QUANTITATIVE ASSESSMENT OF THE IMPACT OF USE OF PORTLAND LIMESTONE CEMENTS IN NORTH CAROLINA CONCRETE PAVEMENTS

by

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ABSTRACT

ROHIT REDDY CHIMMULA. Quantitative assessment of the impact of use of Portland limestone cements in North Carolina concrete pavements. (Under the direction of DR. TARA L. CAVALLINE)

Production of portland cement contributes significantly to global carbon emissions. In order to reduce the carbon footprint of concrete and to construct more sustainable highway infrastructure, blended cements are increasingly being utilized in pavement concrete mixtures. Blended cements, including portland limestone cements (PLC) require less clinker, and therefore, carbon emissions associated with calcinations and other production processes are reduced. PLC has been accepted as an alternative to ordinary portland cement (OPC) in many European and Latin American countries as well as in Canada. In the United States a number of state highway agencies are showing increasing interest in using PLC in highway concrete. North Carolina Department of Transportation (NCDOT) has recently enabled the use of PLC by updating its concrete specifications, but does not currently have data to support performance of concrete made with PLC and other local materials. Use of PLC in concrete pavements could have both economic and sustainability benefits, but a quantitative assessment of PLC with North Carolina materials is needed to support the state's decision to allow and potentially promote PLC use in highway concrete.

In this study, eighteen different concrete pavement mixtures were produced using three different cements (two OPC and one PLC) and two different fly ash sources, along with coarse and fine aggregates from the Mountain, Piedmont, and Coastal regions of North Carolina. Laboratory tests were performed to evaluate the mechanical properties and

durability performance of the concrete, and to facilitate comparison of the performance of the OPC and PLC concretes. To quantify the potential sustainability benefits of use of PLC concrete, the web-based life cycle assessment (LCA) tool, Green Concrete, was utilized to model emissions linked to cement manufacture. Using the web-based tool, an LCA analysis was performed to evaluate the impacts of increasing limestone percentage, including fly ash with the PLC, changing the technology for finish milling/grinding/blending of portland cement, and changing the energy source for the electricity grid on the criteria air pollutant emissions.

Results from laboratory testing indicated that mechanical properties of the PLC concrete and OPC concrete batched using materials locally available to North Carolina were similar. Results from durability performance tests also tended to show similar results for OPC and PLC concrete when fly ash was not used. Enhanced durability performance of concrete, particularly reduced permeability, appears to result from the pairing of both OPC and fly ash, as well as PLC and fly ash. Results from LCA with the Green Concrete web tool show that use of PLC can result in significant reduction of criteria air pollutant emissions associated with concrete production. By increasing the limestone content in cement from 0% to 20%, criteria air pollutant emissions may be reduced up to 20%.

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AASHTO	American Association of State Highway and Transportation Officials
ACC	asphalt cement concrete
ASTM	American Society for Testing and Materials
BRE	Building Research Establishment
CBA	cost-benefit analysis
CML	Center for Environmental Science of Leiden University
CO	carbon monoxide
CO_2	carbon dioxide
CRCP	continuously reinforced concrete pavement
CSA	Canadian Standards Association
CSOL	cracking, seating, and overlaying
EPA	Environmental Protection Agency
EPD	Environment Product Declaration
FHWA	Federal Highway Administration
GHG	greenhouse gas
GWP	global warming potential
HMA	hot mix asphalt
ISO	International Organization for Standardization
IVL	Swedish Environmental Research Institute
JRCP	jointed reinforced concrete pavement
LCA	life-cycle assessment
LCCA	life-cycle cost analysis

LCI	life cycle inventory
LCIA	life cycle inventory assessment
MDOT	Michigan Department of Transportation
MEPDG	Mechanistic-Empirical Pavement Design Guide
MIT	Massachusetts Institute of Technology
NCDOT	North Carolina Department of Transportation
NO_x	nitrogen oxides
OPC	ordinary portland cement
OZ	ounce
PC	portland cement
PCC	portland cement concrete
PLC	portland limestone cement
PM	particulate matter
PM_{10}	particulates
PSRC	Puget Sound Regional Council
RAP	reclaimed asphalt pavement
RAS	recycled asphalt pavement
SCM	supplementary cementitious material
SETAC	Society of environmental toxicology and chemistry
SO_2	sulfur dioxide
SRPC	sulfate resisting portland cement
TRACI	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts

TSA	thaumasite sulfate attack
TxDOT	Texas Department of Transportation
VOC	volatile organic compounds

CHAPTER 1: INTRODUCTION

In response to climate change and other factors (such as increased energy and water usage), development and use of construction materials technologies that are environmentally friendly is becoming increasingly common. Global warming is primarily attributable to carbon emission into the atmosphere (Huntzinger et al., 2009). One of the leading producers of carbon emissions is the transportation industry and in particular, the cement production industry. Cement production alone contributes about 5% of the total global carbon emissions annually (Huntzinger et al., 2009). Attempts are being made to develop more sustainable pavements which include alternative materials to lower the carbon footprint of the pavement.

One strategy for reducing the carbon emissions associated with portland cement concrete (PCC) pavements includes the use of blended cements. These cements are produced by intergrinding or blending materials such as slag or limestone into ordinary portland cement (OPC). Blended cements have been found to be more environmentally friendly than traditional OPC because the amount of clinker produced is less, which in turn reduces energy consumption (Huntzinger et al. 2009). Sustainability benefits have driven the decision to utilize portland limestone cement (PLC) in a number of countries, including many countries in Europe and Canada (Lothenbach et al., 2008). PLCs have been accepted for a fairly wide variety of uses worldwide, and are becoming of increased interest in the United States. The North Carolina Department of Transportation (NCDOT) has recently changed its specifications to allow use of PLC in North Carolina highway concrete, and therefore this research is aimed at producing data to support satisfactory use of PLCs in concrete pavement mixtures.

