without reports of oxygen levels inside the kiln during the pyroprocess.

The sulfur dioxide emissions were increased during the construction and demolition waste, variable feed 15 %, and soybean seed trials compared to the baseline. The increase of SO_2 in the construction and demolition waste and soybean seed trails was thought to be caused by those trials' elevated kiln feed and coal sulfur contents. The increase in SO_2 observed in the variable feed 5 % to 15 % trials was probably not caused by the increase in woodchip substitution. The sulfur content of the woodchips was significantly lower than the coal and plastics blend. The kiln feed sulfur content increased in each phase of the variable feed trials, and therefore, possibly contributed to the progressively increasing SO_2 emissions seen in the variable feed trials.

The baseline burn produced the highest VOC emissions during this study. The construction and demolition waste and variable feed trials were reduced at least 60 percent compared to the baseline. As previously mentioned, the baseline burn and soybean seed trials exceeded the allowable VOC limits. Research has proven that control of volatile organic emissions depends more on system design and control than the fuels utilized.

The carbon monoxide emissions remained fairly consistent throughout all trial burns. The decease seen in the variable feed 15 % trial is thought to be partially caused by a 10 % decrease in carbon content within the coal utilized during that trial. Similarly to the NO_x, oxygen-to-fuel ratio and the rate of clinker cooling are the primary factors that contribute to CO emissions. These data were not collected, so their contribution could not be evaluated.

The cement plant was successful in implementing alternative fuels to produce a consistent, high-quality product that increased cement performance while reducing the environmental footprint of the plant. The utilization of construction and demolition waste, woodchips and soybean seeds proved to be viable replacements for traditional fuels. The future use of these fuels depends on local availability, associated costs, and compatibility with a facility's production process.

5.3 Recommendations

A major factor limiting the effectiveness of this study was the low substitution rate of the alternative fuels. Coal accounted for 70 to 90 percent of the total energy consumed during production. The alternative fuels tested during this study contributed only 5 to 16 percent of the total energy used during the pyroprocess. Changes in cement chemistry could not be solely attributed to the alternative fuels. This was due to observed cement physical changes paralleling significant fluctuations in kiln feed or coal chemical compositions. Increasing the substitution rate would allow the trial fuel's effects to be more pronounced and thus provide a better understanding of the interactions that occur between a utilized fuel and the performance of the portland cement. If the minimum substitution rates were increased, as well as implementing a variable feed approach similar to the woodchip trial performed in this study, an optimum replacement rate could be established.

Although a thorough sampling plan was developed for each burn, determining the effects of the alternative fuels on the cement chemistry and performance proved a difficult task. If the sampling plan was expanded to include enough samples of kiln feed, coal, and cement kiln dust to perform statistical analysis, a greater understanding of the consistency of these process inputs throughout a trial burn could be achieved. Increasing the number of specimens tested could also limit the number of inconsistent results between testing agencies. A sampling plan, however, is often limited by funding, personnel, and time.

Several results from the physical properties of cement and concrete could not be explained. One example being the significantly extended setting times of the VF 10 % Mix 0.44 concrete. The concrete mixture was repeated and similar results were obtained. The cement chemistry for Mix 0.44 concrete did not provide any indication of why setting times for the majority of trials were delayed compared to the baseline. An additional study of how the admixtures used in Mix 0.44 and 0.37 concrete mixtures influenced the trial cements' physical properties could be beneficial in explaining the observed results.

There were several trends that could not be explained regarding the emissions produced during the trial burns. Oxygen levels should be measured within the kiln. Knowing the oxygen level present in the pyroprocess, which significantly effects the emissions formed, could be beneficial in order to explain the fluctuations observed in the NO_x, SO_2, and CO emissions.

References

Abbas, T., P. G. Costen, and F. C. Lockwood. 1996. Solid Fuel Utilization: From Coal to Biomass. *Symposium (International) on Combustion* 26, no. 2:3041-3058.

ACI. 1992. State-of-the-Art Report on High-Strength Concrete. Farmington Hills, Michigan. American Concrete Institute.

ADEM. 2007. *Major Source Operating Permit*. Alabama Department of Environmental Management. Montgomery, AL. Issuance date: March 20, 2007.

Aïtcin, P. 2000. Cements of yesterday and today: Concrete of tomorrow. *Cement and Concrete Research* 30, no. 9:1349-1359.

Akkapeddi, S. 2008. *Alternative Solid Fuels for the Production of Portland Cement*, M.S. Thesis, Auburn University, Alabama.

Akkapeddi, S., Swart, D. W., Schindler, A. K., Duke, S. R., and Stafford, D. 2008. Impact of Using Alternative Fuels to Produce Portland Cement on Cement and Concrete Properties. *Proceedings of NRMCA's Symposium on Focus on Sustainable Development*. Denver, CO. February 2008.

Al-Salem, S. M., P. Lettieri, and J. Baeyens. 2010. The Valorization of Plastic Solid Waste (PSW) by Primary to Quaternary Routes: From Re-use to Energy and Chemicals. *Progress in Energy and Combustion Science* 36, no. 1:103-129.

ASA. 2011. 2010 Soy Statistics. American Soybean Association. http://www.soystats.com/2010/Default-frames.htm (accessed September 17, 2011)

ASA. 2011. 2011 Soy Statistics. American Soybean Association. http://www.soystats.com/2011/page_29.htm (accessed September 17, 2011).

ASTM C 185. 2002. *Standard Test Method for Air Content of Hydraulic Cement Mortar*. ASTM International. West Conshohocken, PA.

ASTM C 230. 2003. *Standard Specification for Flow Table for Use in Tests of Hydraulic Cement*. ASTM International. West Conshohocken, PA.

ASTM C 187. 2004. *Standard Test Method for Normal Consistency of Hydraulic Cement*. ASTM International. West Conshohocken, PA.

ASTM C 496. 2004. *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*. ASTM International. West Conshohocken, PA.

ASTM C 39. 2005. *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. ASTM International. West Conshohocken, PA.

ASTM C 151. 2005. *Standard Test Method for Autoclave Expansion of Hydraulic Cement*. ASTM International. West Conshohocken, PA.

ASTM C 157. 2006. *Standard Test Method for Length Change of Hardened Hydraulic – Cement Mortar and Concrete*. ASTM International. West Conshohocken, PA.

ASTM C109. 2007. *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens)*. ASTM International. West Conshohocken, PA.

ASTM C 150. 2007. *Standard Specification for Portland Cement*. ASTM International. West Conshohocken, PA.

ASTM C 192. 2007. *Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*. ASTM International. West Conshohocken, PA.

ASTM C 204. 2007. *Standard Test Methods for Fineness of Hydraulic Cement by Air-Permeability Apparatus*. ASTM International. West Conshohocken, PA.

ASTM C 596. 2007. *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement*. ASTM International. West Conshohocken, PA.

ASTM C 1202. 2007. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. ASTM International. West Conshohocken, PA.

ASTM C 1437. 2007. *Standard Test Method for Flow of Hydraulic Cement Mortar*. ASTM International. West Conshohocken, PA.

ASTM C 143. 2008. *Standard Test Method for Slump of Hydraulic-Cement Concrete*. ASTM International. West Conshohocken, PA.

ASTM C 191. 2008. *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle*. ASTM International. West Conshohocken, PA.

ASTM C 231. 2008. *Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method*. ASTM International. West Conshohocken, PA.

ASTM C 266. 2008. *Standard Test Method for Time of Setting of Hydraulic-Cement Paste by Gillmore Needles*. ASTM International. West Conshohocken, PA.

ASTM C 403. 2008. *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. ASTM International. West Conshohocken, PA.

Ayala, N. I. 2006. Used Oil Derived Fuel Utilization for the Production of Portland Cement. *Journal of ASTM International* 3, no. 8.

Bech, C, and A. Mishulovich. 2004. Preheaters and Precalciners. Chap. 3.2 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Bhatty, J. I., and J. Gajda. 2004. Use of Alternative Materials in Cement Manufacturing. Chap. 2.4 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Bhatty, J. I. 2004. Minor Elements in Cement Manufacturing. Chap. 3.6 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Bridge, Patrick D., Sawilowsky, Shlomo S. 1999. Increasing Physicians' Awareness of the Impact of Statistics on Research Outcomes: Comparative Power of the t-test and Wilcoxin Rank-Sum Test in Small Samples Applied Research. *Journal of Clinical Epidemiology* 52, no. 3:229-235.

McCrae, Michael A. Consol Energy reports fifth consecutive quarter of record coal revenue; US thermal coal sold out due to hot weather. http://www.mining.com/2011/07/28/consol-energy-reports-fifth-consecutive-quarter-of-record-coal-revenue-us-thermal-coal-sold-out-due-to-hot-weather/ (accessed August 2, 2011).

Chatterjee, A. K. 2004. Raw Materials Selection. Chap. 2.1 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Cembureau. 2010. World Cement Production 2010 by region and main countries. The European Cement Association. http://www.cembureau.be/about-cement/key-facts-figures (accessed July 21, 2011)

Chen, I. A., and M. C. G. Juenger. 2009. Incorporation of Waste Materials into Portland Cement Clinker Synthesized from Natural Raw Materials. *Journal of Materials Science* 44, no. 10:2617-2627.

Conesa, J. A. 2008. Organic and Inorganic Pollutants from Cement Kiln Stack Feeding Alternative Fuels. *Journal of Hazardous Materials* 158, no. 2-3:585-592.

Cordwell, P. 2006. Handling Alternative Fuels. *World Cement* 37, no. 10:31-36.

Cuiping, L., Chuangzhi, W., Yanyongjie, and Haitao, H. 2004. Chemical elemental characteristics of biomass fuels in China. *Journal of Biomass & Bioenergy* 27 119-130.

Edmeades, R. M., and P. C. Hewlett. 1998. Cement Admixtures. Chap. 15 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

EPA. 1995. "Chapter 11.6, Portland Cement Manufacturing." *Compilation of Air Pollutant Emission Factors, AP-42.* Research Triangle Park, NC: U.S. Environmental Protection Agency.

EPA. 2010. Greenhouse Gas Emissions. *U.S. Environmental Protection Agency..*. http://www.epa.gov/climatechange/emissions/index.html (accessed June 24, 2010).

EPA. 2011. Major Crops Grown in the United States. United States Environmental Protection Agency. http://www.epa.gov/agriculture/ag101/cropmajor.html (accessed September 17, 2011)

Ewing, Nick. 2009. Tour with *Lafarge North America* quality assurance manager. Calera, AL. 6 November.

Folta, A. 2010. *Alternative Fuels and their Effects on Portland Cement*, M.S. Thesis, Auburn University, Alabama.

Gingerich, Philip D. 1995. Statistical power of EDF tests of normality and the sample size required to distinguish geometric-normal (lognormal) from arithmetic-normal distributions of low variability. *Journal of Theoretical Biology* 173, no. 2:126-136.

Glasser, F. P. 2004. Advances in Cement Clinkering. Chap. 3.4 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Greco, C., G. Picciotii, R. B. Greco, and G. M. Ferreira. 2004. Fuel Selection and Use. Chap. 2.5 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Greer, W. L. 1989. SO_2/NO_x Control Compliance with Environmental Regulations. *IEEE Transactions on Industry Applications* 25, no. 3:475-485.

Greer, W. L. 2004. A Qualitative Examination of the Control of Major Gaseous Pollutants Generated in Portland Cement Kilns. (Proceedings of the A and WMA's 97th Annual Conference and Exhibition; Sustainable Development: Gearing up for the Challenge, Indianapolis, IN, June 22-25).

Greer, W. L., G. J. Hawkins, and T. B. Carter. 2004. Air Emissions and Control Measures. Chap. 6.1 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Hawkins, G. J., J. I. Bhatty, and A. T. O'Hare. 2004. Cement Kiln Dust Generation and Management. Chap. 6.3 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Hendrik, G. O., and A. C. Padovani. 2003. Cement Manufacture and the Environment, Part II: Environmental Challenges and Opportunities. *Journal of Industrial Ecology* 7, no. 1:93-126.

ICR. 2011. World Cement Overview. International Cement Review. http://www.cembureau.be/about-cement/key-facts-figures (accessed July 21, 2011).

Jackson, Peter J. 1998. Portland Cement: Classification and Manufacture. Chap. 2 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

Kääntee, U., R. Zevenhoven, R. Backman, and M. Hupa. 2004. Cement Manufacturing Using Alternative Fuels and the Advantages of Process Modeling. *Fuel Processing Technology* 85:293-301.

Karstensen, K. H. 2008. Formation, Release and Control of Dioxins in Cement Kilns. *Chemosphere* 70, no. 4:543-560.

Kikuchi, R., J. Kukacka, and R. Raschman. 2008. Grouping of Mixed Waste Plastics According to Chlorine Content. *Separation and Purification Technology* 61, no. 1:75-81.

Kirk, L. B. 2000. Potential Dioxin Release Associated with Tire Derived Fuel use in a Cement Kiln Gallatin County, Montana. *Principles of Environmental Toxicology*. University of Idaho, December 2000.

Kirk, L. H. III. 2004. Health and Industrial Hygiene. Chap. 7.3 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Kosmatka, S. H., B. Kerkhoff, and W. C. Panarese. 2002. *Design and Control of Concrete Mixtures*. 14th ed. Skokie, Illinois: Portland Cement Association.

Lawrence, C. D. 1998a. The Constitution and Specification of Portland Cements. Chap. 4 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

Lawrence, C. D. 1998b. Physicochemical and Mechanical Properties of Portland Cement. Chap. 8 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

Lechtenberg, D. 2009. The Use of Alternative Fuels in the Cement Industry of Developing Countries – an opportunity to reduce production costs? *Cement International* 7, no. 2:66-70.

Loo, W. 2007. Dioxin/furan formation and release in the cement industry. *Environmental Toxicology and Pharmacology* 25, no ?:128-130.

Macphee, D. E., and E. E. Lachowski. 1998. Cement Components and Their Phase Relations. Chap. 3 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

Manias, C. G. 2004. Kiln Burning Systems. Chap. 3.1 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Mehta, P. K., and Monteiro, P. 2006. *Concrete: Microstructure, Properties, and Materials*. 3rd ed. New York: McGraw-Hill.

Miller, F. M. 1976. Minor Elements in Cement Clinker. *Paper No. 16, PCA Cement Chemist's Seminar*. Skokie, Illinois: Portland Cement Association.

Miller, F. M. 2004. Raw Mix Design Considerations. Chap. 2.2 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Mokrzycki, E., and A. Uliasz-Bocheńczyk. 2003. Alternative Fuels for the Cement Industry. *Applied Energy* 74, no. 1-2:95-100.

Mokrzycki, E., A. Uliasz-Bocheńczyk, and M. Sarna. 2003. Use of Alternative Fuels in the Polish Cement Industry. *Applied Energy* 74, no. 1-2:101-111.

Naik, T. R. 2005. Sustainability of Cement and Concrete Industries. (Proceedings of the International Conference on Achieving Sustainability in Construction, Dundee, Scotland, United Kingdom, July 5-7).

Network Solutions. 2010. www.ful-services.com/images/gratecoolerspict.jpg. (accessed February 12, 2010).

Nurse, R. W. 1952. The Effect of Phosphate on the Constitution and Hardening of Portland Cement. *Journal of Applied Chemistry* 2, no. 12:708.

Odler, I. 1998. Hydration, Setting, and Hardening of Portland Cement. Chap. 6 in *Lea's Chemistry of Cement and Concrete*. 4th ed. London: Arnold.

Olmo, I. F., E. Chacon, and A. Irabien. 2001. Influence of Lead, Zinc, Iron (III) and Chromium (III) Oxides in the Setting Time and Strength Development of Portland Cement. *Cement and Concrete Research* 31, no. 8:1213-1219.

PCA. 2009. Report on Sustainable Manufacturing. *Portland Cement Association*. http://www.cement.org/smreport09/index.htm. (accessed March 12, 2010).

Prisciandaro, M., G. Mazziotti, and F. Veglió. 2003. Effect of burning supplementary waste fuels on the pollutant emissions by cement plants: A statistical analysis of process data. *Resources, Conservation and Recycling* 39, no. 2:161-184.

Raphael, J.M. 1984. Tensile Strength of Concrete. *Journal of the American Institute of Concrete* 81:158-165

Richards, J. R. 2004. Pariculate Matter Control. Chap. 6.2 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Schuhmacher, M., J. L. Domingo, and J. Garreta. 2004. Pollutants Emitted by a Cement Plant: Health Risks for the Population Living in the Neighborhood. *Environmental Research* 95, no. 2:198-206.

Shafiee, S., and E. Topal. 2010. A long-term view of worldwide fossil fuel prices. *Applied Energy* 87, no. 3:988-1000.

Siddique, R., J. Khatib, and I. Kaur. 2008. Use of Recycled Plastic in Concrete: A Review. *Waste Management* 28, no. 10:1835-1852.

Steuch, H. E. 2004. Clinker Coolers. Chap. 3.8 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Strohman, N. R. 2004. Finish Milling and Grinding. Chap. 4.1 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Swart, D. W. 2007. *The Utilization of Alternative Fuels in the Production of Portland Cement*, M.S. Thesis, Auburn University, Alabama.

Syverud, T. 1994. Utilization of Chipped Car Tyres for Reducing NO_x Emissions in a Precalciner Kiln. *World Cement* 25, no. 11:39-43.

Taniguchi, M. 2001. The Metamorphosis from Manufacturing to Ecofacturing of Cement Industry. *Kami pa gikyōshi* 44, no. 4:68-77.

Tankersley, J. 2010. EPA: U.S. Saw Record Decline in Greenhouse Gas Emissions in 2008. *Greenspace – Environmental News from California and Beyond*, March 9. http://latimesblogs.latimes.com/greenspace/2010/03/epa-us-saw-record-emissions-decline-in-2008.html. (accessed March 12, 2010).

Taylor, H. F. W. 1997. *Cement Chemistry*. 2nd edition. Thomas Telford Publishing, London, U.K. 459 pages.

Tennis, P. D., S. H. Kosmatka. 2004. Cement Characteristics. Chap. 9.1 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Walters, L. J., Jr., M. S. May III, D. E. Johnson, R. S. Macmann, and W. A. Woodward. 1999. Time-variability of NO_x Emissions from Portland Cement Kilns. *Environmental Science & Technology* 33, no. 5:700-704.

Weakley, Richard. 2009. Evaluation of Semi-Adiabatic Calorimetry to Quantify Concrete Setting, M.S. Thesis, Auburn University, Alabama.

Willitsch, F. W., and G. Sturm. 2002. Processing and Handling Alternative Fuels in the Cement Industry. *ZKG International* 55, no. 10:62-69.

WCI. 2010. http://www.worldcoal.org/resources/coal-statistics/. Accessed February 15, 2010. World Coal Institute.

Worrell, E., L. Price, N. Martin, C. Hendriks, and L. O. Meida. 2001. Carbon Dioxide Emissions from the Global Cement Industry. *Annu. Rev. Energy Environ.* 26:303-329.

Worst, F. 2003. Dioxin Emissions When Using Alternative Fuels in the Cement Industry. *ZKG international* 56, no. 4:74-77.

Young, G. L., and F. M. Miller. 2004. Kiln System Operations in Cement Manufacturing. Chap. 3.3 in *Innovations in Portland Cement Manufacturing*. Skokie, Illinois: Portland Cement Association.

Appendix A

Raw Data for the Baseline Burn

A.1 General Comments

- Raw data from the baseline burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal and waste plastics were the fuels utilized during this burn.
- This burn lasted from 4 PM on 6/9/10 to 4 PM on 6/12/10

A.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

[1]As-Received

[2]Dry Basis

A.3 Chemical Composition of Kiln Feed

Table A.1: CPR – Chemical composition of kiln feed for baseline burn

Property (wt. %)	Sample Number						
	1	2	3	4	5	6	7
Al_2O_3	3.18	3.11	3.11	3.14	3.11	3.06	3.10
CaO	42.68	42.54	42.38	42.36	42.45	42.57	42.63
Fe_2O_3	1.92	1.90	1.93	1.91	1.91	1.91	1.91
K_2O	0.30	0.28	0.29	0.29	0.29	0.29	0.30
MgO	2.22	2.28	2.28	2.29	2.31	2.35	2.35
Na_2O	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Na_2O_{eq}	0.25	0.23	0.24	0.24	0.24	0.24	0.25
P_2O_5	NC	NC	NC	NC	NC	NC	NC
SiO_2	13.60	13.50	13.69	13.54	13.55	13.49	13.54
SO_3	0.18	0.14	0.18	0.14	0.14	0.13	0.13
LOI	35.93	35.87	35.75	35.74	35.83	35.98	36.02

A.4 Chemical Composition of Cement Kiln Dust

Table A.2: CPR – Chemical composition of CKD for baseline burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.73	4.07	3.60	3.69	3.63	3.46
CaO	43.50	43.34	44.39	44.02	44.23	44.84
Fe_2O_3	2.14	2.08	1.99	2.02	2.01	1.91
K_2O	0.38	0.40	0.38	0.38	0.38	0.37
MgO	1.40	1.40	1.45	1.46	1.44	1.50
Na_2O	0.09	0.09	0.09	0.09	0.09	0.09
SiO_2	12.31	12.17	11.60	11.82	11.63	11.48
SO_3	0.16	0.19	0.08	0.09	0.08	0.18

Table A.3: ELR – Chemical composition of CKD for baseline burn

Property (wt. %)	**Sample Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	4.11	3.96	3.88	3.89	3.85	3.69
CaO	43.41	43.41	43.96	43.73	43.88	45.22
Fe_2O_3	2.01	2.07	1.93	2.00	1.94	1.83
K_2O	0.36	0.38	0.36	0.37	0.38	0.37
MgO	1.38	1.37	1.45	1.49	1.44	1.57
Na_2O	0.07	0.04	0.06	0.04	0.04	0.05
P_2O_5	0.05	0.04	0.04	0.05	0.04	0.04
SiO_2	12.47	12.07	11.39	11.53	11.37	10.96
SO_3	0.23	0.18	0.15	0.13	0.19	0.37
TiO_2	0.21	0.20	0.18	0.18	0.18	0.17
Moisture	1.36	0.38	0.33	0.39	0.27	0.18
LOI	35.62	36.18	36.52	36.51	36.59	35.66
Property (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	22	18	27	29	36	28
Cd	< 6	< 6	< 6	< 6	< 6	< 6
Cl	588	124	150	150	199	160
Co	13	11	14	8	10	10
Cr	50	46	65	37	54	55
Cu	46	52	38	48	48	35
Hg	0.132	< 0.005	0.016	< 0.005	1.310	0.572
Mo	7	< 5	< 5	5	< 5	8
Ni	19	14	13	20	17	11
Pb	81	93	49	37	5	14
Se	< 2	< 2	< 2	< 2	< 2	< 2
V	62	62	63	61	65	55
Zn	88	104	87	86	78	80

A.5 Chemical Composition of Fuels

Table A.4: ELR – Proximate and ultimate analysis of waste plastics for baseline burn

Test	**Parameter**	**Sample Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Proximate Analysis	**Ash**	9.18	5.44	8.03	9.55	6.51	7.81	4.95	5.36	5.52	5.51	7.62	2.79
	Fixed Carbon	9.59	12.43	10.6	10.57	11.28	4.1	11.3	9.54	16.06	12.4	18.89	8.16
	Moisture [1]	20.63	32.76	25.2	21.92	29.06	20.41	22.62	20.38	14.7	10.48	17.32	1.63
	Volatile Matter	81.23	82.13	81.37	79.88	82.21	88.09	83.75	85.1	78.42	82.09	73.49	89.05
Ultimate Analysis	**Carbon**	58.37	55.74	53.17	55.19	59.26	61.72	56.09	62.85	60.22	49.47	55.31	64.82
	Hydrogen	5.45	6	5.1	5.71	6.12	6.84	5.36	7	4.64	5.32	5.53	6.93
	Nitrogen	1.92	0.97	1.34	1.86	0.67	1.89	0.65	1.97	0.42	0.55	0.14	1.32
	Oxygen	24.81	31.67	32.26	27.52	27.35	21.67	32.82	22.65	29.11	38.98	31.32	23.96
	Sulfur	0.27	0.18	0.1	0.17	0.09	0.07	0.13	0.17	0.09	0.17	0.08	0.18
Heat Value [2] **(BTU/lb)**		13126	13273	13330	10765	9449	11811	10738	13748	11341	9444	10410	13173

Table A.5: ELR – Proximate and ultimate analysis of waste plastics for baseline burn (continued)

Test	Parameter	Sample Number												
		13	14	15	16	17	18	19	20	21	22	23	24	25
Proximate Analysis	Ash	7.78	5.87	7.64	24.96	10.41	5.37	4.37	4.22	3.12	5.31	4.52	3.93	4.77
	Fixed Carbon	4.24	9.87	8.69	12.68	8.1	9.52	8.97	9.21	8.28	8.15	9.35	11.27	11.24
	Moisture [1]	0.93	2.09	1.42	3.18	1.07	2.28	2.17	2.06	1.53	1.88	1.16	2.62	1.8
	Volatile Matter	87.98	84.26	83.67	62.36	81.49	85.11	86.66	86.57	88.6	86.54	86.13	84.8	83.99
Ultimate Analysis	Carbon	56.2	54.47	63.51	41.21	60.53	52.49	55	59.94	59.62	58.06	59.95	59.81	58.34
	Hydrogen	6.4	5.74	6.35	3.99	6.87	5.12	6.12	6.29	6.32	5.35	5.77	7.1	6.49
	Nitrogen	0.26	0.89	0.54	0.19	1.97	0.8	0.5	0.69	0.72	0.49	1.6	0.46	1.24
	Oxygen	29.27	32.87	21.74	29.53	20.1	36	33.83	28.66	30.07	30.67	27.9	28.27	28.89
	Sulfur	0.09	0.16	0.22	0.12	0.12	0.22	0.18	0.2	0.15	0.12	0.26	0.43	0.27
Heat Value [2] (BTU/lb)		12466	10204	11482	8155	12736	10018	11693	11910	10430	10434	11841	10285	11032

Table A.6: ELR – Standard parameters of waste plastics for baseline burn

Test	Parameter (wt. %)	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	9.24	9.83	8.91	41.65	13.41	18.14	11.75	13.11	11.30	18.46	21.09	16.49
	CaO	28.53	15.86	40.00	18.97	22.49	22.88	12.81	22.50	14.98	17.35	11.26	24.80
	Fe_2O_3	4.32	3.04	1.59	2.31	2.37	2.54	7.47	8.15	4.19	3.31	2.02	3.90
	K_2O	1.39	4.84	5.52	3.18	4.12	2.76	1.76	1.45	1.39	4.47	0.66	0.96
	MgO	3.59	5.95	6.71	3.22	6.49	2.94	5.49	1.50	2.44	3.90	3.37	5.78
	Na_2O	2.76	8.95	10.47	6.10	8.79	4.95	2.36	1.53	2.05	8.69	0.49	2.12
	P_2O_5	0.44	0.91	0.71	0.44	0.71	0.87	0.58	0.90	0.77	0.94	0.16	0.62
	SiO_2	40.61	34.39	19.89	18.16	33.33	28.36	47.77	37.30	37.23	34.11	46.14	34.83
	SO_3	4.17	6.37	2.10	2.08	3.98	5.19	3.57	4.99	7.36	3.19	1.86	3.43
	TiO_2	2.24	1.24	1.34	1.97	2.33	4.13	2.77	3.31	2.33	2.83	1.55	4.29
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	< 5	< 5	< 5	14.00	< 5	< 5	23.00	< 5	< 5	< 5	< 100	< 5
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	1749	3053	6206	6203	2673	2029	812	667	572	2158	1200	374
	Co	308	172	65	60	98	93	152	217	208	130	21	729
	Cr	835	353	197	356	218	250	437	2510	596	269	253	476
	Cu	769	416	3620	3740	659	753	8070	612	745	1940	528	1610
	Hg	0.016	0.005	< 0.005	0.011	< 0.005	< 0.005	0.039	0.024	< 0.005	0.009	< 0.005	0.026
	Mo	21	17	< 5	15	19	39	29	102	< 5	< 5	18	13
	Ni	196	106	61	141	93	64	163	1080	199	114	85	164
	Pb	158	101	3450	140	392	298	185	367	991	977	28100	724
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	157	104	58	122	144	320	196	183	23	79	139	182
	Zn	18400	39200	8550	8390	11000	6110	17400	30600	114000	15900	58000	14100

Table A.7: ELR – Standard parameters of waste plastics for baseline burn (continued)

Test	Parameter (wt. %)	Sample Number												
		13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Standard Parameters	**Al_2O_3**	21.37	12.81	33.62	9.97	13.07	12.32	56.28	37.19	31.83	9.10	15.06	8.97	8.85
	CaO	32.18	37.63	26.04	10.97	17.58	25.09	9.59	16.80	17.50	30.10	21.81	28.70	50.62
	Fe_2O_3	1.37	2.05	1.16	5.99	3.25	1.84	0.62	2.62	1.92	5.01	1.93	6.30	4.30
	K_2O	0.35	0.76	0.26	0.51	0.40	0.60	0.27	0.58	0.82	0.46	0.73	0.47	0.57
	MgO	1.61	5.28	1.21	1.06	2.07	2.12	1.86	2.93	4.14	9.64	4.99	9.54	4.28
	Na_2O	0.69	1.48	1.28	0.36	0.83	0.93	1.18	1.92	2.38	1.56	2.07	1.53	0.96
	P_2O_5	0.18	0.41	0.37	0.10	0.26	0.33	0.20	0.40	0.42	0.70	0.60	0.68	0.76
	SiO_2	35.92	35.18	16.38	67.39	56.53	37.85	24.22	32.07	34.18	26.42	26.19	26.18	18.97
	SO_3	0.86	1.18	2.62	0.63	1.67	7.86	2.06	1.16	1.75	4.81	8.42	5.17	3.54
	TiO_2	4.77	2.14	6.60	0.42	1.93	5.46	1.98	3.11	2.96	4.75	4.81	4.13	3.87
	Parameter (ppm)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
	As	< 5	< 5	< 5	263	< 5	< 5	21	< 5	5	19	27	5	8
	Cd	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6	< 6
	Cl	552	275	378	1156	179	175	189	366	463	276	595	289	275
	Co	71	91	58	25	135	307	59	139	159	253	243	179	175
	Cr	242	605	143	630	874	814	286	778	452	4900	1154	3240	3320
	Cu	395	1630	95	3440	527	588	43	397	549	504	963	486	495
	Hg	0.069	0.043	0.028	0.027	0.006	0.030	0.014	0.009	0.008	< 0.005	0.019	0.016	0.026
	Mo	28	42	< 5	21	15	8	6	20	13	146	21	89	134
	Ni	74	227	18	216	220	200	25	147	128	2130	279	1350	1610
	Pb	327	419	197	2150	1000	709	219	350	332	68	161	119	127
	Se	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
	V	233	64	268	30	139	596	97	85	59	281	316	83	225
	Zn	1580	3000	446	11900	6320	10300	992	4000	3430	656	1560	480	693

A.6 Chemical Composition of Clinker

Table A.8: CPR – Chemical composition of clinker for baseline burn

Property (wt. %)	**Sample Number**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Al_2O_3	4.93	4.64	4.72	4.65	4.64	4.63	4.63	4.75	4.57	4.66	4.63	4.85
CaO	63.62	64.29	64.84	65.00	65.08	65.01	65.05	64.76	64.75	64.82	64.66	64.53
Fe_2O_3	3.54	3.29	3.32	3.31	3.26	3.23	3.26	3.35	3.27	3.31	3.35	3.34
K_2O	0.44	0.46	0.45	0.48	0.48	0.48	0.51	0.49	0.49	0.46	0.49	0.42
MgO	3.56	3.48	3.45	3.48	3.41	3.43	3.48	3.49	3.51	3.51	3.53	3.58
Na_2O	0.06	0.07	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.05	0.06	0.05
Na_2O_{eq}	0.35	0.37	0.37	0.39	0.39	0.39	0.41	0.39	0.39	0.35	0.38	0.33
SiO_2	20.80	21.26	21.35	21.45	21.02	21.32	21.36	21.43	21.56	21.62	21.55	21.43
SO_3	1.51	1.11	0.98	0.94	1.10	0.96	0.97	1.03	0.90	0.93	0.89	1.10
F CaO	0.62	0.66	1.04	1.99	3.07	1.83	1.70		1.00	1.04	1.58	1.54
C_3A	7.07	6.73	6.90	6.72	6.78	6.80	6.75	6.92	6.58	6.74	6.59	7.22
C_4AF	10.77	10.01	10.09	10.07	9.92	9.83	9.92	10.19	9.95	10.07	10.19	10.15
C_3S	62.74	64.27	65.22	65.62	69.36	66.90	66.72	64.07	64.36	63.59	63.55	62.44
C_2S	12.31	12.47	12.01	11.99	7.94	10.65	10.91	13.11	13.26	14.00	13.85	14.35

Table A.9: CPR – Chemical composition of clinker for baseline burn (continued)

Property (wt. %)	**Sample Number**												
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Al_2O_3	4.71	4.41	4.70	4.60	4.64	4.65	4.78	4.63	4.60	4.57	4.49	4.57	4.56
CaO	64.45	59.94	64.95	64.85	64.77	64.66	64.13	64.99	64.76	64.99	64.78	64.70	65.16
Fe_2O_3	3.31	3.14	3.29	3.26	3.31	3.40	3.47	3.29	3.31	3.33	3.26	3.26	3.24
K_2O	0.46	0.43	0.46	0.48	0.49	0.49	0.51	0.48	0.48	0.48	0.48	0.49	0.49
MgO	3.61	3.15	3.55	3.60	3.63	3.65	3.61	3.65	3.65	3.67	3.70	3.69	3.69
Na_2O	0.06	0.03	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.05	0.05	0.06	0.05
Na_2O_{eq}	0.36	0.31	0.36	0.37	0.38	0.38	0.39	0.37	0.37	0.37	0.37	0.37	0.37
SiO_2	21.55	19.88	21.50	21.55	21.54	21.46	21.25	21.33	21.53	21.48	21.56	21.56	21.54
SO_3	1.01	0.87	0.86	0.87	0.93	1.04	1.49	1.02	0.91	0.67	1.03	0.96	0.71
F CaO	0.71	0.87	0.66	0.79	0.62	0.62	1.78	2.41	1.66	1.70	0.75	0.83	1.70
C_3A	6.87	6.37	6.90	6.69	6.71	6.57	6.79	6.70	6.60	6.47	6.39	6.61	6.60
C_4AF	10.08	9.56	10.01	9.90	10.06	10.35	10.56	10.01	10.07	10.13	9.92	9.91	9.87
C_3S	62.26	58.81	64.69	64.63	64.07	64.04	62.52	66.65	64.36	65.86	65.02	64.17	66.27
C_2S	14.81	12.63	12.85	13.04	13.41	13.20	13.75	10.88	13.17	11.90	12.76	13.40	11.77

Table A.10: ELR – Chemical composition of clinker for baseline burn

Property (wt. %)	**Sample Number**			
	1	**2**	**3**	**4**
Al_2O_3	4.97	32.34	5.03	4.97
CaO	64.25	0.37	63.87	64.20
Fe_2O_3	3.33	1.13	3.35	3.29
K_2O	0.41	1.86	0.42	0.44
MgO	3.57	0.45	3.69	3.68
Na_2O	0.06	0.21	0.06	0.05
P_2O_5	0.05	0.03	0.05	0.05
SiO_2	21.89	62.55	22.21	21.66
SO_3	0.94	0.05	0.79	1.06
TiO_2	0.23	0.66	0.24	0.23
Moisture	0.03	0.02	0.01	0.02
LOI	0.15	0.25	0.18	0.25
Property (ppm)	**1**	**2**	**3**	**4**
As	52	34	39	41
Cd	< 6	< 6	< 6	< 6
Cl	138	315	178	97
Co	9	14	15	11
Cr	53	56	50	35
Cu	91	42	39	34
Hg	0.294	0.080	0.032	< 0.005
Mo	14	< 5	8	< 5
Ni	15	14	16	14
Pb	< 5	48	14	32
Se	< 2	< 2	< 2	< 2
V	52	51	57	56
Zn	87	99	65	82

Table A.11: SLR – Rietveld analysis of clinker in baseline burn

Property	**Sample Number**			
	1	**2**	**3**	**4**
Alite (C_3S)	59.51	59.55	60.81	57.13
Belite (C_2S)	23.56	22.39	21.63	24.09
Ferrite (C_4AF)	9.93	10.43	10.58	10.50
Aluminate (C_3A)	3.11	3.22	3.31	2.47

A.7 Chemical Composition of Cement

Table A.12: CPR – Chemical composition of cement for baseline burn

Property (wt. %)	**Sample Number**				
	1	**2**	**3**	**4**	**5**
Al_2O_3	4.60	4.54	4.46	4.47	4.47
CaO	62.62	62.73	62.85	62.81	62.76
Fe_2O_3	3.17	3.14	3.09	3.06	3.08
K_2O	0.41	0.42	0.46	0.43	0.44
MgO	3.44	3.49	3.48	3.42	3.37
Na_2O	0.07	0.06	0.07	0.07	0.07
Na_2O_{eq}	0.34	0.34	0.37	0.35	0.36
SiO_2	19.78	20.01	19.89	19.96	20.01
SO_3	3.40	3.01	3.18	3.11	3.21
F CaO	0.83	NC	1.58	NC	1.20
LOI	2.10	2.44	2.62	2.73	2.63
C_3A	6.85	6.72	6.61	6.68	6.65
C_4AF	9.64	9.57	9.40	9.32	9.37
C_3S	52.66	52.93	54.51	53.95	53.07
C_2S	16.99	17.45	15.89	16.53	17.33
Blaine SSA (m^2/kg)	388	383	388	384	393

Table A.13: ELR – Chemical composition of cement for baseline burn

Property (wt. %)	Sample Number	
	1	2
Al_2O_3	4.65	4.62
CaO	62.43	62.33
Fe_2O_3	3.11	3.05
K_2O	0.40	0.35
MgO	3.48	3.42
Na_2O	0.04	0.06
P_2O_5	0.05	0.06
SiO_2	20.06	20.05
SO_3	2.95	3.11
TiO_2	0.21	0.21
Moisture	0.10	0.13
LOI	2.48	2.61
Property (ppm)	**1**	**2**
As	34	51
Cd	< 6	< 6
Cl	271	575
Co	11	9
Cr	53	61
Cu	16	40
Hg	< 0.005	< 0.005
Mo	5	5
Ni	11	15
Pb	< 5	< 5
Se	< 2	< 2
V	57	59
Zn	80	110

Table A.14: SLR – Rietveld analysis of cement for baseline burn

Property (wt. %)	**Sample Number**	
	1	**2**
Alite (C_3S)	53.40	53.39
Belite (C_2S)	26.12	23.25
Ferrite (C_4AF)	10.85	9.84
Aluminate (C_3A)	4.50	3.31

A.8 Plant Emissions

Table A.15: CPR – Normalized plant emissions for baseline burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
6/9/10 16:00	7.32E-04	2.30E-05	2.73E-05	4.11E-04
6/9/10 17:00	7.46E-04	2.35E-05	2.48E-05	3.86E-04
6/9/10 18:00	7.93E-04	1.98E-05	3.24E-05	3.79E-04
6/9/10 19:00	7.92E-04	1.98E-05	2.99E-05	3.37E-04
6/9/10 20:00	8.18E-04	2.09E-05	2.94E-05	3.30E-04
6/9/10 21:00	8.53E-04	1.95E-05	3.19E-05	3.38E-04
6/9/10 22:00	8.28E-04	2.02E-05	3.19E-05	3.31E-04
6/9/10 23:00	7.76E-04	2.02E-05	2.87E-05	3.21E-04
6/10/10 0:00	8.35E-04	1.92E-05	3.29E-05	3.38E-04
6/10/10 1:00	8.95E-04	2.58E-05	3.30E-05	3.77E-04
6/10/10 2:00	8.25E-04	2.03E-05	3.20E-05	3.81E-04
6/10/10 3:00	9.14E-04	1.73E-05	3.68E-05	3.64E-04
6/10/10 4:00	1.03E-03	1.20E-05	4.08E-05	3.68E-04
6/10/10 5:00	9.94E-04	1.21E-05	4.08E-05	3.62E-04
6/10/10 6:00	1.04E-03	1.25E-05	3.36E-05	3.92E-04
6/10/10 7:00	9.92E-04	1.76E-05	3.85E-05	4.25E-04
6/10/10 8:00	8.63E-04	4.30E-06	3.16E-05	2.85E-04
6/10/10 9:00	8.19E-04	4.87E-06	3.27E-05	-
6/10/10 10:00	1.05E-03	5.65E-06	3.17E-05	-
6/10/10 11:00	1.06E-03	5.70E-06	3.39E-05	4.12E-04
6/10/10 12:00	9.70E-04	5.31E-06	3.43E-05	3.75E-04
6/10/10 13:00	8.78E-04	5.20E-06	3.43E-05	3.55E-04
6/10/10 14:00	8.85E-04	5.94E-06	3.33E-05	3.48E-04
6/10/10 15:00	8.03E-04	4.75E-06	3.41E-05	3.86E-04
6/10/10 16:00	6.98E-04	1.06E-05	3.12E-05	4.80E-04
6/10/10 17:00	9.61E-04	1.34E-05	3.01E-05	4.69E-04
6/10/10 18:00	9.96E-04	1.30E-05	4.00E-05	3.76E-04
6/10/10 19:00	8.75E-04	1.09E-05	4.29E-05	3.54E-04
6/10/10 20:00	9.56E-04	9.64E-06	3.82E-05	3.86E-04
6/10/10 21:00	8.67E-04	1.12E-05	3.80E-05	4.08E-04
6/10/10 22:00	7.65E-04	1.36E-05	3.64E-05	4.91E-04
6/10/10 23:00	7.24E-04	1.35E-05	3.56E-05	4.67E-04
6/11/10 0:00	9.02E-04	1.06E-05	3.38E-05	4.70E-04
6/11/10 1:00	9.60E-04	9.24E-06	3.01E-05	3.90E-04
6/11/10 2:00	8.53E-04	8.65E-06	3.62E-05	4.10E-04

Table A.16: CPR – Normalized plant emissions for baseline burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
6/11/10 3:00	8.09E-04	1.00E-05	3.73E-05	4.19E-04
6/11/10 4:00	9.23E-04	1.14E-05	3.65E-05	4.18E-04
6/11/10 5:00	1.13E-03	1.04E-05	3.60E-05	4.10E-04
6/11/10 6:00	1.02E-03	1.05E-05	5.59E-05	4.17E-04
6/11/10 7:00	9.34E-04	9.75E-06	-	3.90E-04
6/11/10 8:00	8.54E-04	4.94E-06	-	-
6/11/10 9:00	8.81E-04	4.65E-06	-	-
6/11/10 10:00	1.01E-03	4.21E-06	5.61E-05	2.76E-04
6/11/10 11:00	1.06E-03	3.37E-06	5.42E-05	3.99E-04
6/11/10 12:00	1.11E-03	2.45E-06	5.47E-05	4.41E-04
6/11/10 13:00	1.05E-03	3.02E-06	5.31E-05	4.29E-04
6/11/10 14:00	9.41E-04	4.16E-06	5.02E-05	4.00E-04
6/11/10 15:00	1.04E-03	5.08E-06	5.02E-05	4.56E-04
6/11/10 16:00	1.01E-03	2.97E-06	4.98E-05	4.89E-04
6/11/10 17:00	9.99E-04	3.64E-06	5.58E-05	3.99E-04
6/11/10 18:00	9.21E-04	4.29E-06	5.39E-05	3.40E-04
6/11/10 19:00	1.00E-03	6.03E-06	5.59E-05	3.40E-04
6/11/10 20:00	8.31E-04	5.83E-06	5.51E-05	3.47E-04
6/11/10 21:00	7.21E-04	5.66E-06	5.59E-05	3.48E-04
6/11/10 22:00	6.55E-04	3.82E-06	5.07E-05	3.57E-04
6/11/10 23:00	6.32E-04	5.13E-06	5.18E-05	3.62E-04
6/12/10 0:00	8.08E-04	3.80E-06	5.07E-05	3.79E-04
6/12/10 1:00	9.05E-04	3.17E-06	4.91E-05	3.77E-04
6/12/10 2:00	9.91E-04	4.33E-06	5.60E-05	3.54E-04
6/12/10 3:00	8.89E-04	3.46E-06	5.69E-05	3.70E-04
6/12/10 4:00	9.58E-04	3.72E-06	5.76E-05	3.91E-04
6/12/10 5:00	1.15E-03	4.81E-06	6.10E-05	4.05E-04
6/12/10 6:00	9.20E-04	4.04E-06	5.22E-05	4.12E-04
6/12/10 7:00	1.10E-03	5.91E-06	5.18E-05	4.18E-04
6/12/10 8:00	1.16E-03	7.88E-06	5.39E-05	4.22E-04
6/12/10 9:00	1.30E-03	7.23E-06	5.94E-05	3.68E-04
6/12/10 10:00	1.39E-03	9.70E-06	5.82E-05	3.89E-04
6/12/10 11:00	1.26E-03	7.19E-06	5.10E-05	4.30E-04
6/12/10 12:00	1.37E-03	8.09E-06	5.62E-05	3.91E-04
6/12/10 13:00	1.33E-03	7.31E-06	5.47E-05	3.40E-04
6/12/10 14:00	1.22E-03	7.24E-06	5.26E-05	3.03E-04
6/12/10 15:00	1.18E-03	7.40E-06	3.02E-05	3.59E-04
6/12/10 16:00	1.26E-03	8.12E-06	3.30E-05	3.67E-04

Appendix B

Raw Data for the Construction and Demolition Burn

B.1 General Comments

- Raw data from the construction and demolition burn (C&D) are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, waste plastics, and construction and demolition waste were the fuels utilized during this burn.
- This burn lasted from 11 PM on 7/6/10 to 7 AM on 7/10/10

B.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

^{1}As-Received

^{2}Dry Basis

B.3 Chemical Composition of Kiln Feed

Table B.1: CPR – Chemical composition of kiln feed for C&D burn

Property (wt. %)	Sample Number						
	1	2	3	4	5	6	7
Al_2O_3	3.38	3.26	3.28	3.16	3.24	3.30	3.38
CaO	43.51	43.24	43.28	42.70	43.37	43.30	43.50
Fe_2O_3	1.86	1.86	1.83	1.78	1.80	1.90	1.86
K_2O	0.34	0.34	0.35	0.34	0.35	0.35	0.36
MgO	1.96	2.01	2.04	2.10	2.06	2.06	2.00
Na_2O	0.05	0.05	0.05	0.04	0.05	0.05	0.05
Na_2O_{eq}	0.27	0.27	0.28		0.28	0.28	0.29
P_2O_5	NC	NC	NC	NC	NC	NC	NC
SiO_2	13.39	13.42	13.37	13.03	13.23	13.52	13.40
SO_3	0.26	0.19	0.23	0.16	0.22	0.21	0.22
LOI	36.29	36.13	36.19	36.45	36.29	36.23	36.32

B.4 Chemical Composition of Cement Kiln Dust

Table B.2: CPR – Chemical composition of CKD for C&D burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.48	3.41	3.8	3.51	3.36	3.75
CaO	45.96	48.01	43.93	47.19	49.36	46.4
Fe_2O_3	1.74	1.76	1.9	1.82	1.73	1.84
K_2O	0.41	0.42	0.43	0.43	0.44	0.43
MgO	1.33	1.61	1.31	1.58	1.61	1.56
Na_2O	0.09	0.09	0.09	0.1	0.1	0.09
SiO_2	10.85	10.57	11.69	10.8	10.25	11.57
SO_3	0.33	1.24	0.17	1.04	2.04	0.99

Table B.3: ELR – Chemical composition of CKD for C&D burn

Property (wt. %)	**Sample Number**				
	1	**2**	**3**	**4**	**5**
Al_2O_3	3.97	4.07	2.83	4.07	3.99
CaO	44.72	47.00	40.49	47.87	49.88
Fe_2O_3	1.67	1.84	1.82	1.90	1.91
K_2O	0.35	0.41	0.20	0.41	0.45
MgO	1.40	1.56	1.86	1.59	1.57
Na_2O	0.06	0.05	0.07	0.06	0.06
P_2O_5	0.05	0.05	0.44	0.05	0.05
SiO_2	10.74	10.95	13.16	10.98	10.62
SO_3	0.30	1.00	0.96	0.90	1.70
TiO_2	0.16	0.17	0.13	0.16	0.17
Moisture	0.26	0.15	0.27	0.14	0.05
LOI	36.50	32.81	37.89	31.92	29.54
Property (ppm)	**1**	**2**	**3**	**4**	**5**
As	32	34	6	52	65
Cd	< 6	< 6	< 6	< 6	< 6
Cl	95	134	96	133	370
Co	16	19	6	14	20
Cr	66	73	192	49	58
Cu	31	32	18	18	< 5
Hg	0.04	0.04	0.04	0.03	0.09
Mo	< 5	< 5	< 5	< 5	< 5
Ni	23	25	24	26	26
Pb	18	14	30	25	< 5
Se	< 2	< 2	< 2	< 2	< 2
V	59	45	123	44	56
Zn	64	76	93	68	84

B.5 Chemical Composition of Fuels

Table B.4: ELR – Proximate and ultimate analysis of plastic waste for C&D burn

Test	Parameter	Sample Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Proximate Analysis	**Ash**	2.29	2.05	8.93	4.76	2.57	6.32	4.4	4.11	5.9	11.34	7.63	3.72
	Fixed Carbon	12.55	10.73	10.02	9.59	8.95	11.25	10.49	12.04	11.22	9.42	11.36	10.44
	Moisture [1]	4.6	3.72	1.75	3.86	1.57	4.58	2.54	3.65	2.75	3.55	1.96	1.87
	Volatile Matter	85.16	87.22	81.05	85.65	88.48	82.43	85.11	83.85	82.88	79.24	81.01	85.84
Ultimate Analysis	**Carbon**	45.97	52	54.91	51.51	69.43	48.18	50.31	45.48	49.95	47.85	48.86	32.53
	Hydrogen	4.95	5.8	5.24	5.7	8.43	5.2	5.27	4.83	5.09	5.24	5.34	4.05
	Nitrogen	0.02	0.08	1.5	0.01	0.18	0.01	0.17	0.17	0.35	0.01	0.08	0.54
	Oxygen	46.54	39.77	29.25	37.76	19.24	40.07	39.61	45.18	38.54	35.42	37.89	58.95
	Sulfur	0.23	0.3	0.17	0.26	0.15	0.22	0.24	0.23	0.17	0.14	0.2	0.21
Heat Value [2] (BTU/lb)		7318	8846	8946	8759	13465	8206	9674	7661	9723	8438	8087	10126

Table B.5: ELR – Proximate and ultimate analysis of plastic waste for C&D burn (continued)

Test	Parameter	Sample Number										
		13	14	15	16	17	18	19	20	21	22	23
Proximate Analysis	Ash	4.78	7.56	3.4	7.44	7.52	5.84	9.17	9.58	7.14	2.66	5.01
	Fixed Carbon	9.46	10.16	8.49	7.73	5.73	13.53	8.19	9.18	9.67	11.95	10.14
	Moisture [1]	2.01	2.31	2.49	1.7	1.06	2.18	3.27	2.56	3.11	3.98	1.93
	Volatile Matter	85.76	82.28	88.11	84.83	86.75	80.63	82.64	81.24	83.19	85.39	84.85
Ultimate Analysis	Carbon	51.54	50.52	49.09	52.84	58.81	61.02	55.8	48.31	43.54	55.92	49.28
	Hydrogen	5.18	5.18	4.45	6.32	5.43	6.02	4.73	5.29	4.69	5.96	5.4
	Nitrogen	0.96	0.03	0.81	0.46	1.69	2.54	1.58	1.5	0.64	0.01	0.1
	Oxygen	37.32	36.54	42.02	32.8	26.48	24.33	28.56	35.13	43.81	35.25	40.05
	Sulfur	0.22	0.17	0.23	0.14	0.07	0.25	0.16	0.19	0.18	0.2	0.16
Heat Value [2] (BTU/lb)		10075	9564	10492	10094	8549	87	8774	8950	8311	8694	10915

Table B.6: ELR – Proximate and ultimate analysis of C&D waste for C&D burn

Test	Parameter	Sample Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Proximate Analysis	Ash	7.85	35.08	19.1	18.79	21.31	15.97	2.6	16.43	13.99	18.53	16.24	12.29
	Fixed Carbon	18.31	12.54	16.5	15.96	15.76	16.4	18.15	15.33	15.36	15.12	14.25	16.9
	Moisture [1]	5.19	4.45	5.67	45.55	37.69	31.11	4.73	4.78	37.78	43	33.45	44.37
	Volatile Matter	73.84	52.38	64.4	65.25	62.93	67.63	79.25	68.24	70.65	66.35	69.51	70.81
Ultimate Analysis	Carbon	48.2	32.13	42.72	40.81	41.45	45.2	52.53	46.1	46.11	43.46	45.27	47.17
	Hydrogen	5.32	3.82	4.92	4.62	4.68	5.06	5.6	5.11	4.96	4.79	5.19	5.14
	Nitrogen	1.03	1.19	1.94	1.49	1.54	0.96	0.57	1.25	1.11	1.21	1.46	0.64
	Oxygen	37.49	27.65	31.1	34.21	30.92	32.71	38.57	30.9	33.77	31.96	31.7	34.72
	Sulfur	0.11	0.13	0.22	0.08	0.1	0.1	0.13	0.21	0.06	0.05	0.14	0.04
Heat Value [2] (BTU/lb)		7462	5200	6521	3668	4134	5139	7962	6708	4761	4075	5029	4237

Table B.7: ELR – Proximate and ultimate analysis of C&D waste for C&D burn (continued)

Test	Parameter	Sample Number										
		13	14	15	16	17	18	19	20	21	22	23
Proximate Analysis	**Ash**	12.54	13.13	14.77	11.99	12.88	17.52	15.47	13.99	14.69	4.68	3.19
	Fixed Carbon	14.31	15.77	15.75	15.55	18.63	16.39	15.52	16.84	15.84	16.89	18.28
	Moisture [1]	47.27	38.7	4.31	4.05	4.86	4.16	4	3.99	5.09	4.43	5.61
	Volatile Matter	73.15	71.1	69.48	72.46	68.49	66.09	69.01	69.17	69.47	78.43	78.53
Ultimate Analysis	**Carbon**	46.4	45.94	45.46	46.8	45.34	44.45	44.22	45.62	42.15	51.43	50.8
	Hydrogen	5.06	5.04	5.03	5.15	5.01	4.89	5.04	5.15	4.73	5.73	5.69
	Nitrogen	0.75	0.6	0.96	1.17	1.01	0.78	1.08	1.45	0.92	0.63	0.96
	Oxygen	35.21	35.23	33.64	34.7	35.62	32.22	33.98	33.63	37.39	37.42	39.29
	Sulfur	0.04	0.06	0.14	0.19	0.14	0.14	0.21	0.16	0.12	0.11	0.07
Heat Value [2] **(BTU/lb)**		3833	4536	7008	7358	8175	6915	7024	7088	6893	7872	7605

Table B.8: ELR – Chemical composition of plastic waste for C&D burn

Test	Parameter (wt. %)	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	10.56	21.19	29.23	50.49	44.06	60.01	59.14	22.34	63.17	63.22	27.97	34.88
	CaO	12.06	11.01	56.71	16.90	11.87	8.71	9.50	4.57	12.68	14.02	27.00	19.60
	Fe_2O_3	0.75	1.23	0.44	0.56	1.73	0.16	0.28	0.83	0.26	0.10	1.18	1.70
	K_2O	10.39	4.07	0.22	0.25	1.04	0.26	0.28	0.49	0.48	0.25	0.23	1.37
	MgO	13.55	14.04	1.80	4.22	3.40	4.32	5.20	15.71	1.35	1.82	12.88	4.50
	Na_2O	9.12	4.13	0.79	1.79	1.60	1.88	1.81	1.85	1.62	1.67	1.03	2.43
	P_2O_5	2.43	1.88	0.15	0.21	0.38	0.19	0.39	0.65	0.25	0.15	0.19	0.44
	SiO_2	38.29	37.23	8.71	22.54	32.84	22.88	21.86	51.46	18.38	16.66	25.62	29.92
	SO_3	2.11	2.31	0.48	0.69	0.93	0.52	0.18	1.20	0.28	0.19	0.67	1.17
	TiO_2	0.37	2.33	1.24	2.15	1.79	0.91	1.18	0.67	1.42	0.89	2.97	3.43
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	22	5	11	13	5	7	12	12	10	7	14	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	235	271	312	202	218	205	229	219	154	122	149	361
	Co	50	69	52	38	9	15	83	16	13	6	54	161
	Cr	71	117	156	122	804	53	103	110	204	51	459	343
	Cu	373	1240	298	188	5	5	5	108	5	5	112	345
	Hg	0.005	0.006	0.006	0.015	0.008	0.023	0.019	0.037	0.023	0.005	0.005	0.005
	Mo	15	54	5	11	5	11	22	5	24	5	6	42
	Ni	59	72	35	23	786	3	3	42	251	3	163	146
	Pb	204	316	54	74	460	43	156	162	77	14	80	196
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	5	5	30	100	5	36	47	5	65	68	161	220
	Zn	1515	1905	229	313	882	124	141	652	181	73	364	1231

Table B.9: ELR – Chemical composition of plastic waste for C&D burn (continued)

Test	**Parameter (wt. %)**	**Sample Number**										
		13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Standard Parameters	Al_2O_3	16.85	25.10	2.24	1.80	4.00	7.38	5.83	29.58	55.40	16.31	44.80
	CaO	59.61	51.10	70.87	68.08	59.95	36.71	60.50	36.28	18.47	16.22	34.15
	Fe_2O_3	0.92	0.52	1.15	1.15	2.14	2.86	1.14	0.69	0.38	3.69	1.12
	K_2O	0.41	0.42	0.18	0.23	0.78	1.18	0.25	0.44	0.48	11.33	0.51
	MgO	4.18	8.19	17.49	14.94	18.48	6.32	21.07	9.03	4.08	9.63	2.24
	Na_2O	1.08	0.84	0.54	4.02	0.58	7.69	1.29	1.22	1.26	1.89	1.24
	P_2O_5	0.24	0.23	0.05	0.39	0.25	0.68	0.12	0.21	0.24	2.94	0.56
	SiO_2	13.17	11.60	3.79	6.05	10.13	29.31	7.47	17.81	18.08	33.88	11.94
	SO_3	0.69	0.49	0.66	0.79	2.05	5.78	0.74	0.90	0.10	1.12	0.74
	TiO_2	2.50	1.26	2.47	2.02	0.69	1.62	0.97	2.81	1.35	1.22	2.26
	Parameter (ppm)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	As	5	5	5	5	5	13	5	5	13	6	16
	Cd	6	6	6	6	6	6	6	6	6	6	6
	Cl	265	316	202	350	157	322	94	192	136	201	154
	Co	70	52	96	162	126	54	74	32	6	99	117
	Cr	152	131	171	397	292	231	171	132	163	202	292
	Cu	278	5	782	434	490	219	250	16	6	1911	211
	Hg	0.005	0.01	0.005	0.005	0.012	0.082	0.08	0.073	0.104	0.005	0.092
	Mo	5	12	5	5	5	9	5	25	21	5	5
	Ni	88	18	112	49	44	60	20	3	25	138	36
	Pb	156	63	118	148	65	60	79	160	81	554	59
	Se	2	2	2	2	2	2	2	2	2	2	2
	V	80	57	35	5	5	90	27	119	68	5	92
	Zn	637	297	374	437	235	760	823	899	116	7038	499

Table B.10: ELR – Chemical composition of C&D waste for C&D burn

Test	**Parameter (wt. %)**	**Sample Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	13.32	14.70	12.48	11.40	10.31	12.13	11.80	10.81	10.59	11.69	16.40	11.61
	CaO	8.84	6.46	6.79	6.08	12.28	10.84	16.11	11.38	16.49	14.98	14.15	11.12
	Fe_2O_3	5.10	6.07	5.23	5.16	3.37	4.44	4.42	4.75	4.84	4.91	5.19	4.86
	K_2O	3.30	2.16	2.78	2.48	2.10	2.33	4.13	2.49	2.85	2.81	3.44	2.99
	MgO	2.14	2.17	1.38	1.10	1.68	1.93	2.51	1.40	1.75	2.03	2.30	1.70
	Na_2O	2.74	2.33	2.13	1.98	1.75	2.43	3.57	1.78	2.02	1.92	3.64	2.42
	P_2O_5	0.59	0.24	0.30	0.26	0.26	0.44	3.15	0.89	0.65	0.41	0.58	0.78
	SiO_2	58.15	59.84	64.70	67.98	65.45	61.22	47.11	62.04	56.83	57.60	48.80	60.99
	SO_3	4.55	1.42	3.10	2.46	2.00	3.13	5.86	3.45	2.58	2.65	3.64	2.36
	TiO_2	0.65	0.56	0.74	0.62	0.50	0.65	0.49	0.67	0.90	0.62	0.93	0.71
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	185	10	26	131	28	13	5	7	163	10	5	7
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	538	792	1169	1285	1174	675	257	655	891	919	2721	594
	Co	23	26	19	23	9	48	46	20	25	21	30	21
	Cr	692	606	347	371	350	332	1011	339	583	303	221	400
	Cu	1258	97	256	285	141	267	773	211	745	269	212	557
	Hg	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.011	0.005	0.005	0.005	0.005
	Mo	5	10	5	10	9	9	16	9	10	5	16	13
	Ni	238	156	144	117	132	135	429	152	134	115	88	167
	Pb	155	51	53	64	31	75	158	261	114	81	100	117
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	23	93	86	78	61	62	11	81	85	60	102	73
	Zn	433	30869	626	1714	594	1356	964	368	670	568	2985	629

Table B.11: ELR – Chemical composition of C&D waste for C&D burn (continued)

Test	**Parameter (wt. %)**	**Sample Number**										
		13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Standard Parameters	**Al_2O_3**	10.20	8.40	12.54	10.88	11.13	13.35	12.04	11.23	9.57	11.72	12.19
	CaO	23.14	14.80	16.93	21.93	15.74	9.28	10.80	14.54	16.68	14.56	14.28
	Fe_2O_3	4.51	4.24	5.17	4.24	5.00	5.20	4.35	4.80	8.20	4.91	5.82
	K_2O	2.44	2.13	2.58	2.34	2.65	3.26	2.40	2.51	2.19	2.79	3.60
	MgO	1.83	1.42	2.39	2.41	1.78	1.68	1.66	1.71	2.04	2.21	2.42
	Na_2O	1.59	1.59	1.65	1.44	1.65	1.92	1.61	1.81	1.73	2.89	3.82
	P_2O_5	0.64	0.60	0.67	0.66	0.58	0.46	0.53	0.44	0.60	0.75	1.18
	SiO_2	51.92	62.93	53.89	49.83	56.72	61.15	63.34	58.87	54.91	54.56	52.14
	SO_3	2.73	2.81	2.99	4.15	3.23	2.63	2.33	2.99	2.55	4.44	3.21
	TiO_2	0.62	0.67	0.70	1.71	0.98	0.67	0.58	0.67	0.68	0.58	0.66
	Parameter (ppm)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
	As	12	7	22	16	12	5	15	147	19	5	25
	Cd	6	6	6	6	6	6	6	6	6	6	6
	Cl	406	349	575	358	1486	472	429	623	708	357	412
	Co	18	18	6	42	26	23	15	22	53	22	34
	Cr	561	574	708	309	324	326	311	451	386	406	580
	Cu	307	454	385	234	402	135	202	251	688	801	206
	Hg	0.005	0.005	0.005	0.005	0.005	0.005	0.203	0.025	0.005	0.008	0.005
	Mo	8	5	59	5	15	15	5	10	22	26	62
	Ni	132	203	295	125	153	142	126	128	164	210	204
	Pb	83	79	166	123	64	80	63	61	168	228	115
	Se	2	2	2	2	2	2	2	2	2	2	2
	V	61	64	5	130	93	69	66	76	71	5	5
	Zn	373	333	600	403	377	419	345	846	2487	489	746

B.6 Chemical Composition of Clinker

Table B.12: CPR – Chemical composition of clinker for C&D burn

Property (wt. %)	Sample Number														
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Al_2O_3	5.00	4.96	4.97	5.23	5.12	5.11	5.07	4.97	4.74	4.99	4.83	4.90	5.05	4.98	5.17
CaO	65.02	64.49	64.79	64.34	64.61	64.70	64.75	65.02	65.17	64.87	65.39	65.25	64.80	65.00	64.23
Fe_2O_3	3.47	3.40	3.47	3.41	3.44	3.42	3.45	3.43	3.35	3.35	3.26	3.25	3.26	3.29	3.17
K_2O	0.46	0.56	0.52	0.53	0.55	0.55	0.57	0.52	0.49	0.54	0.49	0.51	0.57	0.51	0.66
MgO	3.06	2.96	3.02	3.08	3.10	3.07	3.05	3.05	2.98	2.98	3.04	3.10	3.04	3.06	2.88
Na_2O	0.06	0.06	0.06	0.07	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.06
Na_2O_{eq}	0.36	0.43	0.40	0.42	0.42	0.42	0.44	0.39	0.37	0.41	0.37	0.39	0.44	0.39	0.49
SiO_2	20.80	20.57	20.90	20.62	20.56	20.39	20.27	20.67	20.79	20.72	21.08	20.93	20.99	20.97	20.36
SO_3	1.34	1.54	1.31	1.70	1.71	1.81	1.78	1.57	1.28	1.36	1.04	0.90	1.07	0.74	2.15
F CaO	1.78	2.28	1.58	1.08	0.95	1.33	1.49	1.04	1.37	3.11	1.45	1.58	1.83	1.25	4.95
C_3A	7.40	7.39	7.31	8.09	7.75	7.75	7.60	7.36	6.89	7.56	7.29	7.49	7.87	7.63	8.34
C_4AF	10.54	10.35	10.56	10.38	10.47	10.41	10.50	10.45	10.19	10.19	9.91	9.89	9.92	10.01	9.65
C_3S	68.04	68.02	66.52	65.20	67.46	69.21	70.55	69.33	70.67	68.30	68.86	69.00	65.69	67.08	67.48
C_2S	8.31	7.66	9.75	9.93	8.06	6.25	4.89	6.95	6.29	7.88	8.50	7.95	10.62	9.51	7.47

Table B.13: CPR – Chemical composition of clinker for C&D burn (continued)

Property (wt. %)	**Sample Number**															
	16	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**
Al_2O_3	5.14	5.11	5.04	5.09	5.04	5.04	5.11	5.11	5.13	5.06	4.96	4.98	4.97	5.13	5.18	5.28
CaO	65.19	64.73	65.01	64.98	65.13	65.15	64.89	64.43	64.60	64.63	65.00	64.75	64.98	65.01	65.02	64.91
Fe_2O_3	3.24	3.22	3.19	3.21	3.18	3.22	3.27	3.30	3.29	3.29	3.25	3.26	3.25	3.36	3.22	3.23
K_2O	0.55	0.58	0.57	0.58	0.58	0.54	0.55	0.57	0.59	0.55	0.59	0.61	0.58	0.56	0.60	0.61
MgO	3.13	3.11	3.08	3.03	3.07	3.10	3.06	3.10	3.13	3.15	3.10	3.10	3.13	3.08	3.06	3.05
Na_2O	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.05	0.06	0.06	0.07	0.06	0.06	0.06
Na_2O_{eq}	0.41	0.44	0.44	0.44	0.44	0.42	0.42	0.43	0.45	0.41	0.45	0.46	0.45	0.43	0.45	0.46
SiO_2	20.98	21.00	21.05	20.93	21.02	20.94	21.11	21.17	21.04	21.15	20.96	20.93	21.08	21.06	21.06	21.10
SO_3	0.52	1.05	0.96	0.93	0.99	0.78	0.89	0.97	0.93	0.89	0.95	1.10	1.10	0.72	0.77	0.72
F CaO	3.20	1.37	1.12	1.29	1.70	1.58	1.12	1.20	1.45	1.20	2.20	NC	1.16	1.49	1.78	3.07
C_3A	8.14	8.09	7.96	8.06	7.98	7.91	8.01	7.96	8.03	7.84	7.65	7.68	7.68	7.91	8.28	8.53
C_4AF	9.86	9.80	9.71	9.77	9.68	9.80	9.95	10.04	10.01	10.01	9.89	9.92	9.89	10.22	9.80	9.84
C_3S	66.78	64.98	66.26	66.68	66.99	67.62	64.73	62.35	63.91	63.67	67.35	66.41	66.25	65.33	65.24	63.78
C_2S	9.77	11.18	10.37	9.70	9.73	9.02	11.69	13.65	12.10	12.60	9.28	9.91	10.46	11.09	11.16	12.37

Table B.14: ELR – Chemical composition of clinker for C&D burn

Property (wt. %)	**Sample Number**		
	1	**2**	**3**
Al_2O_3	5.06	5.30	5.25
CaO	63.56	64.86	64.94
Fe_2O_3	3.48	3.28	3.30
K_2O	0.47	0.56	0.51
MgO	3.16	3.24	3.26
Na_2O	0.07	0.06	0.07
P_2O_5	0.06	0.06	0.07
SiO_2	20.29	21.00	21.30
SO_3	1.30	1.05	0.81
TiO_2	0.24	0.24	0.22
Moisture	0.00	0.01	0.01
LOI	2.18	0.19	0.13
Property (ppm)	**1**	**2**	**3**
As	46	31	15
Cd	< 6	< 6	< 6
Cl	92	121	208
Co	17	8	7
Cr	86	60	62
Cu	8	24	< 5
Hg	0.105	< 0.005	0.017
Mo	< 5	< 5	< 5
Ni	17	19	22
Pb	14	29	99
Se	< 2	< 2	< 2
V	40	48	49
Zn	78	97	57

Table B.15: SLR – Rietveld analysis of clinker for C&D burn

Property	**Sample Number**		
	1	**2**	**3**
Alite (C_3S)	56.98	53.40	56.55
Belite (C_2S)	24.56	26.12	23.73
Ferrite (C_4AF)	11.16	10.85	10.94
Aluminate (C_3A)	3.46	4.50	4.40

B.7 Chemical Composition of Cement

Table B.16: CPR – Chemical composition of cement for C&D burn

Property (wt. %)	**Sample Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Al_2O_3	5.01	4.98	4.94	4.88	5.00	4.96	4.93	4.89	4.90	4.97
CaO	63.08	63.27	63.28	62.94	62.97	63.13	63.21	63.20	63.19	63.01
Fe_2O_3	3.13	3.05	3.03	3.02	3.08	3.05	3.06	3.01	3.14	3.23
K_2O	0.49	0.55	0.52	0.51	0.52	0.51	0.52	0.56	0.51	0.50
MgO	3.16	3.15	3.09	3.06	3.16	3.15	3.15	3.14	3.15	3.14
Na_2O	0.06	0.07	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Na_2O_{eq}	0.38	0.43	0.40	0.41	0.41	0.41	0.41	0.44	0.41	0.40
SiO_2	19.76	19.79	19.51	19.32	19.87	19.63	19.63	19.63	19.59	19.27
SO_3	2.70	2.58	2.74	2.81	2.77	2.66	2.78	2.74	2.81	3.23
F CaO	NR	1.58	NR	1.54	NR	1.37	NR	1.91	NR	1.16
LOI	1.89	1.90	2.29	2.23	1.76	2.15	2.25	2.16	2.13	2.05
C_3A	7.99	8.04	7.97	7.81	8.04	7.99	7.89	7.87	7.68	7.70
C_4AF	9.52	9.28	9.22	9.20	9.37	9.28	9.31	9.16	9.55	9.84
C_3S	54.03	55.24	57.25	57.59	52.69	55.79	55.96	56.38	56.24	56.15
C_2S	15.89	15.07	12.75	11.93	17.22	14.19	14.06	13.75	13.72	12.87
Blaine SSA (m^2/kg)	350	371	377	391	378	379	381	376	366	375

Table B.17: ELR – Chemical composition of cement for C&D burn

Property (wt. %)	Sample Number	
	1	2
Al_2O_3	5.12	5.34
CaO	63.06	62.02
Fe_2O_3	3.03	3.21
K_2O	0.45	0.50
MgO	3.15	3.15
Na_2O	0.06	0.06
P_2O_5	0.06	0.06
SiO_2	19.82	20.54
SO_3	2.66	3.16
TiO_2	0.20	0.23
Moisture	0.20	0.18
LOI	2.24	1.62
Property (ppm)	**1**	**2**
As	25	29
Cd	< 6	< 6
Cl	173	226
Co	11	12
Cr	57	71
Cu	13	< 5
Hg	0.019	0.016
Mo	< 5	< 5
Ni	22	17
Pb	35	68
Se	< 2	< 2
V	38	43
Zn	74	73

Table B.18: SLR – Rietveld analysis of cement for C&D burn

Property	Sample Number	
	1	2
Alite (C_3S)	51.88	51.26
Belite (C_2S)	23.79	24.82
Ferrite (C_4AF)	10.17	10.15
Aluminate (C_3A)	4.17	3.75

B.8 Plant Emissions

Table B.19: CPR – Normalized plant emissions for C&D burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/6/10 23:00	5.84E-04	1.59E-05	1.98E-05	3.37E-04
7/7/10 0:00	5.34E-04	1.67E-05	2.01E-05	3.49E-04
7/7/10 1:00	7.18E-04	2.43E-05	2.54E-05	4.38E-04
7/7/10 2:00	5.59E-04	1.82E-05	2.06E-05	3.46E-04
7/7/10 3:00	5.63E-04	1.78E-05	3.78E-05	3.14E-04
7/7/10 4:00	5.86E-04	1.58E-05	4.34E-05	3.24E-04
7/7/10 5:00	7.42E-04	1.94E-05	3.47E-05	3.59E-04
7/7/10 6:00	7.31E-04	2.04E-05	1.31E-05	3.53E-04
7/7/10 7:00	7.13E-04	1.85E-05	1.19E-05	3.51E-04
7/7/10 8:00	8.42E-04	1.34E-05	2.34E-05	3.60E-04
7/7/10 9:00	7.91E-04	1.41E-05	2.56E-05	3.73E-04
7/7/10 10:00	6.28E-04	1.60E-05	2.31E-05	3.29E-04
7/7/10 11:00	6.61E-04	1.55E-05	2.31E-05	3.59E-04
7/7/10 12:00	6.42E-04	1.50E-05	6.43E-06	3.65E-04
7/7/10 13:00	7.88E-04	1.97E-05	4.84E-06	3.52E-04
7/7/10 14:00	7.53E-04	1.76E-05	3.17E-06	3.86E-04
7/7/10 15:00	7.83E-04	1.99E-05	2.40E-05	3.41E-04
7/7/10 16:00	7.63E-04	1.73E-05	1.99E-05	3.61E-04
7/7/10 17:00	6.51E-04	1.81E-05	1.95E-05	3.40E-04
7/7/10 18:00	7.11E-04	1.17E-05	1.82E-05	2.89E-04
7/7/10 19:00	8.18E-04	1.18E-05	7.71E-06	3.19E-04
7/7/10 20:00	7.35E-04	1.68E-05	5.85E-06	3.67E-04
7/7/10 21:00	6.51E-04	1.04E-05	8.31E-06	3.76E-04
7/7/10 22:00	6.81E-04	7.48E-06	1.80E-05	3.72E-04
7/7/10 23:00	6.62E-04	6.41E-06	1.89E-05	3.49E-04
7/8/10 0:00	7.12E-04	7.36E-06	1.66E-05	3.27E-04
7/8/10 1:00	1.03E-03	6.10E-06	1.96E-05	4.36E-04
7/8/10 2:00	9.02E-04	8.89E-06	1.80E-05	3.86E-04
7/8/10 3:00	8.87E-04	9.97E-06	1.60E-05	3.96E-04
7/8/10 4:00	8.83E-04	1.50E-05	1.83E-05	3.98E-04
7/8/10 5:00	8.73E-04	1.12E-05	1.55E-05	3.48E-04
7/8/10 6:00	9.26E-04	1.62E-05	1.55E-05	3.96E-04
7/8/10 7:00	8.18E-04	9.64E-06	2.05E-05	3.99E-04
7/8/10 8:00	7.35E-04	1.82E-05	1.94E-05	4.13E-04
7/8/10 9:00	7.08E-04	1.85E-05	1.59E-05	4.11E-04
7/8/10 10:00	9.31E-04	2.04E-05	1.00E-05	4.07E-04

Table B.20: CPR – Normalized plant emissions for C&D burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/8/10 11:00	9.03E-04	1.82E-05	7.16E-06	3.58E-04
7/8/10 12:00	8.36E-04	2.05E-05	5.67E-06	3.38E-04
7/8/10 13:00	1.00E-03	3.08E-05	5.96E-06	4.53E-04
7/8/10 14:00	8.01E-04	1.71E-05	5.49E-06	3.22E-04
7/8/10 15:00	8.45E-04	2.03E-05	4.47E-06	3.56E-04
7/8/10 16:00	9.00E-04	2.29E-05	3.76E-06	3.68E-04
7/8/10 17:00	9.44E-04	2.44E-05	1.14E-05	3.40E-04
7/8/10 18:00	8.53E-04	2.15E-05	7.23E-06	3.30E-04
7/8/10 19:00	8.77E-04	2.20E-05	9.33E-06	3.34E-04
7/8/10 20:00	9.00E-04	2.09E-05	1.02E-05	3.59E-04
7/8/10 21:00	9.75E-04	1.49E-05	1.32E-05	3.17E-04
7/8/10 22:00	1.01E-03	1.24E-05	1.32E-05	3.23E-04
7/8/10 23:00	1.01E-03	1.44E-05	1.22E-05	3.34E-04
7/9/10 0:00	9.99E-04	1.44E-05	1.08E-05	3.37E-04
7/9/10 1:00	1.01E-03	1.50E-05	9.95E-06	3.39E-04
7/9/10 2:00	1.04E-03	2.03E-05	9.85E-06	3.71E-04
7/9/10 3:00	9.79E-04	2.12E-05	1.03E-05	3.51E-04
7/9/10 4:00	9.86E-04	1.87E-05	1.16E-05	3.45E-04
7/9/10 5:00	1.21E-03	1.09E-05	1.35E-05	3.65E-04
7/9/10 6:00	9.60E-04	1.04E-05	1.72E-05	3.75E-04
7/9/10 7:00	9.30E-04	1.07E-05	1.80E-05	3.92E-04
7/9/10 8:00	9.06E-04	8.05E-06	1.59E-05	4.00E-04
7/9/10 9:00	8.27E-04	1.19E-05	1.10E-05	3.97E-04
7/9/10 10:00	7.74E-04	7.95E-06	1.01E-05	3.87E-04
7/9/10 11:00	7.15E-04	1.01E-05	5.70E-06	4.58E-04
7/9/10 12:00	6.94E-04	9.36E-06	3.21E-06	4.15E-04
7/9/10 13:00	7.05E-04	7.32E-06	2.81E-06	4.27E-04
7/9/10 14:00	7.66E-04	8.06E-06	1.08E-05	4.20E-04
7/9/10 15:00	7.44E-04	9.86E-06	1.05E-05	4.25E-04
7/9/10 16:00	7.55E-04	9.63E-06	1.44E-05	4.51E-04
7/9/10 17:00	7.95E-04	1.03E-05	9.30E-06	4.03E-04
7/9/10 18:00	7.28E-04	1.77E-05	8.70E-06	3.33E-04
7/9/10 19:00	7.96E-04	1.73E-05	7.89E-06	3.59E-04
7/9/10 20:00	8.79E-04	2.23E-05	8.80E-06	4.08E-04
7/9/10 21:00	8.68E-04	1.98E-05	9.75E-06	4.07E-04
7/9/10 22:00	7.33E-04	1.36E-05	1.05E-05	3.48E-04
7/9/10 23:00	7.14E-04	1.77E-05	1.66E-05	3.15E-04
7/10/10 0:00	6.95E-04	1.48E-05	1.46E-05	3.25E-04
7/10/10 1:00	8.54E-04	1.92E-05	1.48E-05	3.68E-04
7/10/10 2:00	9.30E-04	1.55E-05	1.57E-05	3.81E-04
7/10/10 3:00	9.22E-04	1.48E-05	2.02E-05	3.49E-04
7/10/10 4:00	9.02E-04	1.75E-05	2.19E-05	3.42E-04
7/10/10 5:00	7.79E-04	1.68E-05	1.58E-05	3.62E-04
7/10/10 6:00	8.27E-04	2.27E-05	1.63E-05	4.05E-04

Appendix C

Raw Data for the Variable Feed 5% Burn

C.1 General Comments

- Raw data from the variable feed 5% burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, waste plastics, and woodchips were the fuels utilized during this burn.
- This burn lasted from 12 AM on 7/12/10 to 12 AM on 7/14/10

C.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

[1]As-Received

[2]Dry Basis

C.3 Chemical Composition of Kiln Feed

Table C.1: CPR Chemical composition of kiln feed for VF 5% burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.12	3.05	3.04	3.08	3.13	3.10
CaO	42.55	43.00	42.96	42.94	42.85	41.84
Fe_2O_3	1.92	1.86	1.87	1.98	1.95	1.97
K_2O	0.32	0.31	0.32	0.31	0.31	0.32
MgO	2.17	2.12	2.07	2.19	2.17	2.11
Na_2O	0.05	0.05	0.05	0.06	0.05	0.05
Na_2O_{eq}	0.26	0.25	NC	0.26	0.25	NC
P_2O_5	NC	NC	0.05	NC	NC	0.04
SiO_2	13.28	13.00	12.89	13.17	13.19	13.16
SO_3	0.19	0.19	0.13	0.20	0.18	0.12
LOI	35.76	36.35	NC	36.09	36.00	NC

C.4 Chemical Composition of Cement Kiln Dust

Table C.2: CPR – Chemical composition of CKD for VF 5% burn

Property (wt. %)	Sampel Number			
	1	2	3	4
Al_2O_3	3.69	3.1	3.56	3.54
CaO	45.42	47.2	45.13	47.5
Fe_2O_3	1.98	1.77	1.93	1.81
K_2O	0.39	0.35	0.39	0.46
MgO	1.63	1.55	1.51	1.74
Na_2O	0.1	0.09	0.08	0.12
SiO_2	11.54	10.76	11.73	10.75
SO_3	0.46	0.55	0.54	1.76

Table C.3: ELR – Chemical composition of CKD for VF 5%

Property (wt. %)	Sampel Number			
	1	2	3	4
Al_2O_3	3.78	3.47	4.04	3.86
CaO	46.75	46.92	43.89	50.67
Fe_2O_3	1.88	1.76	1.90	1.91
K_2O	0.40	0.33	0.34	0.38
MgO	1.59	1.56	1.48	1.75
Na_2O	0.04	0.03	0.04	0.07
P_2O_5	0.05	0.04	0.06	0.06
SiO_2	11.31	10.60	11.70	10.57
SO_3	0.80	0.50	0.27	1.66
TiO_2	0.18	0.17	0.20	0.19
Moisture	0.10	0.11	0.19	0.04
LOI	33.14	34.53	36.00	28.80
Property (ppm)	**1**	**2**	**3**	**4**
As	35	26	40	52
Cd	< 6	< 6	< 6	< 6
Cl	170	122	89	386
Co	14	13	16	13
Cr	84	70	81	50
Cu	30	32	161	57
Hg	0.052	0.035	0.031	0.101
Mo	< 5	< 5	< 5	< 5
Ni	14	15	17	22
Pb	24	41	33	7
Se	< 2	< 2	< 2	< 2
V	51	58	77	59
Zn	78	46	75	62

C.5 Chemical Composition of Fuels

Table C.4: ELR -- Proximate and ultimate analysis of waste plastics for VF 5% burn

Test	Parameter	Sample Number														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Proximate Analysis	**Ash**	5.48	4.39	2.6	2.26	3.04	3.68	4.54	3.54	2.73	5.87	7.27	6.87	7.35	5.92	2.18
	Fixed Carbon	13.53	11.81	11.01	12.82	11.54	10	11.53	13.97	11.53	10.57	11.04	11.77	7.38	7.01	1.6
	Moisture [1]	9.11	12.08	2.99	1.35	1.05	4.09	1.84	4.23	1.47	3.16	4.89	4.3	0.9	1.37	0.48
	Volatile Matter	80.99	83.8	86.39	84.92	85.42	86.32	83.93	82.49	85.74	83.56	81.69	81.36	85.27	87.07	96.22
Ultimate Analysis	**Carbon**	57.58	56.19	54.72	45.04	54.58	53.5	57.07	59.84	58.3	59.18	54.14	46.7	59.34	61.26	72.6
	Hydrogen	4.97	4.87	6.87	5.4	5.11	5.6	4.69	5.27	6.04	4.44	4.02	5.32	5.79	6.73	9.17
	Nitrogen	1.39	1.26	1.01	0.01	0.47	0.54	1	1.68	1.32	1.73	1.87	0.13	2.2	1.9	0.01
	Oxygen	30.43	33.11	34.58	47.04	36.49	36.47	32.41	29.52	31.41	28.61	32.57	40.74	24.87	24.03	15.81
	Sulfur	0.15	0.18	0.22	0.25	0.31	0.21	0.29	0.15	0.2	0.17	0.13	0.24	0.45	0.16	0.23
Heat Value [2] **(BTU/lb)**		9953	8957	7655	10412	11416	9384	10326	9815	10326	9887	9331	7923	10819	11362	15866

Table C.5: ELR – Proximate and ultimate analysis of woodchips for VF 5%

Test	**Parameter**	**Sample Number**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Proximate Analysis	**Ash**	6.72	5.9	17.37	12.32	11.84	13.42	11.74	15.35	11.76	13.66	4.78	10.65	6.94	9.1	7.35
	Fixed Carbon	17.63	17.81	16.47	16.92	16.15	16.41	16.39	16.33	16.6	16.24	17.07	16.35	18.15	17.24	17.32
	Moisture [1]	29.26	20.07	50.03	47.52	46.02	43.96	38.57	53.37	48.2	23.44	44.26	40.74	29.28	42.42	36.9
	Volatile Matter	75.65	76.29	66.16	70.76	72.01	70.17	71.87	68.32	71.64	70.1	78.15	73	74.91	73.66	75.33
Ultimate Analysis	**Carbon**	49.71	51.31	44.66	46.69	45.45	46.34	48.29	44.54	48.48	45.16	52.37	49.12	49.57	49.09	51.35
	Hydrogen	5.41	5.68	4.88	5.11	4.85	5.04	5.3	4.94	5.41	4.88	5.5	5.25	5.3	5.22	5.43
	Nitrogen	0.31	0.23	0.43	0.41	0.35	0.41	0.26	0.34	0.31	0.33	0.2	0.33	0.29	0.28	0.22
	Oxygen	37.83	36.85	32.65	35.46	37.5	34.78	34.4	34.82	34.03	35.95	37.14	34.63	37.88	36.3	35.63
	Sulfur	0.02	0.03	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.01	0.02
Heat Value [2] (BTU/lb)		7942	8027	7063	7557	7201	7517	7423	7195	7720	7180	8281	7865	7830	7869	8190

Table C.6: ELR – Chemical composition of waste plastics for VF 5% burn

Test	**Parameter (wt. %)**	**Sample Number**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Standard Parameters	**Al_2O_3**	10.27	11.91	8.88	7.86	11.64	15.44	5.08	11.91	11.43	7.34	33.11	47.61	3.42	22.76	27.81
	CaO	31.97	20.94	10.48	16.83	32.20	23.06	31.50	41.10	28.79	58.08	40.00	19.17	45.20	42.82	39.12
	Fe_2O_3	1.68	2.33	1.62	2.89	6.36	2.05	1.21	2.94	2.12	0.83	0.28	0.22	0.98	0.70	1.74
	K_2O	0.50	0.78	0.39	0.69	0.54	0.61	0.43	0.98	0.73	0.34	0.20	0.26	0.38	0.56	0.20
	MgO	7.90	8.96	17.57	11.54	6.06	10.23	4.72	4.06	7.33	4.62	11.09	5.37	3.60	13.96	13.51
	Na_2O	1.68	5.80	3.53	1.78	2.69	1.86	1.22	1.10	1.25	0.76	0.78	1.28	0.68	1.21	0.81
	P_2O_5	0.78	0.60	0.37	1.62	0.69	0.61	0.59	0.56	0.69	0.48	0.26	0.19	0.41	0.23	0.29
	SiO_2	30.53	36.47	52.60	35.89	23.59	37.08	16.49	24.24	30.49	17.90	12.26	23.67	11.87	13.45	11.16
	SO_3	30.53	36.47	52.60	35.89	23.59	37.08	16.49	24.24	30.49	17.90	12.26	23.67	11.87	13.45	11.16
	TiO_2	6.68	1.67	2.69	3.74	2.37	2.48	2.84	3.12	4.44	2.77	1.20	0.91	2.06	2.61	4.68
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	As	5	5	18	5	5	38	5	30	21	17	12	5	6	5	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	363	242	367	792	474	188	2648	488	265	508	733	227	416	195	81
	Co	94	117	67	97	82	172	84	47	166	61	46	6	100	158	49
	Cr	256	248	149	203	148	362	67	196	521	181	277	46	194	559	182
	Cu	294	1190	128	272	641	570	462	518	706	200	5	5	386	73	5
	Hg	0.098	0.217	0.056	0.022	0.005	0.005	0.040	0.069	0.040	0.047	0.034	0.040	0.018	0.092	0.023
	Mo	13	5	44	5	23	5	5	5	10	5	49	23	5	5	5
	Ni	42	48	54	40	448	25	16	68	117	20	10	3	12	3	6
	Pb	322	229	168	305	291	181	174	264	394	73	98	45	193	103	101
	Se	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	V	273	93	5	91	1770	16	205	132	160	136	96	30	186	128	236
	Zn	2030	3010	467	1301	668	2150	703	1170	3140	599	229	70	396	290	181

Table C.7: ELR – Chemical composition of woodchips for VF 5% burn

Test	**Parameter (wt. %)**	**Sample Number**														
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Standard Parameters	**Al_2O_3**	9.37	9.19	9.15	9.52	6.73	8.71	7.96	8.04	8.41	7.17	5.98	7.54	8.55	8.70	9.88
	CaO	11.92	10.43	6.28	6.81	22.62	5.90	16.29	5.87	5.51	15.34	31.26	9.21	12.33	9.89	10.23
	Fe_2O_3	6.20	6.00	7.54	7.70	6.46	8.13	9.52	8.72	8.80	7.44	6.70	6.38	6.97	8.99	8.84
	K_2O	2.13	1.94	1.49	1.61	1.35	1.58	1.54	1.35	1.49	1.23	1.71	1.33	2.15	1.52	1.90
	MgO	1.78	1.97	1.71	1.29	10.15	1.45	2.99	1.52	1.33	7.36	10.72	2.22	2.10	2.99	2.51
	Na_2O	1.33	1.38	0.30	0.28	0.29	0.29	0.62	0.34	0.36	0.47	0.52	0.40	1.37	0.41	0.45
	P_2O_5	0.26	0.25	0.20	0.22	0.18	0.21	0.21	0.16	0.19	0.17	0.24	0.19	0.33	0.20	0.24
	SiO_2	64.83	65.91	71.88	71.03	51.04	72.37	59.37	72.61	72.40	59.59	41.66	70.66	64.12	65.81	64.22
	SO_3	64.83	65.91	71.88	71.03	51.04	72.37	59.37	72.61	72.40	59.59	41.66	70.66	64.12	65.81	64.22
	TiO_2	0.84	1.86	0.88	0.95	0.65	0.82	0.76	0.81	0.86	0.75	0.56	0.72	0.79	0.85	1.01
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
	As	47	40	28	18	22	16	29	20	16	12	8	16	219	24	29
	Cd	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	175	126	543	278	197	222	168	215	307	622	125	289	140	278	235
	Co	337	58	25	29	31	23	32	20	24	25	92	23	38	60	57
	Cr	743	973	489	497	599	509	919	379	1020	615	1550	352	1760	329	704
	Cu	719	354	162	313	143	191	219	230	183	108	147	155	387	131	147
	Hg	0.015	0.092	0.023	0.059	0.049	0.055	0.029	0.044	0.050	0.009	0.009	0.022	0.012	0.022	0.011
	Mo	26	20	21	18	18	14	24	11	26	25	29	16	42	17	13
	Ni	331	437	191	183	193	163	263	144	378	182	657	177	610	159	291
	Pb	98	168	54	64	82	72	75	45	90	67	119	61	103	52	89
	Se	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	V	41	107	76	102	57	81	54	70	54	57	5	63	43	87	75
	Zn	1090	915	250	267	262	284	667	253	300	601	260	1590	1210	488	314

C.6 Chemical Composition of Clinker

Table C.8: CPR – Chemical composition of clinker for VF 5% burn

Property (wt. %)	Sample Number											
	1	2	3	4	5	6	7	8	9	10	11	12
Al_2O_3	5.01	4.95	5.03	4.92	4.92	4.92	4.83	4.91	4.83	5.01	4.91	5.11
CaO	64.29	64.69	64.26	64.93	64.81	64.67	65.17	64.78	64.97	64.46	64.34	63.86
Fe_2O_3	3.32	3.31	3.31	3.27	3.28	3.31	3.29	3.42	3.43	3.55	3.50	3.65
K_2O	0.58	0.54	0.55	0.55	0.58	0.53	0.53	0.56	0.51	0.51	0.57	0.53
MgO	3.30	3.35	3.29	3.31	3.25	3.25	3.24	3.21	3.21	3.27	3.27	3.36
Na_2O	0.08	0.07	0.08	0.06	0.07	0.07	0.07	0.07	0.07	0.06	0.07	0.07
Na_2O_{eq}	0.46	0.42	0.44	0.42	0.45	0.42	0.41	0.43	0.41	0.40	0.45	0.42
SiO_2	21.19	21.35	21.15	21.20	21.17	20.99	20.89	20.87	20.69	20.65	20.67	20.82
SO_3	0.99	0.76	0.77	0.59	0.98	1.12	1.06	1.20	1.23	1.33	1.39	1.33
F CaO	1.33	0.95		2.31	2.18	1.53	1.43	1.50	0.85	0.85	1.39	0.71
C_3A	7.66	7.51	7.73	7.51	7.49	7.44	7.24	7.24	7.00	7.27	7.09	7.37
C_4AF	10.10	10.08	10.07	9.95	9.98	10.07	10.00	10.39	10.44	10.80	10.65	11.11
C_3S	62.28	63.09	62.34	65.48	65.21	65.96	69.41	67.22	69.90	66.74	66.85	62.19
C_2S	13.77	13.62	13.61	11.38	11.50	10.42	7.52	9.12	6.59	8.85	8.83	12.77

Table C.9: CPR – Chemical composition of clinker for VF 5% burn (continued)

Property (wt. %)	Sample Number				
	13	**14**	**15**	**16**	**17**
Al_2O_3	5.19	5.14	5.00	5.04	5.02
CaO	63.79	63.37	64.00	64.05	63.94
Fe_2O_3	3.63	3.63	3.66	3.47	3.48
K_2O	0.52	0.59	0.50	0.53	0.50
MgO	3.44	3.44	3.34	3.33	3.35
Na_2O	0.08	0.09	0.06	0.07	0.07
Na_2O_{eq}	0.42	0.48	0.39	0.42	0.40
SiO_2	20.95	21.01	21.06	21.39	21.08
SO_3	1.40	1.54	1.12	0.91	1.15
F CaO	0.71	1.05	1.29	1.63	1.33
C_3A	7.61	7.48	7.06	7.48	7.41
C_4AF	11.03	11.05	11.14	10.56	10.59
C_3S	60.43	58.58	61.66	59.36	61.39
C_2S	14.49	16.04	13.86	16.54	14.12

Table C.10: ELR – Chemical composition of clinker for VF 5% burn

Property (wt. %)	Sample Number		
	1	2	3
Al_2O_3	5.39	5.32	5.34
CaO	63.40	63.27	63.22
Fe_2O_3	3.28	3.41	3.27
K_2O	0.51	0.36	0.45
MgO	3.57	3.60	3.59
Na_2O	0.08	0.07	0.06
P_2O_5	0.07	0.07	0.07
SiO_2	22.21	21.98	22.20
SO_3	0.91	1.39	1.14
TiO_2	0.25	0.24	0.26
Moisture	0.02	0.00	0.00
LOI	0.22	0.17	0.28
Property (ppm)	**1**	**2**	**3**
As	49	51	23
Cd	< 6	< 6	< 6
Cl	612	606	265
Co	12	8	10
Cr	68	83	66
Cu	59	24	46
Hg	0.123	0.036	0.023
Mo	9	11	< 5
Ni	250	15	17
Pb	< 5	33	82
Se	< 2	< 2	< 2
V	61	59	71
Zn	67	63	65

Table C.11: SLR – Rietveld analysis of clinker for VF 5% burn

Property (wt. %)	Sample Number		
	1	2	3
Alite (C_3S)	55.46	54.82	49.84
Belite (C_2S)	25.62	25.65	30.80
Ferrite (C_4AF)	10.71	11.40	11.12
Aluminate (C_3A)	4.40	3.00	3.25

C.7 Plant Emissions

Table C.12: Normalized plant emissions for VF 5% burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/12/2010 12:00	9.91E-04	4.54E-07	1.36E-05	4.52E-04
7/12/2010 13:00	9.52E-04	6.07E-07	1.33E-05	4.15E-04
7/12/2010 14:00	9.70E-04	7.25E-07	1.45E-05	4.40E-04
7/12/2010 15:00	8.37E-04	3.67E-06	8.40E-06	4.23E-04
7/12/2010 16:00	8.15E-04	3.58E-06	8.20E-06	4.22E-04
7/12/2010 17:00	8.07E-04	3.45E-06	8.20E-06	4.22E-04
7/12/2010 18:00	9.36E-04	2.06E-06	1.43E-05	3.93E-04
7/12/2010 19:00	9.38E-04	2.89E-06	1.53E-05	3.66E-04
7/12/2010 20:00	8.50E-04	2.10E-06	1.44E-05	3.63E-04
7/12/2010 21:00	8.53E-04	1.54E-06	1.49E-05	3.71E-04
7/12/2010 22:00	8.00E-04	2.08E-06	1.44E-05	3.59E-04
7/12/2010 23:00	7.99E-04	2.34E-06	1.35E-05	3.79E-04
7/13/2010 0:00	8.77E-04	2.74E-06	1.42E-05	3.96E-04
7/13/2010 1:00	7.81E-04	2.75E-06	8.52E-06	4.00E-04
7/13/2010 2:00	8.23E-04	2.23E-06	8.79E-06	3.95E-04
7/13/2010 3:00	8.12E-04	1.99E-06	8.89E-06	3.71E-04
7/13/2010 4:00	8.33E-04	1.72E-06	1.50E-05	3.59E-04
7/13/2010 5:00	7.71E-04	2.61E-06	1.52E-05	3.66E-04
7/13/2010 6:00	7.40E-04	1.59E-06	1.57E-05	3.54E-04
7/13/2010 7:00	6.59E-04	1.91E-06	1.57E-05	3.77E-04
7/13/2010 8:00	8.22E-04	2.69E-06	1.93E-05	3.84E-04
7/13/2010 9:00	7.82E-04	2.77E-06	1.93E-05	3.94E-04
7/13/2010 10:00	7.30E-04	1.86E-06	1.71E-05	3.69E-04
7/13/2010 11:00	7.13E-04	2.79E-06	1.66E-05	3.76E-04
7/13/2010 12:00	6.02E-04	2.93E-06	9.19E-06	4.03E-04
7/13/2010 13:00	6.54E-04	2.64E-06	8.78E-06	4.09E-04
7/13/2010 14:00	6.53E-04	3.14E-06	8.97E-06	4.09E-04
7/13/2010 15:00	7.02E-04	2.15E-06	1.52E-05	3.77E-04
7/13/2010 16:00	6.61E-04	2.29E-06	1.58E-05	3.78E-04
7/13/2010 17:00	5.76E-04	2.23E-06	1.62E-05	3.83E-04
7/13/2010 18:00	6.15E-04	2.04E-06	1.65E-05	3.93E-04
7/13/2010 19:00	5.75E-04	3.02E-06	1.72E-05	3.93E-04
7/13/2010 20:00	6.08E-04	1.94E-06	1.80E-05	4.00E-04
7/13/2010 21:00	6.15E-04	2.74E-06	1.76E-05	3.91E-04
7/13/2010 22:00	5.84E-04	4.12E-06	1.16E-05	3.96E-04

Table C.13: Normalized plant emissions for VF 5% burn (continued)

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/13/2010 23:00	5.88E-04	4.90E-06	8.99E-06	3.91E-04
7/14/10 0:00	6.42E-04	4.48E-06	1.11E-05	4.43E-04
7/14/10 1:00	6.56E-04	4.08E-06	1.64E-05	3.99E-04
7/14/10 2:00	7.17E-04	3.47E-06	1.69E-05	4.10E-04
7/14/10 3:00	6.53E-04	3.08E-06	1.64E-05	4.01E-04
7/14/10 4:00	7.34E-04	3.14E-06	1.74E-05	3.83E-04
7/14/10 5:00	8.30E-04	4.76E-06	1.78E-05	3.74E-04
7/14/10 6:00	7.96E-04	4.21E-06	1.18E-05	3.85E-04
7/14/10 7:00	7.81E-04	1.45E-06	1.07E-05	4.14E-04
7/14/10 8:00	6.56E-04	8.14E-07	9.71E-06	4.07E-04
7/14/10 9:00	8.95E-04	1.52E-06	1.13E-05	4.43E-04
7/14/10 10:00	8.62E-04	8.41E-07	7.75E-06	3.89E-04
7/14/10 11:00	8.38E-04	8.73E-07	6.14E-06	3.59E-04

Appendix D

Raw Data for the Variable Feed 10% Burn

D.1 General Comments

- Raw data from the variable feed 10% burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, waste plastics, and woodchips were the fuels utilized during this burn.
- This burn lasted from 12 AM on 7/14/10 to 12 AM on 7/16/10

D.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

^{1}As-Received

^{2}Dry Basis

D.3 Chemical Composition of Kiln Feed

Table D.1: CPR – Chemical composition of kiln feed for VF 10% burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	2.99	2.91	3.02	3.02	3.00	3.07
CaO	42.99	43.00	42.50	42.78	43.30	42.90
Fe_2O_3	1.87	1.83	1.89	1.86	1.83	1.89
K_2O	0.30	0.30	0.32	0.31	0.31	0.33
MgO	2.18	2.18	2.14	2.22	2.18	2.17
Na_2O	0.05	0.05	0.05	0.05	0.05	0.05
Na_2O_{eq}	0.25	0.25	NC	0.25	0.25	NC
P_2O_5	NC	NC	0.04	NC	NC	0.05
SiO_2	13.21	12.93	13.06	13.07	12.88	13.03
SO_3	0.18	0.18	0.12	0.19	0.24	0.23
LOI	36.12	36.12	NC	36.00	36.36	NC

D.4 Chemical Composition of Cement Kiln Dust

Table D.2: CPR – Chemical composition of CKD for VF 10% burn

Property (wt. %)	Sample Number			
	1	2	3	4
Al_2O_3	3.75	3.46	3.43	3.75
CaO	43.78	47.15	45.37	46.19
Fe_2O_3	1.96	1.87	1.91	1.88
K_2O	0.39	0.42	0.38	0.48
MgO	1.47	1.74	1.52	1.89
Na_2O	0.1	0.11	0.09	0.11
SiO_2	11.78	10.85	11.08	11.07
SO_3	0.16	1.21	0.32	1.57

Table D.3: ELR – Chemical composition of CKD for VF 10% burn

Property (wt. %)	**Sample Number**		
	1	**2**	**3**
Al_2O_3	3.88	3.71	4.16
CaO	48.63	47.28	46.29
Fe_2O_3	1.98	1.84	1.97
K_2O	0.44	0.36	0.46
MgO	1.80	1.72	1.72
Na_2O	0.05	0.05	0.05
P_2O_5	0.06	0.05	0.06
SiO_2	10.86	10.69	11.40
SO_3	1.39	0.75	0.99
TiO_2	0.19	0.17	0.20
Moisture	0.03	0.08	0.11
LOI	30.66	33.31	32.62
Property (ppm)	**1**	**2**	**3**
As	44	36	46
Cd	< 6	< 6	< 6
Cl	439	152	143
Co	12	9	15
Cr	62	57	65
Cu	38	36	38
Hg	0.063	0.029	0.028
Mo	6	7	11
Ni	24	18	26
Pb	40	16	39
Se	< 2	< 2	< 2
V	71	61	78
Zn	92	78	66

D.5 Chemical Composition of Fuels

Table D.4: ELR – Proximate, Ultimate, and Combustion analysis of waste plastics for VF 10% burn

Test	Parameter	Sample Number												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Proximate Analysis	**Ash**	6.45	7.74	4.23	4.88	8.51	8.07	10.43	6.73	5.61	3.63	1.78	7.28	10.59
	Fixed Carbon	7.25	6.16	7.35	11.65	6.14	7.12	3.07	4.59	8.36	10.69	10.66	8.51	8.02
	Moisture [1]	0.59	1.45	1.04	1.57	0.93	1.27	0.5	0.87	1.55	1.08	2.12	0.17	0.92
	Volatile Matter	86.3	86.1	88.42	83.47	85.35	84.81	86.5	88.68	86.03	85.68	87.56	84.21	81.39
Ultimate Analysis	**Carbon**	58.93	58.67	64.17	52.77	54.14	56.1	53.86	60.39	55.67	55.45	61.46	64.09	55.81
	Hydrogen	5.6	6.35	6.8	4.9	4.69	5.73	4.8	6.55	6.2	5.82	7.55	6.42	5.73
	Nitrogen	0.47	1.27	6.38	0.35	2.44	2.12	2.93	1.78	1.4	1.25	1.2	0.01	0.53
	Oxygen	28.17	25.7	17.56	36.58	29.73	27.57	27.6	24.02	30.73	33.4	27.55	21.86	26.89
	Sulfur	0.38	0.27	0.86	0.52	0.49	0.41	0.38	0.53	0.39	0.45	0.46	0.34	0.45
Heat Value [2] **(BTU/lb)**		10496	9756	11661	8873	10732	10358	10333	10878	9825	10663	11959	11187	10406

Table D.5: ELR – Proximate, Ultimate, and Combustion analysis of woodchips for VF 10% burn

Test	Parameter	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Proximate Analysis	**Ash**	7.11	8.65	16.27	9.71	7.93	22.13	20.08	4.7	1.11	3.47	5.13	6.44
	Fixed Carbon	16.32	17.26	14.82	16.78	17	14.8	14.73	17.7	17.87	17.29	17.88	18.09
	Moisture [1]	43	43.23	42.52	40.9	44.77	41.67	39.72	34.83	35.89	34.95	38.84	33.87
	Volatile Matter	76.57	74.09	68.91	73.51	75.07	63.07	65.19	77.6	81.02	79.24	76.99	75.47
Ultimate Analysis	**Carbon**	49.55	48.65	44.02	50.17	49.7	41.15	42.98	51.98	54.06	53.45	51.98	49.98
	Hydrogen	5.3	5.21	4.61	5.39	5.28	4.45	4.64	5.68	5.79	5.77	5.55	5.31
	Nitrogen	0.25	0.24	0.26	0.24	0.24	0.28	0.41	0.24	0.17	0.18	0.19	0.22
	Oxygen	37.78	37.24	34.83	34.48	36.84	31.98	31.88	37.39	38.81	37.11	37.13	38.03
	Sulfur	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.06	0.02	0.02	0.02
Heat Value [2] **(BTU/lb)**		8002	7945	7152	8001	7965	6575	6808	8333	8585	8496	8328	8051

Table D.6: ELR – Chemical composition of waste plastics for VF 10% burn

Test	Parameter (wt. %)	Sample Number												
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Standard Parameters	**Al_2O_3**	4.11	28.83	3.23	52.40	3.87	14.34	1.36	18.52	27.11	28.06	12.86	5.57	36.14
	CaO	62.96	43.75	43.14	15.16	58.94	55.71	68.74	51.47	19.51	34.72	14.73	35.24	5.50
	Fe_2O_3	1.67	0.90	4.50	0.97	7.52	1.37	2.29	1.02	2.07	0.52	3.79	2.92	2.13
	K_2O	0.40	0.26	0.28	0.25	0.25	0.29	0.20	0.24	0.32	0.20	1.84	0.17	0.29
	MgO	9.73	10.54	5.85	1.67	6.04	11.67	16.50	11.51	5.86	17.15	17.99	34.10	15.38
	Na_2O	0.97	1.12	0.53	1.43	0.42	0.81	0.27	0.57	1.07	0.93	1.45	0.62	0.79
	P_2O_5	0.53	0.25	0.32	0.37	0.21	0.20	0.09	0.15	0.40	0.21	0.71	0.30	0.26
	SiO_2	9.51	9.17	6.97	21.70	7.14	8.81	6.21	10.47	22.42	12.45	42.76	9.59	32.46
	SO_3	9.51	9.17	6.97	21.70	7.14	8.81	6.21	10.47	22.42	12.45	42.76	9.59	32.46
	TiO_2	5.41	2.52	3.36	2.56	0.96	1.50	1.09	1.79	3.33	2.41	1.45	10.07	3.77
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
	As	5	5	5	5	5	5	7	5	5	5	5	9	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	238	366	236	369	147	96	86	225	243	358	286	96	224
	Co	112	131	1320	659	225	123	120	94	142	166	212	83	206
	Cr	116	149	453	288	6970	867	1750	475	940	478	552	1580	2520
	Cu	137	37	1900	423	477	174	299	124	138	211	1440	345	86
	Hg	0.022	0.008	0.025	0.005	0.005	0.005	0.016	0.049	0.031	0.005	0.005	0.005	0.011
	Mo	5	5	5	7	152	34	46	17	30	20	5	81	53
	Ni	18	4	145	64	2510	204	681	193	267	254	342	814	748
	Pb	191	63	290	145	83	58	26	71	93	92	287	98	102
	Se	2	2	2	2	2	2	2	2	2	2	2	2	2
	V	197	161	99	108	91	76	24	71	131	212	5	595	359
	Zn	333	237	378	384	219	271	71	243	153	287	1990	374	257

Table D.7: ELR – Chemical composition of woodchips for VF 10% burn

Test	Parameter (wt. %)	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	8.78	9.09	6.08	7.78	9.42	8.22	6.84	8.58	12.68	8.29	9.77	9.21
	CaO	7.76	8.88	19.17	13.41	9.41	7.50	6.46	11.95	11.97	36.09	10.91	18.68
	Fe_2O_3	9.42	11.10	6.24	8.15	8.25	8.35	18.22	7.53	5.45	6.20	7.45	6.91
	K_2O	1.67	1.69	1.09	1.61	1.69	1.20	1.08	2.77	6.89	2.54	2.38	1.83
	MgO	1.88	2.75	5.96	3.61	3.21	2.27	1.46	4.18	2.90	2.83	3.54	3.39
	Na_2O	0.55	0.50	0.31	0.44	0.42	0.17	0.23	1.26	2.19	0.74	0.69	0.87
	P_2O_5	0.24	0.24	0.15	0.21	0.25	0.16	0.15	0.29	0.48	0.26	0.25	0.25
	SiO_2	68.09	63.99	59.89	63.23	65.80	70.95	64.44	61.52	55.70	41.52	63.70	52.86
	SO_3	68.09	63.99	59.89	63.23	65.80	70.95	64.44	61.52	55.70	41.52	63.70	52.86
	TiO_2	0.96	0.97	0.72	0.81	0.95	0.80	0.66	0.88	0.55	0.69	0.78	0.83
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	13	23	14	23	18	23	23	56	977	114	86	39
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	212	285	346	179	213	230	283	180	108	125	183	157
	Co	30	19	18	37	14	19	34	17	858	141	64	175
	Cr	580	750	479	1103	624	550	1090	1010	2680	520	834	697
	Cu	188	216	102	113	157	91	83	546	938	168	161	89
	Hg	0.018	0.005	0.005	0.005	0.005	0.005	0.033	0.001	0.022	0.029	0.032	0.013
	Mo	5	32	12	21	9	17	25	35	133	39	5	15
	Ni	246	323	182	448	269	208	279	598	463	157	309	276
	Pb	111	69	44	137	74	38	42	170	612	175	77	106
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	52	77	53	57	81	80	64	5	5	5	5	46
	Zn	426	436	191	715	255	158	364	497	1220	358	277	776

D.6 Chemical Composition of Clinker

Table D.8: CPR – Chemical composition of clinker for VF 10% burn

Property (wt. %)	Sample Number											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Al_2O_3	5.12	5.06	4.87	4.75	4.89	4.77	4.73	4.65	4.82	4.84	4.84	4.85
CaO	63.78	63.91	64.46	64.87	64.79	64.64	65.13	65.06	64.69	64.38	64.65	64.37
Fe_2O_3	3.41	3.36	3.27	3.21	3.27	3.24	3.23	3.19	3.29	3.29	3.28	3.28
K_2O	0.53	0.58	0.53	0.54	0.51	0.52	0.49	0.50	0.51	0.55	0.54	0.55
MgO	3.36	3.38	3.35	3.42	3.42	3.37	3.40	3.40	3.43	3.44	3.47	3.48
Na_2O	0.07	0.07	0.07	0.06	0.05	0.06	0.06	0.06	0.06	0.06	0.07	0.06
Na_2O_{eq}	0.42	0.45	0.42	0.42	0.39	0.40	0.38	0.39	0.40	0.42	0.42	0.42
SiO_2	21.36	21.30	21.25	21.22	21.29	21.01	21.04	21.20	21.30	21.14	21.11	21.25
SO_3	0.94	1.00	0.79	0.67	0.42	0.71	0.55	0.78	0.88	1.09	1.03	1.08
F CaO	0.92	1.26	1.46	1.80	2.55	2.62	2.86	1.39	0.68	1.05	1.19	0.75
C_3A	7.80	7.72	7.37	7.16	7.43	7.16	7.07	6.93	7.21	7.26	7.26	7.30
C_4AF	10.38	10.22	9.95	9.77	9.95	9.86	9.83	9.71	10.01	10.01	9.99	9.98
C_3S	58.04	59.50	63.52	66.31	64.43	66.80	68.85	67.94	64.39	64.21	65.57	63.28
C_2S	17.45	16.18	13.00	10.81	12.43	9.85	8.38	9.53	12.49	12.17	11.06	13.19

Table D.9: CPR – Chemical composition of clinker for VF 10% burn (continued)

Property (wt. %)	**Sample Number**				
	13	**14**	**15**	**16**	**17**
Al_2O_3	4.86	4.91	4.98	4.96	4.95
CaO	64.54	64.43	64.30	64.50	64.19
Fe_2O_3	3.31	3.33	3.37	3.38	3.42
K_2O	0.50	0.50	0.52	0.52	0.52
MgO	3.47	3.50	3.47	3.40	3.48
Na_2O	0.06	0.07	0.06	0.06	0.06
Na_2O_{eq}	0.39	0.40	0.40	0.40	0.40
SiO_2	21.24	21.25	21.20	21.01	21.14
SO_3	0.86	0.85	0.78	0.98	1.01
F CaO	1.26	0.82	1.60	1.26	1.29
C_3A	7.28	7.38	7.49	7.43	7.33
C_4AF	10.07	10.13	10.25	10.29	10.41
C_3S	63.94	63.05	62.37	64.75	62.51
C_2S	12.66	13.36	13.73	11.39	13.45

Table D.10: ELR – Chemical composition of clinker for VF 10% burn

Property (wt. %)	Sample Number		
	1	2	3
Al_2O_3	5.14	5.24	4.89
CaO	63.72	63.42	63.45
Fe_2O_3	3.13	3.22	3.00
K_2O	0.49	0.47	0.54
MgO	3.65	3.69	3.68
Na_2O	0.05	0.06	0.05
P_2O_5	0.07	0.06	0.07
SiO_2	22.31	22.23	22.60
SO_3	0.95	1.08	1.26
TiO_2	0.24	0.27	0.21
Moisture	0.00	0.01	0.00
LOI	0.10	0.14	0.12
Property (ppm)	**1**	**2**	**3**
As	33	47	49
Cd	< 6	< 6	< 6
Cl	359	944	770
Co	15	12	13
Cr	64	58	73
Cu	24	48	17
Hg	0.013	0.012	0.010
Mo	8	9	11
Ni	15	18	12
Pb	39	19	9
Se	< 2	< 2	< 2
V	50	66	63
Zn	40	36	32

Table D.11: SLR – Rietveld analysis of clinker for VF 10% burns

Property (wt. %)	Sample Number		
	1	2	3
Alite (C_3S)	56.51	59.95	50.08
Belite (C_2S)	24.39	22.01	29.45
Ferrite (C_4AF)	10.92	10.27	11.04
Aluminate (C_3A)	3.70	3.73	4.38

D.7 Plant Emissions

Table D.12: CPR – Normalized plant emissions for VF 10% burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/14/2010 12:00:00	8.15E-04	7.82E-07	5.63E-06	3.69E-04
7/14/2010 13:00:00	8.68E-04	1.71E-06	5.95E-06	3.99E-04
7/14/2010 14:00:00	8.39E-04	4.18E-06	0.00E+00	4.43E-04
7/14/2010 15:00:00	7.65E-04	3.31E-06	8.83E-09	4.07E-04
7/14/2010 16:00:00	9.30E-04	3.41E-06	8.97E-06	3.76E-04
7/14/2010 17:00:00	9.47E-04	2.36E-06	7.83E-06	3.67E-04
7/14/2010 18:00:00	9.53E-04	2.42E-06	7.11E-06	3.73E-04
7/14/2010 19:00:00	8.75E-04	6.01E-06	6.08E-06	4.05E-04
7/14/2010 20:00:00	9.61E-04	3.80E-06	6.77E-06	4.06E-04
7/14/2010 21:00:00	8.31E-04	4.46E-06	3.23E-07	3.56E-04
7/14/2010 22:00:00	8.44E-04	3.58E-06	2.55E-06	3.62E-04
7/14/2010 23:00:00	9.72E-04	4.97E-06	7.48E-06	3.99E-04
7/15/2010 0:00:00	7.81E-04	3.64E-06	6.92E-06	3.23E-04
7/15/2010 1:00:00	9.66E-04	4.85E-06	9.68E-06	3.94E-04
7/15/2010 2:00:00	8.17E-04	4.29E-06	2.81E-06	3.58E-04
7/15/2010 3:00:00	9.62E-04	3.47E-06	8.77E-06	3.80E-04
7/15/2010 4:00:00	1.04E-03	2.48E-06	7.24E-06	4.17E-04
7/15/2010 5:00:00	7.77E-04	1.01E-06	7.93E-07	4.15E-04
7/15/2010 6:00:00	8.25E-04	6.80E-07	3.80E-06	4.55E-04
7/15/2010 7:00:00	6.87E-04	1.11E-06	1.20E-05	4.26E-04
7/15/2010 8:00:00	7.04E-04	2.25E-06	1.90E-05	4.26E-04
7/15/2010 9:00:00	7.39E-04	2.13E-06	1.30E-05	4.24E-04
7/15/2010 10:00:00	7.45E-04	3.38E-06	1.04E-05	4.43E-04
7/15/2010 11:00:00	7.09E-04	2.16E-06	1.03E-05	4.31E-04
7/15/2010 12:00:00	7.25E-04	3.02E-06	8.49E-06	4.36E-04
7/15/2010 13:00:00	6.61E-04	1.33E-06	3.16E-07	4.48E-04
7/15/2010 14:00:00	6.46E-04	1.30E-06	3.85E-08	4.13E-04
7/15/2010 15:00:00	7.10E-04	1.81E-06	1.04E-07	4.05E-04
7/15/2010 16:00:00	7.14E-04	5.19E-06	8.10E-06	3.55E-04
7/15/2010 17:00:00	6.62E-04	8.05E-06	8.28E-06	3.00E-04
7/15/2010 18:00:00	7.10E-04	5.87E-06	1.16E-05	3.37E-04
7/15/2010 19:00:00	7.68E-04	5.36E-06	1.43E-05	3.52E-04
7/15/2010 20:00:00	7.79E-04	4.88E-06	1.58E-05	3.36E-04
7/15/2010 21:00:00	8.12E-04	5.03E-06	1.66E-05	3.60E-04
7/15/2010 22:00:00	8.05E-04	4.94E-06	8.56E-06	3.70E-04

Table D.13: CPR – Normalized plant emissions for VF 10% burn (continued)

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/15/2010 23:00:00	9.84E-04	8.85E-06	9.86E-06	-
7/16/2010 0:00:00	1.06E-03	4.85E-06	1.43E-05	4.45E-04
7/16/2010 1:00:00	9.19E-04	6.63E-06	1.26E-05	3.95E-04
7/16/2010 2:00:00	9.11E-04	3.66E-06	1.41E-05	3.65E-04
7/16/2010 3:00:00	7.67E-04	6.16E-06	9.40E-06	3.79E-04
7/16/2010 4:00:00	7.91E-04	7.02E-06	8.78E-06	3.90E-04
7/16/2010 5:00:00	8.87E-04	3.55E-06	1.31E-05	3.81E-04
7/16/2010 6:00:00	8.55E-04	5.47E-06	1.17E-05	3.79E-04
7/16/2010 7:00:00	8.58E-04	6.06E-06	1.20E-05	3.90E-04
7/16/2010 8:00:00	7.99E-04	7.60E-06	1.20E-05	3.82E-04
7/16/2010 9:00:00	8.44E-04	8.34E-06	1.29E-05	3.67E-04
7/16/2010 10:00:00	8.78E-04	8.10E-06	1.33E-05	3.74E-04
7/16/2010 11:00:00	8.30E-04	7.67E-06	-	3.84E-04

Appendix E

Raw Data for the Variable Feed 15% Burn

E.1 General Comments

- Raw data from the variable feed 15% burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, waste plastics, and woodchips were the fuels utilized during this burn.
- This burn lasted from 12 AM on 7/16/10 to 4 PM on 7/18/10

E.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

^{1}As-Received

^{2}Dry Basis

E.3 Chemical Composition of Kiln Feed

Table E.1: CPR – Chemical composition of kiln feed for VF 15% burn

Property (wt. %)	Sample Number			
	1	2	3	4
Al_2O_3	3.01	3.05	2.91	2.94
CaO	43.07	42.63	42.85	42.98
Fe_2O_3	1.86	1.90	1.88	1.90
K_2O	0.31	0.32	0.30	0.30
MgO	2.28	2.31	2.41	2.35
Na_2O	0.06	0.06	0.05	0.05
Na_2O_{eq}	0.26	0.27	0.25	0.25
P_2O_5	NC	NC	NC	NC
SiO_2	12.97	13.28	13.08	13.14
SO_3	0.19	0.24	0.20	0.20
LOI	36.29	35.98	36.26	36.30

E.4 Chemical Composition of Clinker

Table E.2: CPR – Chemical composition of CKD for VF 15% burn

Property (wt. %)	SampleNumber		
	1	2	3
Al_2O_3	3.41	3.61	3.48
CaO	45.67	45.7	46.1
Fe_2O_3	1.85	1.89	1.86
K_2O	0.44	0.44	0.44
MgO	1.84	1.87	1.96
Na_2O	0.1	0.11	0.1
SiO_2	11.36	11.72	11.48
SO_3	1.12	1.12	1.15

Table E.3: ELR – Chemical composition of CKD for VF 15% burn

Property (wt. %)	Sample Number		
	1	2	3
Al_2O_3	3.78	3.96	3.89
CaO	46.87	46.04	47.61
Fe_2O_3	1.86	1.96	1.96
K_2O	0.46	0.45	0.44
MgO	2.12	1.82	2.00
Na_2O	0.05	0.05	0.06
P_2O_5	0.05	0.05	0.06
SiO_2	11.31	12.01	11.52
SO_3	1.24	0.90	1.29
TiO_2	0.19	0.20	0.20
Moisture	0.09	0.05	0.04
LOI	32.00	32.48	30.91
Property (ppm)	**1**	**2**	**3**
As	34	52	48
Cd	< 6	< 6	< 6
Cl	163	168	188
Co	14	11	12
Cr	107	67	38
Cu	64	40	47
Hg	0.019	0.024	0.025
Mo	8	7	< 5
Ni	112	31	19
Pb	45	< 5	10
Se	< 2	< 2	< 2
V	646	116	59
Zn	64	54	66

E.5 Chemical Composition of Fuels

Table E.4: ELR – Proximate, ultimate, and combustion analysis of waste plastics for VF 15% burn

Test	Parameter	Sample Number								
		1	2	3	4	5	6	7	8	9
Proximate Analysis	**Ash**	2.75	13.05	5.53	9.96	8.13	6.84	5.97	6.75	2.92
	Fixed Carbon	7.05	6.3	11.18	7.68	6.9	8.64	10.65	8.09	7.99
	Moisture [1]	0.26	0.53	1.63	1.03	0.21	1.64	0.95	1.07	0.95
	Volatile Matter	90.2	80.65	83.29	82.36	84.97	84.52	83.38	85.16	89.09
Ultimate Analysis	**Carbon**	62.89	44.43	56.85	61.01	62.93	59.25	53.51	58.32	61.02
	Hydrogen	5	5.05	5.64	6.11	6.22	5.95	5.85	5.85	5.59
	Nitrogen	1.41	0.44	1.62	2.38	0.01	2.35	0.43	1.68	1.57
	Oxygen	27.5	36.67	29.89	20.35	22.69	25.29	33.92	27.05	28.57
	Sulfur	0.45	0.36	0.47	0.19	0.02	0.32	0.32	0.35	0.33
Heat Value [2] (BTU/lb)		10949	10419	10159	11272	11753	12232	9229	10657	10695

Table E.5: ELR – Proximate, ultimate, and combustion analysis of woodchips for VF 15% burn

Test	Parameter	Sample Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Proximate Analysis	**Ash**	19.87	15.2	12.73	1.23	11.13	16.35	16.8	15.13	15.3	11.35	12.01	13.58
	Fixed Carbon	15.82	16.51	17.03	17.66	16.43	13.93	16.04	17.24	16.58	16.49	16.61	16.57
	Moisture [1]	5.52	3.91	52.98	30.21	46.5	50.87	5.11	51.36	47.25	44.09	44.52	39.73
	Volatile Matter	64.31	68.29	70.24	81.11	72.44	69.72	67.16	67.63	68.12	72.16	71.38	69.85
Ultimate Analysis	**Carbon**	42.13	46	46.09	54.03	47.84	42.65	46.37	46.12	45.83	48.2	46.68	46.44
	Hydrogen	4.47	4.89	4.9	5.85	5.15	4.44	5	4.95	4.95	5.18	5.02	5.02
	Nitrogen	0.37	0.3	0.29	0.19	0.29	0.26	0.34	0.33	0.34	0.28	0.34	0.27
	Oxygen	33.12	33.58	35.98	38.68	35.58	36.29	31.46	33.46	33.57	34.98	35.94	34.68
	Sulfur	0.04	0.03	0.01	0.02	0.01	0.01	0.03	0.01	0.01	0.01	0.01	0.01
Heat Value [2] **(BTU/lb)**		7053	7281	7698	8605	7861	7135	7146	7244	7285	7534	7448	7507

Table E.6: ELR – Chemical compositions of waste plastics for VF 15% burn

Test	Parameter (wt. %)	Sample Number								
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Standard Parameters	**Al_2O_3**	8.79	0.72	7.77	11.76	2.91	15.16	23.94	10.09	8.33
	CaO	46.40	78.12	36.87	37.83	3.63	39.62	28.18	38.32	46.61
	Fe_2O_3	1.69	0.35	6.05	3.34	0.99	4.02	2.82	2.40	1.52
	K_2O	0.34	0.11	0.36	0.36	0.05	0.37	0.35	0.51	0.43
	MgO	12.88	15.29	8.54	14.64	74.88	8.64	12.50	16.32	13.10
	Na_2O	0.72	0.04	1.27	1.24	0.13	1.44	1.66	1.25	1.11
	P_2O_5	0.54	0.05	0.52	0.70	0.10	0.75	0.58	0.56	0.45
	SiO_2	13.53	1.67	24.37	21.39	3.86	25.72	21.65	21.37	16.01
	SO_3	13.53	1.67	24.37	21.39	3.86	25.72	21.65	21.37	16.01
	TiO_2	4.13	3.00	1.30	2.93	13.11	1.91	2.55	3.59	4.21
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
	As	13	5	16	18	5	5	5	5	31
	Cd	6	6	6	6	6	6	6	6	6
	Cl	380	156	521	390	126	373	266	267	354
	Co	806	165	440	250	53	109	129	103	359
	Cr	296	64	5440	169	707	196	445	223	373
	Cu	571	68	915	305	151	167	104	476	1050
	Hg	0.020	0.014	0.005	0.009	0.005	0.016	0.005	0.005	0.005
	Mo	5	5	116	11	24	9	6	5	5
	Ni	188	16	2390	108	377	109	116	145	183
	Pb	123	22	86	66	97	94	119	436	183
	Se	2	2	2	2	2	2	2	2	2
	V	269	169	75	302	829	196	226	233	45
	Zn	448	105	320	639	306	543	863	1410	4930

Table E.7: ELR – Chemical compositions of woodchips for VF 15% burn

Test	Parameter (wt. %)	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	7.69	8.85	7.28	11.47	8.71	3.98	8.45	8.15	8.31	8.17	8.84	8.39
	CaO	8.51	7.31	5.01	14.88	9.21	54.09	14.33	6.83	9.75	15.93	12.88	8.55
	Fe_2O_3	15.40	9.06	8.93	7.50	16.02	6.32	9.62	9.17	10.35	13.58	8.70	7.31
	K_2O	1.37	1.53	1.30	3.01	1.81	0.95	1.95	1.44	1.45	1.48	1.59	1.38
	MgO	1.87	1.57	1.35	5.37	1.84	1.44	2.72	1.36	1.41	4.45	1.78	2.21
	Na_2O	0.28	0.39	0.27	1.39	0.36	0.19	0.38	0.33	0.25	0.31	0.34	0.34
	P_2O_5	0.17	0.20	0.16	0.42	0.20	0.09	0.20	0.18	0.18	0.17	0.20	0.16
	SiO_2	63.19	69.66	74.40	53.51	60.23	32.12	60.60	71.15	66.94	54.55	64.10	70.44
	SO_3	63.19	69.66	74.40	53.51	60.23	32.12	60.60	71.15	66.94	54.55	64.10	70.44
	TiO_2	0.74	0.83	0.74	1.17	0.82	0.39	0.92	0.76	0.82	0.75	0.92	0.76
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	23	33	31	5	29	5	24	20	17	15	21	28
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	271	470	222	143	197	175	212	309	237	249	219	220
	Co	25	24	21	7	35	22	26	36	29	137	89	20
	Cr	657	441	1570	1070	441	188	261	590	446	1380	607	778
	Cu	89	361	132	347	126	101	180	241	164	192	117	125
	Hg	0.016	0.027	0.029	0.010	0.050	0.006	0.012	0.092	0.052	0.008	0.027	0.020
	Mo	15	41	31	60	20	5	7	12	9	75	16	19
	Ni	141	191	742	556	194	77	134	257	213	277	243	314
	Pb	47	57	48	592	72	57	113	76	80	68	65	51
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	76	67	67	5	64	5	67	71	83	113	79	77
	Zn	305	279	260	896	337	110	306	296	244	205	220	206

E.6 Chemical Composition of Clinker

Table E.8 CPR – Chemical composition of clinker for VF 15% burn

Property (wt. %)	Sample Number												
	1	2	3	4	5	6	7	8	9	10	11	12	13
Al_2O_3	4.87	4.96	4.80	4.89	4.85	4.91	4.84	4.87	4.80	4.84	4.70	4.62	4.58
CaO	64.47	64.05	64.27	64.04	64.17	64.13	64.19	63.87	64.32	64.04	64.10	64.32	64.56
Fe_2O_3	3.31	3.38	3.31	3.35	3.34	3.39	3.42	3.40	3.38	3.40	3.33	3.38	3.38
K_2O	0.51	0.53	0.55	0.53	0.56	0.55	0.54	0.54	0.57	0.52	0.54	0.52	0.56
MgO	3.52	3.65	3.54	3.62	3.61	3.69	3.71	3.72	3.63	3.81	3.71	3.80	3.45
Na_2O	0.07	0.06	0.07	0.06	0.06	0.07	0.06	0.08	0.07	0.06	0.06	0.06	0.08
Na_2O_{eq}	0.41	0.41	0.43	0.41	0.43	0.43	0.42	0.44	0.45	0.40	0.42	0.40	0.45
SiO_2	21.09	21.26	21.04	21.11	21.14	21.21	21.20	21.14	21.17	21.12	20.92	20.85	20.94
SO_3	1.05	1.07	0.85	1.06	1.00	1.12	0.99	1.13	1.02	1.19	1.13	1.12	1.06
F CaO	1.16	NC	1.63	NC	NC	1.33	1.63	1.02	2.45	0.78	0.68	1.77	2.72
C_3A	7.30	7.43	7.12	7.29	7.20	7.28	7.04	7.15	7.00	7.07	6.82	6.52	6.42
C_4AF	10.07	10.29	10.07	10.19	10.16	10.32	10.41	10.35	10.29	10.35	10.13	10.29	10.29
C_3S	64.72	61.02	64.76	62.63	63.21	62.04	62.79	61.77	63.87	62.82	65.62	67.52	68.08
C_2S	11.64	14.92	11.47	13.27	12.92	14.00	13.41	14.01	12.51	13.16	10.47	8.84	8.68

Table E.9: ELR – Chemical composition of clinker for VF 15% burn

Property (wt. %)	Sample Number	
	1	2
Al_2O_3	5.07	4.99
CaO	63.55	63.60
Fe_2O_3	3.23	3.36
K_2O	0.47	0.35
MgO	3.93	4.02
Na_2O	0.04	0.04
P_2O_5	0.07	0.06
SiO_2	21.77	21.44
SO_3	1.28	1.16
TiO_2	0.24	0.25
Moisture	0.00	0.00
LOI	0.22	0.59
Property (ppm)	**1**	**2**
As	42	47
Cd	< 6	< 6
Cl	494	263
Co	10	13
Cr	59	55
Cu	21	25
Hg	0.006	0.009
Mo	9	8
Ni	11	12
Pb	20	< 5
Se	< 2	< 2
V	56	56
Zn	48	49

Table E.10: SLR – Rietveld analysis of clinker for VF 15% burn

Property (wt. %)	Sample Number	
	1	2
Alite (C_3S)	49.43	40.39
Belite (C_2S)	29.78	35.27
Ferrite (C_4AF)	11.20	10.57
Aluminate (C_3A)	4.13	3.48

E.7 Plant Emissions

Table E.11: CPR – Normalized plant emissions for VF 15% burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
7/16/2010 12:00:00	8.47E-04	9.35E-06	1.30E-05	3.79E-04
7/16/2010 13:00:00	8.58E-04	6.71E-06	1.45E-05	3.48E-04
7/16/2010 14:00:00	8.95E-04	8.60E-06	1.39E-05	3.10E-04
7/16/2010 15:00:00	7.76E-04	-	2.54E-05	3.32E-04
7/16/2010 16:00:00	8.83E-04	7.69E-06	1.21E-05	3.10E-04
7/16/2010 17:00:00	7.78E-04	5.50E-06	9.67E-06	2.96E-04
7/16/2010 18:00:00	7.71E-04	7.05E-06	8.48E-06	3.10E-04
7/16/2010 19:00:00	8.35E-04	6.51E-06	1.28E-05	3.43E-04
7/16/2010 20:00:00	9.62E-04	6.84E-06	1.61E-05	3.05E-04
7/16/2010 21:00:00	9.62E-04	7.06E-06	1.64E-05	3.01E-04
7/16/2010 22:00:00	9.79E-04	7.68E-06	1.64E-05	3.00E-04
7/16/2010 23:00:00	7.84E-04	8.74E-06	1.31E-05	3.45E-04
7/17/2010 0:00:00	7.82E-04	1.06E-05	1.21E-05	3.38E-04
7/17/2010 1:00:00	8.67E-04	8.59E-06	1.49E-05	2.92E-04
7/17/2010 2:00:00	9.71E-04	9.33E-06	1.79E-05	3.33E-04
7/17/2010 3:00:00	9.17E-04	7.48E-06	1.69E-05	3.00E-04
7/17/2010 4:00:00	8.15E-04	9.23E-06	1.36E-05	3.05E-04
7/17/2010 5:00:00	8.03E-04	6.96E-06	1.47E-05	3.07E-04
7/17/2010 6:00:00	8.20E-04	1.07E-05	1.95E-05	2.48E-04
7/17/2010 7:00:00	9.00E-04	6.82E-06	2.22E-05	2.93E-04
7/17/2010 8:00:00	9.63E-04	1.34E-05	2.38E-05	3.37E-04
7/17/2010 9:00:00	9.20E-04	1.45E-05	2.17E-05	3.56E-04
7/17/2010 10:00:00	8.53E-04	1.25E-05	1.70E-05	3.58E-04
7/17/2010 11:00:00	7.76E-04	1.53E-05	1.46E-05	3.65E-04
7/17/2010 12:00:00	8.82E-04	1.32E-05	2.23E-05	3.15E-04
7/17/2010 13:00:00	8.64E-04	1.23E-05	1.60E-05	3.23E-04
7/17/2010 14:00:00	8.27E-04	1.38E-05	1.36E-05	3.33E-04
7/17/2010 15:00:00	8.09E-04	1.63E-05	1.47E-05	3.23E-04
7/17/2010 16:00:00	7.98E-04	1.58E-05	1.40E-05	3.43E-04
7/17/2010 17:00:00	9.13E-04	1.29E-05	1.97E-05	3.46E-04
7/17/2010 18:00:00	8.09E-04	1.76E-05	1.56E-05	3.01E-04
7/17/2010 19:00:00	8.45E-04	1.37E-05	1.53E-05	2.72E-04
7/17/2010 20:00:00	8.13E-04	1.40E-05	1.50E-05	2.56E-04
7/17/2010 21:00:00	9.48E-04	1.37E-05	1.86E-05	2.79E-04
7/17/2010 22:00:00	9.61E-04	1.28E-05	2.01E-05	2.63E-04
7/17/2010 23:00:00	8.60E-04	1.41E-05	1.63E-05	2.93E-04
7/18/2010 0:00:00	8.85E-04	1.42E-05	1.85E-05	2.56E-04
7/18/2010 1:00:00	1.03E-03	1.61E-05	2.38E-05	3.02E-04
7/18/2010 2:00:00	8.82E-04	1.06E-05	1.86E-05	2.93E-04
7/18/2010 3:00:00	9.76E-04	1.65E-05	2.52E-05	3.02E-04

Appendix F

Raw Data for the Soybean seed Burn

F.1 General Comments

- Raw data from the soybean seed burn are presented in this section. Only raw data not presented in former chapters are presented here.
- Coal, waste plastics, and woodchips were the fuels utilized during this burn.
- This burn lasted from 12 AM on 10/18/10 to 9 PM on 10/21/10

F.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

^{1}As-Received

^{2}Dry Basis

F.3 Chemical Composition of Kiln Feed

Table F.1: CPR – Chemical composition of kiln feed for soybean burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.20	3.19	3.14	3.24	3.09	3.24
CaO	42.53	42.62	42.41	42.69	42.65	42.62
Fe_2O_3	1.90	1.91	1.91	1.91	1.86	1.92
K_2O	0.28	0.28	0.27	0.28	0.28	0.28
MgO	2.25	2.30	2.30	2.27	2.41	2.34
Na_2O	0.05	0.05	0.04	0.04	0.05	0.05
Na_2O_{eq}	0.23	0.23	0.22	0.22	0.23	0.23
P_2O_5	NC	NC	NC	NC	NC	NC
SiO_2	13.33	13.29	13.06	13.13	13.10	13.15
SO_3	0.23	0.21	0.20	0.18	0.18	0.16
LOI	35.84	35.97	35.79	35.98	36.11	36.01

F.4 Chemical Composition of Cement Kiln Dust

Table F.2: CPR – Chemical composition of CKD for soybean burn

Property (wt. %)	Sample Number					
	1	2	3	4	5	6
Al_2O_3	3.78	3.82	3.86	3.85	3.86	3.99
CaO	44.74	44.67	44.31	44.25	46.19	44.25
Fe_2O_3	1.97	1.95	2	1.95	1.86	1.99
K_2O	0.37	0.37	0.39	0.36	0.5	0.39
MgO	1.6	1.49	1.59	1.53	2.08	1.47
Na_2O	0.08	0.08	0.08	0.08	0.1	0.08
SiO_2	10.94	10.76	11.04	11.12	10.31	11.04
SO_3	0.43	0.22	0.48	0.11	2.48	0.34

Table F.3: ELR – Chemical composition of CKD for soybean burn

Property (wt. %)	**Sampel Number**					
	1	**2**	**3**	**4**	**5**	**6**
Al_2O_3	3.26	4.19	4.17	4.27	4.38	4.18
CaO	41.79	45.05	45.47	44.72	45.66	43.40
Fe_2O_3	1.87	1.86	2.00	1.91	2.06	1.93
K_2O	0.27	0.38	0.38	0.37	0.38	0.35
MgO	2.37	1.78	1.79	1.63	1.86	1.62
Na_2O	0.03	0.03	0.03	0.04	0.06	0.04
P_2O_5	0.04	0.05	0.06	0.06	0.07	0.06
SiO_2	13.73	11.24	11.12	11.01	11.35	11.14
SO_3	0.21	0.71	0.94	0.60	1.05	0.17
TiO_2	0.17	0.21	0.22	0.21	0.22	0.22
Moisture	0.08	0.12	0.12	0.13	0.09	0.07
LOI	36.19	34.42	33.72	35.07	32.83	36.79
Property (ppm)	**1**	**2**	**3**	**4**	**5**	**6**
As	6.00	69.00	47.00	21.00	72.00	38.00
Cd	< 6	< 6	< 6	< 6	< 6	< 6
Cl	76.00	124.00	155.00	104.00	153.00	89.00
Co	< 6	11.00	10.00	12.00	11.00	16.00
Cr	63.50	50.00	60.00	70.40	49.80	40.00
Cu	82.00	58.00	83.00	60.00	51.00	39.00
Hg	0.12	0.07	0.10	0.46	0.24	0.24
Mo	< 5	< 5	9.00	< 5	< 5	< 5
Ni	30.00	29.00	36.00	25.00	36.00	24.00
Pb	39.00	-2.00	39.00	81.00	< 5	22.00
Se	< 2	< 2	< 2	< 2	3.00	< 2
V	36.00	48.00	44.00	63.00	54.00	55.00
Zn	70.00	101.00	116.00	145.00	160.00	152.00

F.5 Chemical Composition of Fuels

Table F.4: ELR – Proximate, ultimate, and combustion analysis of waste plastics for soybean burn

Test	Parameter	Sample Number											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Proximate Analysis	**Ash**	0.3	3.88	16.2	2.28	1.08	5.13	7.58	5.7	10.6	11.48	3.65	5.6
	Fixed Carbon	10.64	12.37	8.38	9.28	9.01	9.21	9.71	11.53	9.19	8.74	11.85	10.75
	Moisture [1]	2.51	0.57	1.61	1.05	1.98	2.18	2.57	2.5	1.67	2.12	1.98	1.18
	Volatile Matter	89.06	83.75	75.42	88.44	89.91	85.66	82.71	82.77	80.21	79.78	84.5	83.65
Ultimate Analysis	**Carbon**	58.41	61.79	53.45	67.97	61.67	63.87	59.64	50.14	49.87	53.35	56.49	57.51
	Hydrogen	6.15	5.76	5.58	7.62	6.1	6.95	6.19	4.96	4.94	4.9	5.32	5.74
	Nitrogen	1.4	1.25	0.94	0.28	1.23	1.58	1.73	0.58	0.8	0.94	0.92	1.35
	Oxygen	33.35	27.13	23.61	21.68	29.66	22.31	24.64	38.38	33.64	29.15	33.24	29.56
	Sulfur	0.39	0.19	0.22	0.17	0.26	0.16	0.22	0.24	0.15	0.18	0.38	0.24
Heat Value [2] (BTU/lb)		9518	11008	9736	12804	10977	12009	10482	10299	7868	7852	9418	10332

Table F.5: ELR – Proximate, ultimate, and combustion analysis of waste plastics for soybean burn (continued)

Test	Parameter	Sample Number													
		13	14	15	16	17	18	19	20	21	22	23	24	25	26
Proximate Analysis	Ash	0.98	5.52	8.01	4.54	2.9	1.77	6.08	5.16	5.03	1.95	4.6	1.93	18.7	11.2
	Fixed Carbon	9.37	6.54	10.25	3.74	3.41	2.85	3.18	1.96	6.56	8.2	13.43	14.01	12.22	8.45
	Moisture [1]	0.65	0.54	2.8	0.61	1.15	0.04	0.72	0.48	1.37	2.48	10.66	4.35	5.29	9.17
	Volatile Matter	89.65	87.94	81.74	91.72	93.69	95.38	90.74	92.88	88.41	89.85	81.97	84.06	69.08	80.35
Ultimate Analysis	Carbon	66.8	63.04	51.88	64.16	68.92	79.78	75.42	75.6	59.72	57.21	56.97	50.32	55.43	59.32
	Hydrogen	5.22	6.07	5.73	6.18	7.79	9.02	8.59	8.52	6.74	6.81	6.8	5.39	5.31	6.07
	Nitrogen	0.98	1.37	1.33	2.21	0.31	0.1	0.53	0.6	1.93	0.1	6.58	0.1	0.7	0.35
	Oxygen	25.91	23.88	32.76	22.55	19.93	9.3	9.26	10.1	26.26	33.61	24.83	42.03	19.7	22.83
	Sulfur	0.11	0.12	0.29	0.36	0.15	0.03	0.12	0.02	0.32	0.32	0.22	0.23	0.16	0.23
Heat Value [2] (BTU/lb)		11699	12196	9622	11114	13786	16940	14290	14725	12332	10392	10199	7795	9627	10100

Table F.6: ELR – Proximate, ultimate, and combustion analysis of soybean seeds for soybean burn

Test	**Parameter**	**Sample Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Proximate Analysis	**Ash**	4.69	4.5	4.71	4.55	4.58	4.48	4.57	4.78	4.7	4.77	4.51	4.46
	Fixed Carbon	14.17	13.71	13.77	13.91	13.58	13.75	14.34	14.05	14.32	13.8	14.17	13.78
	Moisture [1]	10.67	10.05	10.57	10.15	9.2	10.76	9.31	9.87	10.18	10.54	10.92	11.13
	Volatile Matter	81.14	81.79	81.52	81.54	81.84	81.77	81.09	81.17	80.98	81.43	81.32	81.76
Ultimate Analysis	**Carbon**	56.53	57.81	57.14	57.43	58.37	57.6	57.34	57.14	56.67	57.01	57.14	56.94
	Hydrogen	6.81	6.92	6.88	6.93	7.03	6.89	6.82	6.75	6.83	6.81	6.87	6.76
	Nitrogen	6.74	6.74	6.64	6.62	6.62	6.51	6.67	6.61	6.59	6.62	6.57	6.59
	Oxygen	24.98	23.78	24.37	24.22	23.15	24.28	24.36	24.51	24.99	24.58	24.67	25.03
	Sulfur	0.25	0.25	0.26	0.25	0.25	0.24	0.24	0.21	0.22	0.21	0.24	0.22
Heat Value [2] **(BTU/lb)**		10198	10276	10295	10302	10325	10067	10003	9977	9994	10048	10284	10289

Table F.7: ELR – Proximate, ultimate, and combustion analysis of soybean seeds for soybean burn (continued)

Test	Parameter	Sample Number											
		13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Proximate Analysis	**Ash**	4.53	4.55	4.57	4.53	4.55	4.53	4.76	4.78	4.8	4.61	4.52	4.47
	Fixed Carbon	14.14	13.67	13.22	13.46	14.73	13.83	14.36	13.63	14.35	14.32	13.99	13.9
	Moisture [1]	10.6	10.82	10.48	10.37	10.53	10.5	10.01	10.93	9.33	10.69	10.9	11.43
	Volatile Matter	81.33	81.78	82.21	82.01	80.72	81.64	80.88	81.59	80.85	81.07	81.49	81.63
Ultimate Analysis	**Carbon**	57.61	57.19	56.97	56.9	57.23	56.87	56.56	56.81	56.58	56.99	57.01	57.36
	Hydrogen	6.77	6.82	6.78	6.82	6.81	6.78	6.76	6.79	6.81	6.82	6.82	6.85
	Nitrogen	6.49	6.58	6.6	6.56	6.67	6.57	6.6	6.57	6.62	6.58	6.5	6.58
	Oxygen	24.4	24.64	24.87	24.95	24.52	25.02	25.11	24.85	25	24.8	24.96	24.53
	Sulfur	0.2	0.22	0.21	0.24	0.22	0.23	0.21	0.2	0.19	0.2	0.19	0.21
Heat Value [2] (BTU/lb)		10253	10376	10251	10324	10293	10269	10129	10166	10187	10292	10253	10270

Table F.8: ELR – Chemical composition of waste plastics for soybean burn

Test	**Parameter (wt. %)**	**Sample Number**											
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Standard Parameters	**Al_2O_3**	9.66	1.57	11.52	3.81	6.26	9.27	11.90	7.17	2.56	2.01	2.66	5.75
	CaO	17.51	34.89	25.03	35.79	24.68	30.19	24.77	56.38	60.21	62.57	58.46	54.61
	Fe_2O_3	3.56	0.55	0.53	1.07	1.25	0.62	0.40	1.44	0.45	0.47	0.48	0.71
	K_2O	1.08	0.26	0.45	0.46	0.72	2.05	2.72	0.36	0.45	0.24	0.41	1.15
	MgO	7.05	51.58	4.12	39.17	28.11	15.11	7.28	12.68	27.92	28.17	28.60	17.61
	Na_2O	14.84	0.40	1.03	0.70	3.97	1.33	1.22	1.25	0.41	0.32	0.56	1.19
	P_2O_5	3.52	0.64	0.30	1.20	1.24	1.32	1.86	0.49	0.26	0.17	0.29	1.16
	SiO_2	19.34	3.47	46.39	7.08	18.80	34.75	46.78	17.07	6.35	4.72	5.97	12.45
	SO_3	4.38	0.38	2.58	0.77	1.84	0.60	0.44	1.02	0.41	0.44	0.53	0.87
	TiO_2	17.26	5.86	0.80	9.44	12.76	4.56	2.49	1.84	0.85	0.76	1.92	4.11
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	5	5	8	5	7	5	5	5	5	5	5	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	149	2216	222	294	138	266	356	578	403	338	317	293
	Co	484	82	25	167	130	130	113	36	27	44	72	214
	Cr	1907	226	113	491	124	239	302	94	82	117	139	507
	Cu	3519	111	20	243	1417	603	222	86	61	66	98	287
	Hg	0.079	0.044	0.058	0.060	0.050	0.072	0.062	0.118	0.191	0.147	0.173	0.231
	Mo	5	5	5	5	5	5	5	5	5	10	5	84
	Ni	397	31	50	96	100	30	40	19	14	28	12	29
	Pb	173	5	5	87	80	78	79	98	94	76	156	32
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	1286	373	132	564	962	335	207	103	31	23	78	204
	Zn	8076	332	22216	548	685	311	253	277	118	99	137	311

Table F.9: ELR – Chemical composition of waste plastics for soybean burn (continued)

Test	Parameter (wt. %)	Sample Number													
		13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Standard Parameters	**Al_2O_3**	19.29	6.26	5.10	13.19	7.89	4.88	1.93	2.15	0.95	8.78	0.20	13.26	18.61	5.29
	CaO	25.98	62.94	59.03	41.45	44.33	45.44	69.05	62.35	81.25	40.58	8.03	10.45	38.59	55.18
	Fe_2O_3	2.92	2.31	0.51	0.87	1.48	0.84	0.59	0.69	0.50	1.73	0.38	1.15	0.32	0.51
	K_2O	1.13	0.51	0.28	0.72	0.91	0.33	0.27	0.24	0.86	0.31	49.69	0.79	0.16	0.21
	MgO	19.42	6.49	12.86	18.19	16.21	13.61	16.65	22.19	11.42	15.08	10.26	16.04	10.49	19.76
	Na_2O	3.32	0.59	0.86	1.25	0.61	0.38	0.20	0.23	0.39	1.35	0.51	4.11	0.55	0.44
	P_2O_5	1.34	0.23	0.17	0.71	0.80	0.38	0.26	0.20	0.30	0.99	27.67	0.68	1.23	0.87
	SiO_2	19.09	14.32	17.89	17.20	13.76	9.60	4.94	4.57	2.58	29.34	0.57	39.96	29.07	16.78
	SO_3	1.49	1.71	0.92	1.08	1.26	1.37	0.88	0.93	0.43	0.32	2.15	3.74	0.25	0.39
	TiO_2	4.86	4.31	2.17	4.74	11.10	19.57	4.01	5.20	0.93	1.17	0.13	9.63	0.49	0.25
	Parameter (ppm)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
	As	5	62	5	5	5	20	9	5	5	22	10	5	5	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	99	362	249	416	119	60	103	79	182	401	101	202	570	614
	Co	372	156	77	372	117	142	50	68	169	18	23	6	10	13
	Cr	206	278	130	687	202	165	99	87	308	100	35	37	71	50
	Cu	601	380	201	755	420	657	197	252	323	62	151	119	5	54
	Hg	0.164	0.150	0.108	0.274	0.302	0.135	0.517	0.102	0.072	0.092	0.139	0.076	0.081	0.059
	Mo	15	8	5	6	27	32	5	5	5	8	175	62	5	5
	Ni	39	34	5	3	660	788	11	448	11	22	86	140	10	11
	Pb	209	76	5	126	96	98	23	59	132	21	5	104	29	89
	Se	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	V	313	262	91	266	586	1006	226	257	30	89	5	708	36	5
	Zn	938	604	145	634	8041	18141	3336	4745	188	371	1123	466	244	229

Table F.10: ELR – Chemical composition of soybean seeds for soybean burn

Test	Parameter (wt. %)	Sample Number											
		1	2	3	4	5	6	7	8	9	10	11	12
Standard Parameters	**Al_2O_3**	0.21	0.23	0.23	0.20	0.76	0.31	0.28	0.23	0.21	0.20	0.24	0.24
	CaO	7.80	8.07	8.02	7.76	7.47	7.63	7.79	8.88	9.00	9.13	8.12	7.95
	Fe_2O_3	0.33	0.33	0.34	0.36	0.31	0.35	0.24	0.33	0.26	0.28	0.28	0.41
	K_2O	48.52	48.55	47.75	50.27	49.11	51.31	51.85	50.45	51.05	50.57	52.23	51.00
	MgO	10.18	10.40	10.13	10.32	10.17	10.32	9.87	10.67	10.69	10.73	9.94	10.33
	Na_2O	0.59	0.70	1.21	0.13	0.26	0.14	0.14	0.12	0.24	0.32	0.24	0.30
	P_2O_5	29.01	28.30	28.22	27.84	27.10	27.68	27.95	26.63	26.62	26.70	27.10	27.27
	SiO_2	0.53	0.63	0.84	0.62	3.10	0.95	0.75	0.58	0.55	0.54	0.67	0.68
	SO_3	2.36	2.27	2.71	2.02	1.24	0.83	0.49	1.58	0.89	1.02	0.67	1.30
	TiO_2	0.11	0.12	0.13	0.12	0.12	0.11	0.12	0.12	0.10	0.11	0.12	0.11
	Parameter (ppm)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
	As	5	5	10	5	5	5	33	5	5	5	7	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	93	103	105	106	100	99	111	103	92	84	91	103
	Co	29	16	26	29	12	19	20	20	22	24	21	21
	Cr	24	41	33	15	56	37	30	19	14	29	8	49
	Cu	213	112	266	182	56	64	26	43	41	48	41	64
	Hg	0.122	0.122	0.211	0.117	0.106	0.091	0.085	0.760	0.329	0.124	0.111	0.093
	Mo	135	192	182	173	147	133	87	176	146	147	163	152
	Ni	274	100	91	57	35	61	50	48	35	34	28	66
	Pb	133	5	5	59	192	104	5	53	11	96	5	5
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	5	5	5	5	5	5	5	5	5	5	5	5
	Zn	1094	1103	1088	1123	1090	1142	1487	1182	975	995	1025	1132

Table F.11: ELR – Chemical composition of soybean seeds for soybean burn (continued)

Test	Parameter (wt. %)	Sample Number											
		13	14	15	16	17	18	19	20	21	22	23	24
Standard Parameters	Al_2O_3	0.30	0.24	0.39	0.27	0.27	0.23	0.23	0.23	0.19	0.28	0.23	0.27
	CaO	7.82	8.11	8.04	8.25	8.03	7.95	9.10	8.56	8.84	8.10	7.69	7.75
	Fe_2O_3	0.30	0.34	0.31	0.32	0.34	0.33	0.29	0.34	0.33	0.28	0.41	0.38
	K_2O	52.18	51.78	51.94	53.08	52.00	51.85	51.40	50.21	50.13	52.18	50.56	50.35
	MgO	9.93	10.06	9.77	9.65	9.79	9.88	10.48	10.30	10.55	9.82	10.24	10.33
	Na_2O	0.30	0.27	0.71	0.44	0.30	0.32	0.28	0.40	0.22	0.32	0.33	0.36
	P_2O_5	27.00	27.09	26.42	26.06	26.70	27.05	26.25	26.61	26.62	26.94	27.64	27.54
	SiO_2	0.96	0.66	0.96	0.74	1.04	0.65	0.61	0.60	0.50	0.77	0.65	0.68
	SO_3	0.67	0.93	0.88	0.63	0.92	1.18	0.84	2.22	2.12	0.71	1.80	1.90
	TiO_2	0.11	0.11	0.13	0.12	0.14	0.14	0.12	0.11	0.11	0.14	0.11	0.12
	Parameter (ppm)	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
	As	5	9	5	5	5	9	5	5	5	5	5	5
	Cd	6	6	6	6	6	6	6	6	6	6	6	6
	Cl	100	97	90	93	98	96	104	91	100	91	93	99
	Co	11	22	21	27	25	23	16	17	16	28	24	18
	Cr	24	20	41	27	29	25	23	9	44	30	15	36
	Cu	37	65	54	53	49	61	43	239	197	47	172	259
	Hg	0.096	0.094	0.090	0.092	0.096	0.339	0.282	0.210	0.167	0.188	0.103	0.095
	Mo	144	142	151	123	133	192	129	178	149	137	153	200
	Ni	43	161	58	42	60	54	29	94	61	37	54	60
	Pb	72	5	22	52	102	5	53	129	35	118	96	61
	Se	2	2	2	2	2	2	2	2	2	2	2	2
	V	5	5	5	5	5	5	5	5	5	5	5	5
	Zn	1017	1078	996	958	1009	1046	916	1021	996	980	1110	1147

F.6 Chemical Composition of Clinker

Table F.12: CPR – Chemical composition of clinker for soybean burn

Property (wt. %)	**Sample Number**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Al_2O_3	4.81	4.86	4.96	4.66	4.90	5.16	4.84	4.79	4.86	4.81	4.93	4.87
CaO	65.45	64.52	65.00	64.69	64.86	64.25	65.11	65.16	65.07	65.25	64.48	64.63
Fe_2O_3	3.39	3.41	3.44	3.34	3.53	3.57	3.50	3.42	3.45	3.43	3.54	3.42
K_2O	0.47	0.47	0.52	0.49	0.42	0.53	0.43	0.46	0.46	0.49	0.49	0.58
MgO	3.32	3.25	3.36	3.30	3.46	3.50	3.51	3.51	3.57	3.57	3.60	3.54
Na_2O	0.05	0.04	0.05	0.05	0.04	0.05	0.05	0.05	0.05	0.04	0.05	0.05
Na_2O_{eq}	0.36	0.35	0.39	0.37	0.32	0.39	0.33	0.35	0.35	0.37	0.37	0.44
SiO_2	20.92	20.57	20.87	20.87	20.93	20.69	21.08	21.05	20.97	20.98	21.01	20.97
SO_3	1.36	1.39	1.41	1.11	1.41	1.76	1.10	1.15	1.12	1.11	1.27	1.43
F CaO	0.95	1.43	1.70	1.16	0.44	0.99	0.95	1.39	1.36	1.60	0.68	1.29
C_3A	7.01	7.11	7.32	6.70	7.01	7.62	6.90	6.91	7.04	6.94	7.08	7.12
C_4AF	10.32	10.38	10.46	10.16	10.75	10.86	10.66	10.39	10.50	10.43	10.76	10.39
C_3S	70.29	68.80	67.84	68.66	67.02	64.57	67.35	68.27	67.95	69.00	64.65	66.19
C_2S	6.95	7.07	8.64	8.04	9.44	10.61	9.62	8.84	8.86	8.09	11.47	10.18

Table F.13: CPR – Chemical composition of clinker for soybean burn (continued)

Property (wt. %)	Sample Number										
	13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Al_2O_3	4.70	4.77	4.77	4.92	4.68	4.79	4.68	4.78	4.83	4.99	4.84
CaO	65.26	65.16	65.15	64.96	65.51	65.11	65.42	65.18	64.98	64.60	64.88
Fe_2O_3	3.38	3.41	3.40	3.40	3.34	3.40	3.38	3.40	3.42	3.51	3.42
K_2O	0.49	0.48	0.54	0.53	0.49	0.51	0.48	0.51	0.51	0.47	0.55
MgO	3.60	3.55	3.55	3.54	3.55	3.54	3.50	3.53	3.54	3.58	3.54
Na_2O	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.05	0.05
Na_2O_{eq}	0.37	0.36	0.41	0.40	0.37	0.39	0.37	0.38	0.37	0.35	0.41
SiO_2	21.21	21.13	21.03	21.09	21.11	20.89	20.89	21.07	21.10	20.99	21.08
SO_3	1.12	1.19	1.25	1.18	1.06	1.30	1.13	1.11	1.16	1.27	1.17
F CaO	0.61	0.61	0.65	0.68	1.02	0.75	1.80	1.02	1.19	0.51	1.12
C_3A	6.73	6.87	6.89	7.29	6.75	6.93	6.68	6.91	7.01	7.29	7.04
C_4AF	10.28	10.37	10.33	10.34	10.16	10.34	10.29	10.34	10.42	10.69	10.41
C_3S	68.11	67.79	68.51	66.24	70.04	69.28	71.29	68.24	66.81	64.89	66.51
C_2S	9.42	9.43	8.61	10.49	7.69	7.63	6.11	8.93	10.10	11.23	10.26

Table F.14: ELR – Chemical composition of clinker for soybean burn

Property (wt. %)	Sample Number				
	1	2	3	4	5
Al_2O_3	5.26	5.19	5.10	5.95	5.45
CaO	64.04	64.25	64.22	63.40	63.40
Fe_2O_3	3.45	3.46	3.29	3.37	3.41
K_2O	0.44	0.38	0.45	0.49	0.46
MgO	3.73	3.79	3.89	3.91	3.86
Na_2O	0.04	0.05	0.05	0.04	0.04
P_2O_5	0.07	0.07	0.07	0.08	0.07
SiO_2	21.02	21.26	21.28	21.09	21.25
SO_3	1.44	1.11	1.20	1.17	1.15
TiO_2	0.27	0.27	0.27	0.27	0.27
Moisture	0.00	0.00	0.00	0.00	0.01
LOI	0.10	0.03	0.05	0.11	0.46
Property (ppm)	**1**	**2**	**3**	**4**	**5**
As	34	77	76	42	76
Cd	< 6	< 6	< 6	< 6	< 6
Cl	85	35	35	61	56
Co	11	10	7	8	7
Cr	62	65	72	78	72
Cu	41	44	35	52	42
Hg	0.013	0.065	0.043	0.056	<0.010
Mo	< 5	6	< 5	9	< 5
Ni	22	25	23	44	32
Pb	89	15	8	77	39
Se	< 2	< 2	< 2	< 2	< 2
V	25	48	37	57	35
Zn	69	73	85	107	108

Table F.15: SLR – Rietveld analysis of clinker for soybean burn

Property (wt. %)	Sample Number				
	1	2	3	4	5
Alite (C_3S)	63.26	61.77	63.98	62.44	60.54
Belite (C_2S)	18.59	19.54	17.38	17.68	19.83
Ferrite (C_4AF)	10.56	10.74	10.55	10.93	11.11
Aluminate (C_3A)	2.84	3.34	3.25	3.48	4.13

F.7 Chemical Composition of Cement

Table F.16: ELR – Chemical composition of cement for soybean burn

Property (wt. %)	Sample Number	
	1	2
Al_2O_3	4.92	4.85
CaO	62.38	62.43
Fe_2O_3	3.19	3.16
K_2O	0.39	0.26
MgO	3.68	3.62
Na_2O	0.05	0.05
P_2O_5	0.07	0.09
SiO_2	19.67	19.45
SO_3	3.19	3.28
TiO_2	0.25	0.25
Moisture	0.50	0.56
LOI	2.06	2.43
Property (ppm)	**1**	**2**
As	60	65
Cd	< 6	< 6
Cl	107	135
Co	< 6	< 6
Cr	63	128
Cu	66	47
Hg	0.055	0.219
Mo	< 5	< 5
Ni	29	26
Pb	10	21
Se	< 2	< 2
V	31	43
Zn	94	80

Table F.17: Rietveld analysis of cement for soybean burn

Property (wt. %)	Sample Number	
	1	2
Alite (C_3S)	58.33	56.81
Belite (C_2S)	17.39	18.63
Ferrite (C_4AF)	10.15	10.06
Aluminate (C_3A)	2.93	3.28

F.8 Plant Emissions

Table F.18: CPR – Normalized emissions for soybean burn

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
11/4/09 8:00	1.06E-03	1.30E-05	2.42E-05	3.36E-04
11/4/09 9:00	1.13E-03	1.42E-05	3.14E-05	3.82E-04
11/4/09 10:00	1.08E-03	1.06E-05	2.75E-05	3.76E-04
11/4/09 11:00	1.14E-03	1.39E-05	2.93E-05	3.90E-04
11/4/09 12:00	1.27E-03	1.35E-05	2.99E-05	4.28E-04
11/4/09 13:00	1.12E-03	9.41E-06	2.62E-05	4.19E-04
11/4/09 14:00	1.06E-03	1.08E-05	2.86E-05	3.72E-04
11/4/09 15:00	1.06E-03	1.28E-05	2.75E-05	4.00E-04
11/4/09 16:00	1.15E-03	1.16E-05	-	4.36E-04
11/4/09 17:00	1.32E-03	1.05E-05	-	4.50E-04
11/4/09 18:00	1.15E-03	1.03E-05	-	4.64E-04
11/4/09 19:00	6.65E-04	1.01E-05	2.91E-05	4.82E-04
11/4/09 20:00	6.59E-04	1.27E-05	2.77E-05	4.75E-04
11/4/09 21:00	6.23E-04	1.26E-05	2.41E-05	4.27E-04
11/4/09 22:00	6.84E-04	1.28E-05	2.48E-05	4.02E-04
11/4/09 23:00	7.23E-04	9.56E-06	2.32E-05	3.93E-04
11/5/09 0:00	8.32E-04	1.43E-05	2.36E-05	4.23E-04
11/5/09 1:00	8.16E-04	1.07E-05	2.44E-05	4.55E-04
11/5/09 2:00	8.05E-04	1.35E-05	2.39E-05	2.79E-04
11/5/09 3:00	8.29E-04	1.19E-05	2.31E-05	5.95E-05
11/5/09 4:00	8.37E-04	1.29E-05	2.57E-05	1.29E-07
11/5/09 5:00	8.79E-04	1.06E-05	2.29E-05	5.02E-04
11/5/09 6:00	9.13E-04	9.69E-06	2.28E-05	4.68E-04
11/5/09 7:00	8.96E-04	1.15E-05	2.22E-05	5.04E-04
11/5/09 8:00	8.88E-04	1.57E-05	2.30E-05	3.92E-05
11/5/09 9:00	8.97E-04	1.33E-05	2.02E-05	5.87E-07
11/5/09 10:00	9.38E-04	1.10E-05	2.18E-05	3.26E-09
11/5/09 11:00	9.00E-04	8.72E-06	2.57E-05	4.33E-04
11/5/09 12:00	9.34E-04	1.31E-05	2.74E-05	3.63E-04
11/5/09 13:00	1.00E-03	1.26E-05	3.07E-05	2.81E-06
11/5/09 14:00	6.99E-04	9.91E-06	3.37E-05	5.42E-04
11/5/09 15:00	9.07E-04	1.49E-05	4.28E-05	5.69E-04
11/5/09 16:00	1.12E-03	1.14E-05	3.26E-05	5.94E-04
11/5/09 17:00	8.54E-04	1.02E-05	3.71E-05	5.77E-04
11/5/09 18:00	9.21E-04	1.33E-05	-	1.45E-05

Table F.19: CPR – Normalized emissions for soybean burn (continued)

Time	NOx (tons/ton clinker)	SO2 (tons/ton clinker)	VOC (tons/ton clinker)	CO (tons/ton clinker)
11/5/09 19:00	1.11E-03	1.26E-05	3.79E-05	1.07E-06
11/5/09 20:00	9.16E-04	1.23E-05	3.90E-05	8.03E-05
11/5/09 21:00	9.50E-04	9.92E-06	3.58E-05	5.72E-04
11/5/09 22:00	9.06E-04	1.31E-05	4.21E-05	6.59E-04
11/5/09 23:00	8.91E-04	1.31E-05	3.22E-05	5.83E-04
11/6/09 0:00	9.51E-04	1.70E-05	2.88E-05	1.29E-04
11/6/09 1:00	9.43E-04	1.18E-05	2.93E-05	1.14E-08
11/6/09 2:00	1.02E-03	1.27E-05	2.40E-05	0.00E+00
11/6/09 3:00	9.49E-04	1.43E-05	2.17E-05	1.06E-04
11/6/09 4:00	9.65E-04	1.39E-05	2.40E-05	4.98E-04
11/6/09 5:00	9.98E-04	1.11E-05	2.51E-05	4.95E-04
11/6/09 6:00	9.20E-04	1.65E-05	2.49E-05	9.63E-05
11/6/09 7:00	9.23E-04	9.73E-06	2.63E-05	5.80E-07
11/6/09 8:00	7.92E-04	9.49E-06	2.57E-05	2.07E-07
11/6/09 9:00	8.27E-04	7.69E-06	2.52E-05	4.02E-04
11/6/09 10:00	9.15E-04	6.59E-06	2.78E-05	5.43E-04
11/6/09 11:00	1.03E-03	8.26E-06	2.97E-05	5.50E-04
11/6/09 12:00	9.86E-04	5.33E-06	3.08E-05	5.49E-04
11/6/09 13:00	9.05E-04	7.95E-06	3.05E-05	5.02E-04
11/6/09 14:00	8.55E-04	6.69E-06	3.86E-05	1.59E-04
11/6/09 15:00	1.09E-03	6.96E-06	3.41E-05	2.21E-07
11/6/09 16:00	1.13E-03	1.99E-05	2.87E-05	0.00E+00
11/6/09 17:00	1.09E-03	3.00E-05	3.21E-05	3.00E-07
11/6/09 18:00	8.25E-04	2.42E-05	2.40E-05	3.62E-04
11/6/09 19:00	8.81E-04	1.90E-05	2.55E-05	4.92E-04
11/6/09 20:00	1.19E-03	2.36E-05	2.75E-05	5.37E-04
11/6/09 21:00	8.48E-04	2.59E-05	2.30E-05	4.90E-04
11/6/09 22:00	9.71E-04	-	2.59E-05	8.93E-05
11/6/09 23:00	1.05E-03	2.72E-05	2.10E-05	6.42E-06
11/7/09 0:00	1.01E-03	2.51E-05	1.88E-05	1.71E-07
11/7/09 1:00	9.69E-04	2.74E-05	1.47E-05	5.08E-08
11/7/09 2:00	8.50E-04	1.91E-05	1.31E-05	3.83E-04
11/7/09 3:00	8.97E-04	2.46E-05	2.73E-05	4.76E-04
11/7/09 4:00	9.78E-04	-	2.80E-05	4.99E-04
11/7/09 5:00	9.51E-04	2.92E-05	2.84E-05	5.00E-04

Appendix G

Statistical analysis

G.1 General Comments

- The normality of data sets were checked using the Anderson-Daring test. This test was performed for all raw data containing more than 10 samples.
- The Wilcoxon rank-sum test was used in order to compare the mean of the parameters in each trial burn to the baseline burn mean parameters. This test was performed for all raw data containing more than 10 samples.
- The results of the Anderson-Darling and Wilcoxon rank-sum tests are presented followed by an example of their respective outputs from SAS

G.2 Notation

CPR – Cement Plant Results

ELR – External Laboratory Results

NC – Not Collected

^{1}Data not normally distributed

^{2}Differences between means are statistically significant

G.3 Anderson-Darling Test for Normality

Table G.1: ELR – A-D p-values of waste plastic parameters for all burns

Property	**Burn**					
	B-CP	**C&D**	**VF 5%**	**VF 10%**	**VF 15%**	**Soy**
Ash	0.005[1]	0.25	0.25	0.25	0.25	0.0053[1]
Fixed Carbon	0.0273[1]	0.25	0.005[1]	0.25	0.2259	0.0598[1]
Moisture	0.005[1]	0.25	0.006[1]	0.25	0.25	0.005[1]
Volatile Matter	0.005[1]	0.25	0.0129[1]	0.25	0.25	0.25
Carbon	0.088[1]	0.0485[1]	0.0849[1]	0.25	0.0695[1]	0.2332
Hydrogen	>0.25	0.005[1]	0.0477[1]	0.25	0.25	0.023[1]
Nitrogen	0.0105[1]	0.005[1]	0.25	0.0185[1]	0.25	0.005[1]
Oxygen	>0.25	0.2396	0.25	0.25	0.25	0.25
Sulfur	0.0574[1]	0.25	0.0904[1]	0.0192[1]	0.1046	0.25
HEAT VALUE	>0.25	0.005[1]	0.0222[1]	0.25	0.25	0.1341
Al_2O_3 (wt. %)	0.005[1]	0.1683	0.005[1]	0.1963	0.25	0.1036
CaO (wt. %)	0.2297	0.005[1]	0.25	0.25	0.0828[1]	0.25
Fe_2O_3 (wt. %)	0.027[1]	0.0094[1]	0.0341[1]	0.0346[1]	0.25	0.005[1]
K_2O (wt. %)	0.005[1]	0.005[1]	0.25	0.005[1]	0.25	0.005[1]
MgO (wt. %)	0.1615	0.0214[1]	0.25	0.1374	0.005[1]	0.022[1]
NC2O (wt. %)	0.005[1]	0.005[1]	0.005[1]	0.25	0.0927[1]	0.005[1]
P_2O_5 (wt. %)	>0.25	0.005[1]	0.0138[1]	0.1647	0.0827[1]	0.005[1]
SiO_2 (wt. %)	0.1082	0.25	0.25	0.005[1]	0.1008	0.0123[1]
SO_3 (wt. %)	0.1487	0.005[1]	0.0927[1]	0.005[1]	0.25	0.005[1]
TiO_2 (wt. %)	>0.25	0.25	0.1932	0.0055[1]	0.005[1]	0.005[1]
As (ppm)	NC	0.005[1]	0.005[1]	0.005[1]	0.0131[1]	0.005[1]
Cd (ppm)	NC	NC	NC	NC	NC	NC
Cl (ppm)	0.005[1]	0.25	0.005[1]	0.2185	0.25	0.005[1]
Co (ppm)	0.005[1]	0.1851	0.25	0.005[1]	0.0592[1]	0.005[1]
Cr (ppm)	0.005[1]	0.005[1]	0.0343[1]	0.005[1]	0.005[1]	0.005[1]
Cu (ppm)	0.005[1]	0.005[1]	0.25	0.005[1]	0.1706	0.005[1]
Hg (ppm)	NA	0.005[1]	0.005[1]	0.005[1]	0.0096[1]	0.005[1]
Mo (ppm)	NA	0.005[1]	0.005[1]	0.005[1]	0.005[1]	0.005[1]
Ni (ppm)	0.005[1]	0.005[1]	0.005[1]	0.005[1]	0.005[1]	0.005[1]
Pb (ppm)	0.005[1]	0.005[1]	0.25	0.008[1]	0.005[1]	0.1504
Se (ppm)	NC	NC	NC	NC	NC	NC
V (ppm)	0.0206[1]	0.0192[1]	0.005[1]	0.009[1]	0.0074[1]	0.005[1]
Zn (ppm)	0.005[1]	0.005[1]	0.0135[1]	0.005[1]	0.005[1]	0.005[1]

Table G.2: ELR – A-D p-values of alternative fuel parameters for all burns

Property	Burn				
	C&D	**VF 5%**	**VF 10%**	**VF 15%**	**Soy**
Ash	0.0224[1]	>0.25	0.0745[1]	0.0556[1]	0.005[1]
Fixed Carbon	0.2289	0.087[1]	0.0364[1]	0.019[1]	>0.25
Moisture	0.005[1]	0.2417	>0.25	0.005[1]	0.0989[1]
Volatile Matter	0.0868[1]	>0.25	0.1419	0.069[1]	>0.25
Carbon	0.0246[1]	>0.25	0.1037	0.0138[1]	>0.25
Hydrogen	0.02[1]	>0.25	0.123	0.0268[1]	0.0124[1]
Nitrogen	>0.25	>0.25	0.0211[1]	>0.25	0.0863[1]
Oxygen	>0.25	>0.25	0.0204[1]	>0.25	0.0126[1]
Sulfur	>0.25	0.005[1]	0.005[1]	0.005[1]	0.0877[1]
HEAT VALUE	0.1657	>0.25	0.0244[1]	0.0467[1]	0.005[1]
Al_2O_3 (wt. %)	0.2104	>0.25	0.2405	0.005[1]	0.005[1]
CaO (wt. %)	>0.25	0.0148[1]	0.0058[1]	0.005[1]	0.005[1]
Fe_2O_3 (wt. %)	0.005[1]	>0.25	0.005[1]	0.0422[1]	>0.25
K_2O (wt. %)	0.0695[1]	0.1584	0.005[1]	0.005[1]	0.1269
MgO (wt. %)	>0.25	0.005[1]	>0.25	0.005[1]	>0.25
NC2O (wt. %)	0.005[1]	0.005[1]	0.0174[1]	0.005[1]	0.005[1]
P_2O_5 (wt. %)	0.005[1]	>0.25	0.0115[1]	0.005[1]	0.2244
SiO_2 (wt. %)	>0.25	0.023[1]	0.0943[1]	0.090[1]7	0.005[1]
SO_3 (wt. %)	0.0435[1]	0.005[1]	>0.25	>0.25	0.01[1]
TiO_2 (wt. %)	0.005[1]	0.005[1]	>0.25	0.0229[1]	0.005[1]
As (ppm)	0.005[1]	0.005[1]	0.005[1]	>0.25	NC
Cd (ppm)	NC	NC	NC	NC	NC
Cl (ppm)	0.005[1]	0.005[1]	>0.25	0.01[1]85	>0.25
Co (ppm)	0.006[1]	0.005[1]	0.005[1]	0.00[1]5	>0.25
Cr (ppm)	0.005[1]	0.0311[1]	0.005[1]	0.1128	>0.25
Cu (ppm)	0.005[1]	0.005[1]	0.005[1]	0.024[1]8	0.005[1]
Hg (ppm)	NC	0.0412[1]	0.009[1]	0.023[1]8	0.005[1]
Mo (ppm)	0.005[1]	>0.25	0.005[1]	0.0215[1]	0.219
Ni (ppm)	0.005[1]	0.25	0.1503	0.0094[1]	0.005[1]
Pb (ppm)	0.0221[1]	0.1662	0.005[1]	0.005[1]	0.0296[1]
Se (ppm)	NC	0.0412[1]	0.0099[1]	0.0238[1]	NC
V (ppm)	0.0091[1]	>0.25	0.0288[1]	0.005[1]	NC
Zn (ppm)	0.005[1]	0.005[1]	0.073[1]	0.005[1]	0.00[1]69

Table G.3: CPR – A-D p-values of clinker parameters for all burns

Property	Burn					
	B-CP	C&D	VF 5%	VF 10%	VF 15%	Soy
Al_2O_3	0.0542[1]	0.25	0.25	0.25	0.0579[1]	0.25
CaO	0.005[1]	0.25	0.25	0.25	>0.25	>0.25
Fe_2O_3	0.0057[1]	0.0079[1]	0.0616[1]	0.25	0.1709	0.006[1]
K_2O	0.0336[1]	0.25	0.25	0.25	>0.25	>0.25
MgO	0.0953[1]	0.0304[1]	0.25	0.25	>0.25	0.005[1]
Na_2O	0.0169[1]	0.005[1]	0.0327[1]	0.005[1]	0.005[1]	0.005[1]
$Na2O_{eq}$	0.0436[1]	0.25	0.25	0.2099	0.2322	0.25
SiO_2	0.005[1]	0.005[1]	0.25	0.2185	0.2396	0.099[1]
SO_3	0.005[1]	0.0142[1]	0.25	0.25	>0.25	0.006[1]
F CaO	0.0091[1]	0.005[1]	0.2493	0.0152[1]	0.25	>0.25
C_3A	0.25	0.25	0.25	0.25	0.0911[1]	0.1872
C_4AF	0.0057[1]	0.0079[1]	0.0616[1]	0.25	0.1709	0.006[1]
C_3S	0.2151	0.25	0.25	0.25	0.25	>0.25
C_2S	0.0814[1]	0.25	0.25	0.25	0.2249	>0.25

Table G.4: CPR – A-D p-values of emissions for all burns

Emission	Burn					
	B-CP	C&D	VF 5%	VF 10%	VF 15%	Soy
NO_x	0.0468[1]	>0.25	0.0943[1]	>0.25	0.0829[1]	0.2005
SO_2	<0.005[1]	0.1082	>0.25	>0.25	0.0511[1]	<0.005[1]
VOC	<0.005[1]	0.01[1]	<0.005[1]	0.1102	<0.005[1]	0.0099[1]
CO	>0.25	0.0185[1]	>0.25	>0.25	<0.005[1]	<0.005[1]

G.3.1 Example Anderson-Darling Test output from SAS

Test results were generated from Soybean seed emissions data. The bolded value indicates the Anderson darling statistic.

The UNIVARIATE Procedure

Variable: NO_x

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.982529	**Pr < W**	0.4372
Kolmogorov-Smirnov	**D**	0.086168	**Pr > D**	>0.1500
Cramer-von Mises	**W-Sq**	0.089252	**Pr > W-Sq**	0.1565
Anderson-Darling	**A-Sq**	0.50933	**Pr > A-Sq**	**0.2005**

The UNIVARIATE Procedure

Variable: SO_2

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.845328	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.228715	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.740944	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	4.079757	**Pr > A-Sq**	**<0.0050**

The UNIVARIATE Procedure

Variable: VOC

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.959028	**Pr < W**	0.0286
Kolmogorov-Smirnov	**D**	0.096804	**Pr > D**	0.1266
Cramer-von Mises	**W-Sq**	0.163443	**Pr > W-Sq**	0.0167
Anderson-Darling	**A-Sq**	1.025197	**Pr > A-Sq**	**0.0099**

The UNIVARIATE Procedure

Variable: CO

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.840865	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.209747	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.770901	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	4.575984	**Pr > A-Sq**	**<0.0050**

G.4 Wilcoxon rank-sum Test

Table G.5: ELR – WRS - p-values of waste plastics for all burns

Property	**C&D**	**VF5%**	**VF10%**	**VF15%**	**Soy**
Ash	0.4133	0.0284^2	0.5624	0.5115	0.1870
Fixed Carbon	0.8134	0.2112	0.0138^2	0.0212^2	0.2060
Moisture	0.4018	0.1132	0.0003^2	0.0007^2	0.0069^2
Volatile Matter	0.7818	0.5795	0.1114	0.5115	0.1380
Carbon	0.0005^2	0.3918	1.0000	0.5115	0.2093
Hydrogen	0.0036^2	0.1016	0.9878	0.5174	0.5430
Nitrogen	0.0075^2	0.6178	0.2150	0.3757	0.7786
Oxygen	0.0005^2	0.0816^2	0.3464	0.5365	0.1611
Sulfur	0.0767^2	0.0362^2	0.0001^2	0.0061^2	0.0731^2
HEAT VALUE	0.0001^2	0.0123^2	0.099^2	0.3175	0.3183
Al$_2$O$_3$ (wt. %)	0.079^2	0.2162	0.6915	0.0232^2	0.0001^2
CaO (wt. %)	0.6817	0.0226^2	0.0287^2	0.011^2	0.0003^2
Fe$_2$O$_3$ (wt. %)	0.0001^2	0.0123^2	0.1181	0.3362	0.0001^2
K$_2$O (wt. %)	0.0187^2	0.0132^2	0.0003^2	0.0756^2	0.0301^2
MgO (wt. %)	0.0131^2	0.0009^2	0.0004^2	0.0002^2	0.0001^2
NC2O (wt. %)	0.4386	0.1877	0.0016^2	0.0212^2	0.0013^2
P$_2$O$_5$ (wt. %)	0.0407^2	0.7184	0.011^2	0.5365	0.2027
SiO$_2$ (wt. %)	0.0014^2	0.0293^2	0.0005^2	0.0013^2	0.0002^2
SO$_3$ (wt. %)	0.0001^2	0.8460	0.0076^2	0.2348	0.0001^2
TiO$_2$ (wt. %)	0.0014^2	0.7814	0.5222	0.7276	0.6871
As (ppm)	0.4631	0.5346	0.1915	0.7001	0.5079
Cd (ppm)	1.0000	1.0000	1.0000	1.0000	1.0000
Cl (ppm)	0.0001^2	0.0815^2	0.0008^2	0.0253^2	0.0015^2
Co (ppm)	0.0006^2	0.0468^2	0.3945	0.2823	0.0707^2
Cr (ppm)	0.0001^2	0.0011^2	0.4649	0.1581	0.0001^2
Cu (ppm)	0.0001^2	0.0048^2	0.0043^2	0.0505^2	0.0002^2
Hg (ppm)	0.1981	0.0296^2	0.5150	0.1237	0.0001^2
Mo (ppm)	0.0015^2	0.0053^2	0.5504	0.0143^2	0.0001^2
Ni (ppm)	0.0017^2	0.0003^2	0.3312	0.9382	0.0003^2
Pb (ppm)	0.0003^2	0.0233^2	0.0006^2	0.0039^2	0.0001^2
Se (ppm)	1.0000	1.0000	1.0000	1.0000	1.0000
V (ppm)	0.0003^2	0.7288	0.6691	0.2065	0.3094
Zn (ppm)	0.0001^2	0.0005^2	0.0001^2	0.0016^2	0.0001^2

Table G.6: CPR – WRS p-values of clinker for all burns

Property	C&D	VF 5%	VF 10%	VF 15%	Soy
Al_2O_3	<0.0001[2]	<0.0001[2]	<0.0001[2]	0.0024[2]	<0.0001[2]
CaO	0.1211	0.0356[2]	0.0546[2]	0.0002[2]	0.0075[2]
Fe_2O_3	0.4086	0.0023[2]	0.8977	0.0014[2]	0.0001[2]
K_2O	<0.0001[2]	<0.0001[2]	<0.0001[2]	0.0002[2]	0.0503[2]
MgO	<0.0001[2]	0.0001[2]	0.0001[2]	0.0143[2]	0.1138[2]
Na_2O	0.2035	0.0006[2]	0.4778	0.0885[2]	0.0001[2]
$Na2O_{eq}$	0.0001[2]	0.0001[2]	0.0001[2]	0.0001[2]	0.7875
SiO_2	0.0001[2]	0.0001[2]	0.0001[2]	0.0003[2]	0.0001[2]
SO_3	0.375	0.0002[2]	0.311	0.0023[2]	0.0001[2]
F CaO	0.0424[2]	0.793	0.3822	0.374	0.1976
C_3A	0.0001[2]	0.0001[2]	0.0001[2]	0.0016[2]	0.0001[2]
C_4AF	0.4139	0.0022[2]	0.8877	0.0014[2]	0.0001[2]
C_3S	0.0002[2]	0.5556	0.6263	0.2884	0.0001[2]
C_2S	0.0001[2]	0.8376	0.5386	0.8786	0.0001[2]

Table G.7: CPR – WRS p-values of emissions for all burns

Emission	C&D	VF 5%	VF 10%	VF 15%	Soy
NO_x	<0.0001[2]	<0.0001[2]	0.0001[2]	0.0077[2]	0.7471
SO_2	<0.0001[2]	<0.0001[2]	<0.0001[2]	0.0074[2]	0.001[2]
VOC	<0.0001[2]	<0.0001[2]	<0.0001[2]	<0.0001[2]	<0.0001[2]
CO	0.0075[2]	0.1729	0.5137	<0.0001[2]	0.499

G.4.1 Example Wilcoxon rank - sum output from SAS

Test results were generated from carbon monoxide emissions data collected over all burns. The bolded value indicates the utilized p-value.

CO emission for all burns

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable cd Classified by Variable treatment

treatment	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
baseline	69	5887.50	5175.0	262.676128	85.326087
trial	80	5287.50	6000.0	262.676128	66.093750

Average scores were used for ties.

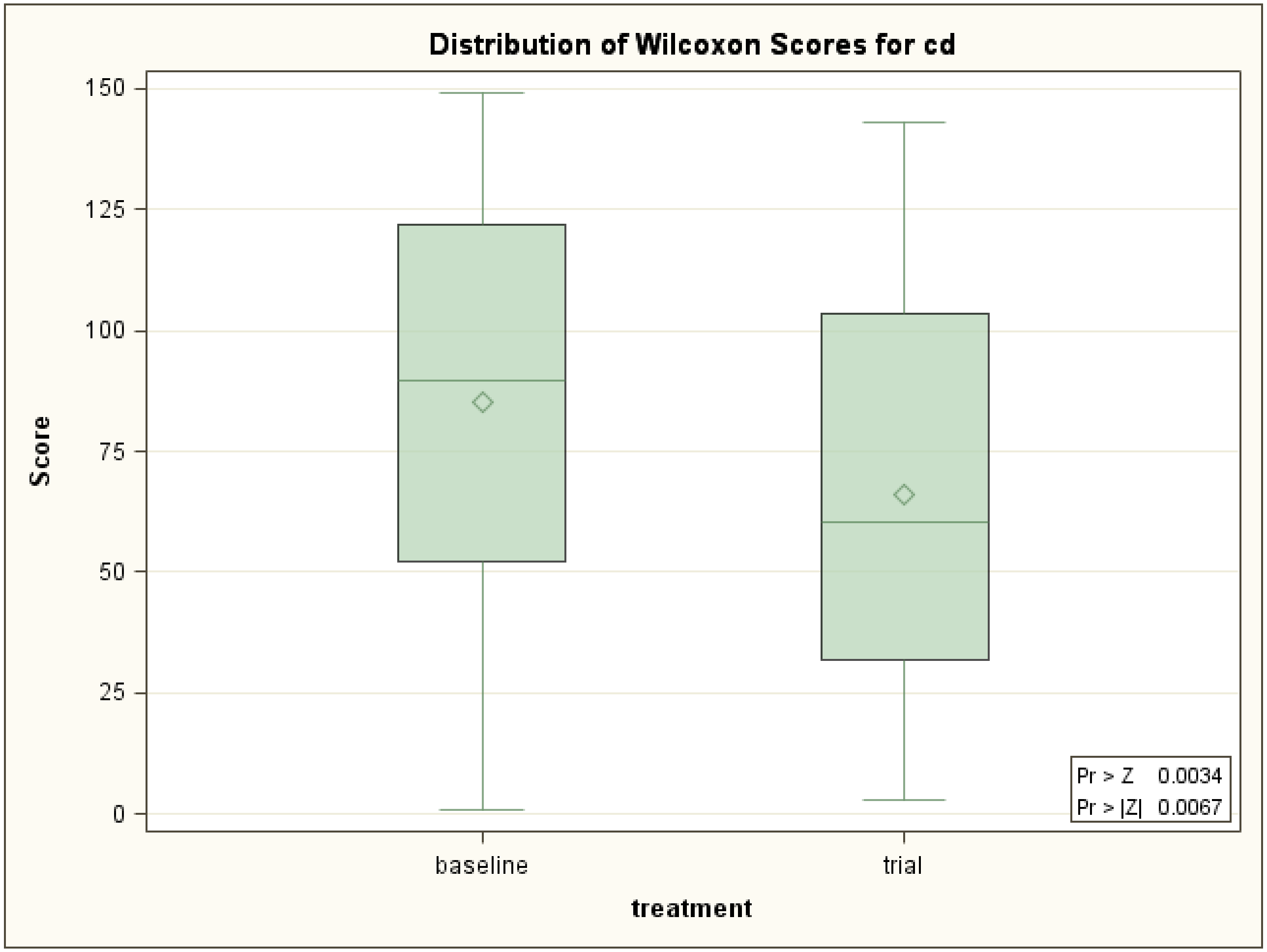
Wilcoxon Two-Sample Test

Statistic	5887.5000
Normal Approximation	
Z	2.7106
One-Sided Pr > Z	0.0034
Two-Sided Pr > |Z|	0.0067
t Approximation	
One-Sided Pr > Z	0.0038
Two-Sided Pr > |Z|	**0.0075**

Z includes a continuity correction of 0.5.

Kruskal-Wallis Test

Chi-Square	7.3575
DF	1
Pr > Chi-Square	0.0067


Distribution of Wilcoxon Scores for cd
Score
150
125
100
75
50
25
0
baseline
trial
treatment
Pr > Z 0.0034
Pr > |Z| 0.0067

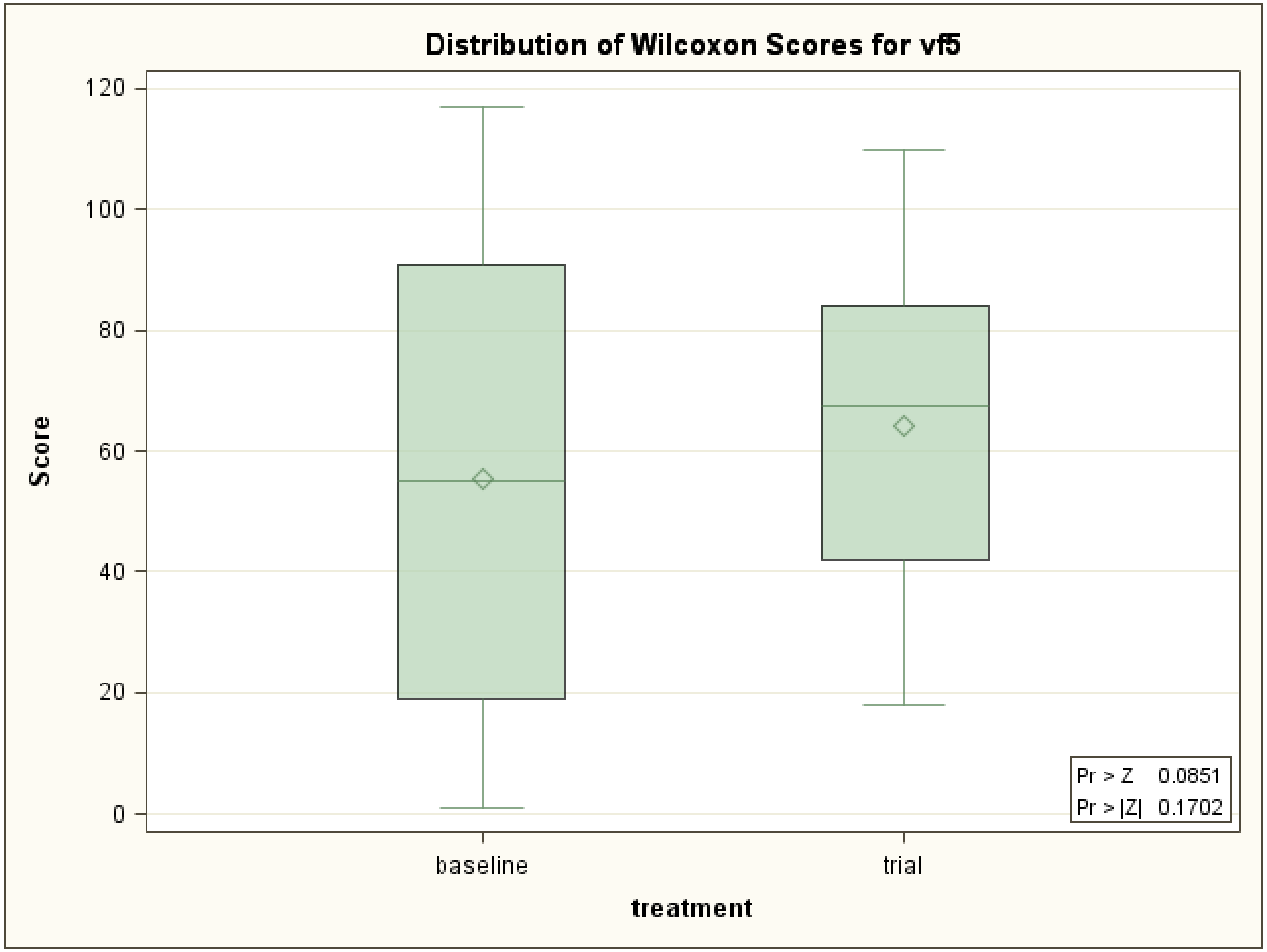
CO emission for all burns

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable vf5 Classified by Variable treatment					
treatment	**N**	**Sum of Scores**	**Expected Under H0**	**Std Dev Under H0**	**Mean Score**
baseline	69	3823.0	4071.0	180.465387	55.405797
trial	48	3080.0	2832.0	180.465387	64.166667
Average scores were used for ties.					

Wilcoxon Two-Sample Test	
Statistic	3080.0000
Normal Approximation	
Z	1.3715
One-Sided Pr > Z	0.0851
Two-Sided Pr > |Z|	0.1702
t Approximation	
One-Sided Pr > Z	0.0864
Two-Sided Pr > |Z|	**0.1729**
Z includes a continuity correction of 0.5.	

Kruskal-Wallis Test	
Chi-Square	1.8885
DF	1
Pr > Chi-Square	0.1694


Distribution of Wilcoxon Scores for vf5
Score
120
100
80
60
40
20
0
baseline
trial
treatment
Pr > Z 0.0851
Pr > |Z| 0.1702

CO emission for all burns

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable vf10 Classified by Variable treatment

treatment	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
baseline	69	3919.50	4036.50	177.816658	56.804348
trial	47	2866.50	2749.50	177.816658	60.989362

Average scores were used for ties.

Wilcoxon Two-Sample Test	
Statistic	2866.5000
Normal Approximation	
Z	0.6552
One-Sided Pr > Z	0.2562
Two-Sided Pr > |Z|	0.5124
t Approximation	
One-Sided Pr > Z	0.2568
Two-Sided Pr > |Z|	**0.5137**

Z includes a continuity correction of 0.5.

Kruskal-Wallis Test	
Chi-Square	0.4329
DF	1
Pr > Chi-Square	0.5106


Distribution of Wilcoxon Scores for vf10
Score
120
100
80
60
40
20
0
baseline
trial
treatment
Pr > Z 0.2562
Pr > |Z| 0.5124

CO emission for all burns

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable vf15 Classified by Variable treatment

treatment	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
baseline	69	4937.50	3795.0	159.059369	71.557971
trial	40	1057.50	2200.0	159.059369	26.437500

Average scores were used for ties.

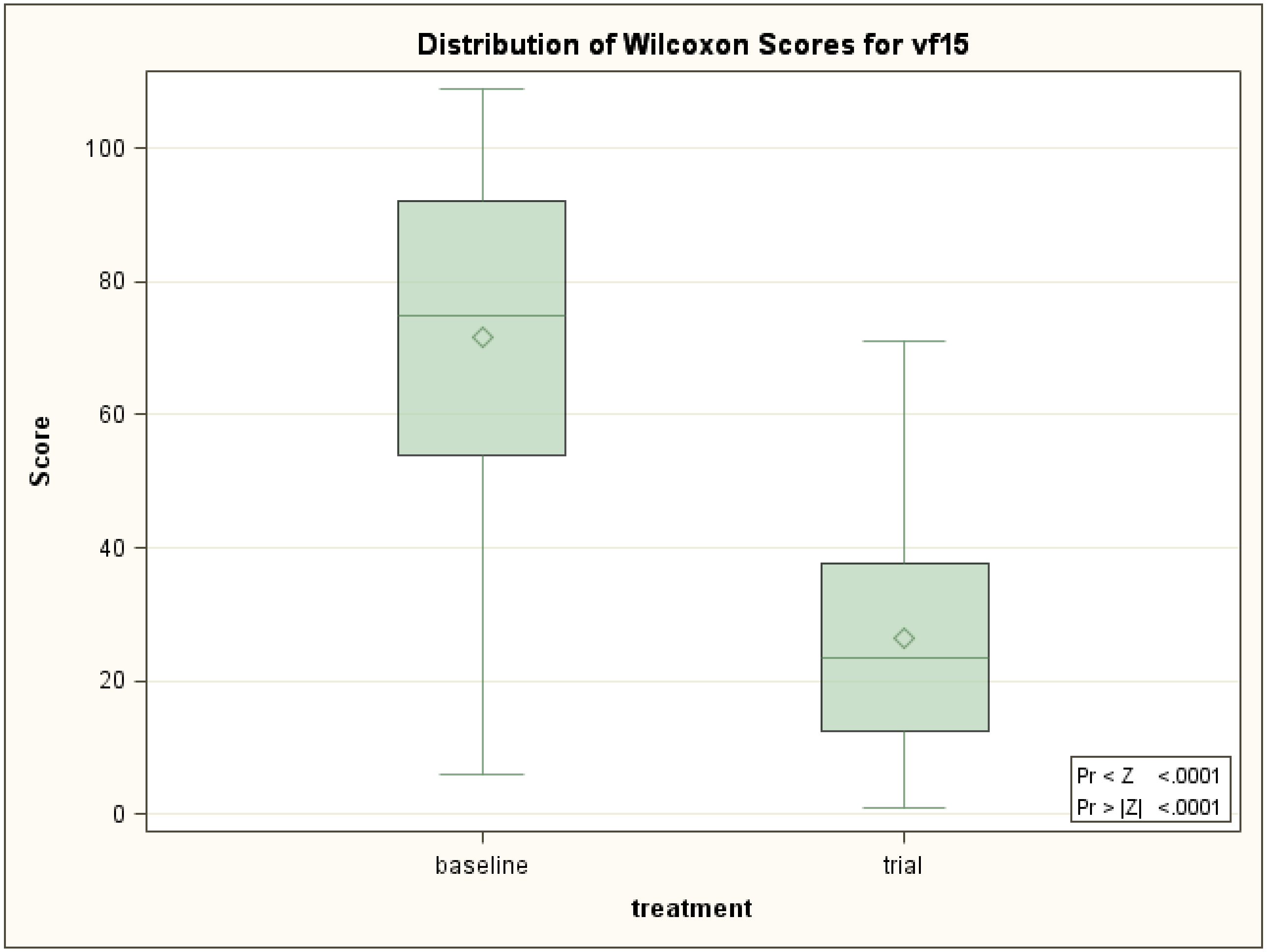
Wilcoxon Two-Sample Test

Statistic	1057.5000
Normal Approximation	
Z	-7.1797
One-Sided Pr < Z	<.0001
Two-Sided Pr > |Z|	<.0001
t Approximation	
One-Sided Pr < Z	<.0001
Two-Sided Pr > |Z|	**<.0001**

Z includes a continuity correction of 0.5.

Kruskal-Wallis Test

Chi-Square	51.5934
DF	1
Pr > Chi-Square	<.0001



Distribution of Wilcoxon Scores for vf15

CO emission for all burns

The NPAR1WAY Procedure

Wilcoxon Scores (Rank Sums) for Variable soy Classified by Variable treatment

treatment	N	Sum of Scores	Expected Under H0	Std Dev Under H0	Mean Score
baseline	69	4669.50	4830.0	237.380754	67.673913
trial	70	5060.50	4900.0	237.380754	72.292857

Average scores were used for ties.

Wilcoxon Two-Sample Test

Statistic	4669.5000
Normal Approximation	
Z	-0.6740
One-Sided Pr < Z	0.2501
Two-Sided Pr > |Z|	0.5003
t Approximation	
One-Sided Pr < Z	0.2507
Two-Sided Pr > |Z|	**0.5014**

Z includes a continuity correction of 0.5.

Kruskal-Wallis Test

Chi-Square	0.4572
DF	1
Pr > Chi-Square	0.4990


Distribution of Wilcoxon Scores for soy
Score
125
100
75
50
25
0
baseline
trial
treatment
Pr < Z 0.2501
Pr > |Z| 0.5003