1.1 Background

PLC is produced by inter-grinding limestone with cement clinker and calcium sulfate. This causes the amount of clinker required to produce the cement to decrease. Additionally, the interground limestone does not require calcination via heating. This results in a substantial energy savings in the production of cement, as the consumption of natural raw materials and the fuel needed for production of clinker is reduced (Ramezanianpor and Hooton, 2013). This also reduces greenhouse gas emissions associated with burning fossil fuels, as well as the release of carbon associated with calcination of the cement clinker, thus decreasing the carbon footprint (Ramezanianpour and Hooton, 2013). The use of PLC has been in fairly wide practice in Europe and Canada because concrete produced with PLC has been shown to obtain satisfactory strength and can exhibit satisfactory or improved durability performance (Tsivilis et al., 2002). The availability of limestone, the reduced amount of clinker required for production, and the energy savings reported, have resulted in an increased use of PLC in Europe and Canada (Voglis et al., 2005).

In the past few years, as sustainability initiatives are being increasingly promoted by state highway agencies, the use of PLC has become an increasingly attractive option in United States. In 2004, after three ASTM approval attempts over a 20 year period, ASTM C150 was finally modified to allow up to 5% limestone to be used in Portland cements (Hooton et al., 2007). ASTM C595 and AASHTO M240 currently allow PLC with limestone content up to 15% by mass. A number of state highway agencies have begun allowing and utilizing PLC in transportation concrete applications. PLC concrete has been successfully utilized in highway concrete applications in several states including Michigan, Texas, Washington, Mississippi, and Louisiana (Shannon et al., 2014). Based on this successful use in similar applications by other state agencies, NCDOT has recently modified its specifications to allow PLC at up to 15% limestone contents. NCDOT is currently sponsoring research on PLC to verify its durability and strength when mixed with aggregates and supplementary cementitious materials (SCMs) locally available in different regions of North Carolina. However, at this time, information to support the decision to utilize PLC in lieu of traditional OPC does not exist in North Carolina.

1.2 Research Objectives

The purpose of this research study was to perform laboratory testing to compare the performance of concrete pavement mixtures containing PLC to companion mixtures containing OPC. Based on these results, analyses will be performed to evaluate the benefits of use of PLC in North Carolina concrete pavements. Tools to evaluate the potential economic and sustainability benefits of PLC concrete will be utilized. To evaluate the sustainability benefits, a web-based life cycle assessment (LCA) tool developed for specifically for concrete will be utilized.

LCA is a tool which helps in understanding the environmental hazards due to the material production and usage of PLC (Muench et al., 2012). This tool can be used to assess any material from the time of production to the end usage, as well as its impact on the environment. In pavement applications, LCA has been performed to quantify the impacts of raw material production, construction, and operation on the environment

(Muench et al., 2012). For pavements, LCA is often performed using commercially available software such as the Athena (Athena 2013), SimaPro SimaPro (Pré 2011) or TRACI (EPA 2012), which require a great level of detail to perform the analysis. GreenConcrete is an online LCA webtool "specifically developed for cement and concrete manufacturers for the purpose of quantifying environmental impacts of their products" (Green Concrete 2016).

The objectives of this study include:

1. Perform laboratory testing on OPC and PLC concrete pavement mixtures utilizing aggregates, cements, and SCMs representative of those used in several different regions of North Carolina to determine the differences in mechanical properties and durability performance.
2. Using a webtool developed to quantify and compare the environmental impacts of concrete and constituent materials, perform an LCA analysis to evaluate and quantify the sustainability benefits that NCDOT could obtain via use of PLC in future concrete pavement projects.

CHAPTER 2: LITERATURE REVIEW

2.1 Sustainability

Sustainable development can be defined as development where the needs of the present are met without compromising the ability of future generations to also meet their needs (WCED, 1987). A pavement can be considered sustainable if it meets engineering goals, human needs, and will preserve the surrounding environment using financial, human, and environmental resources efficiently (WCED, 1987). The sustainability aspect of concrete is an important issue presently because production of portland cement is one of the major sources of greenhouse gas (GHG) emissions. Concrete transportation infrastructure, including pavements, utilizes a large amount of portland cement, thus contributing to the release of those gases into the environment (Thomas et al., 2015). The proportion of greenhouse gas emissions in the United States attributable to the transportation industry is about 83%, which includes GHG from production of raw materials through the emissions resulting from the end use of the pavements (Mack et al., 2012). Of all GHG emissions including CO_2 into the atmosphere, the amount from the transportation industry is 27% (Mack et al., 2012). The construction of pavements is responsible for about 7% of total United States GHG emissions in the transportation sector USDOT, 2010). The rehabilitation, maintenance, and construction of pavements constitutes 5% of total GHG emissions from the transportation sector, and 1.4% of the total

GHG emissions in the United States (Mack et al., 2012). Hence, reduction in greenhouse gas emissions will have an important role in ongoing sustainability initiatives associated with transportation infrastructure. Sustainability initiatives associated with pavements not only involve reduction of GHG emissions, but also addressing other factors which might impact the environment, harm ecosystems, and promote climate change. Such initiatives include those in the following list, which are adapted from Thomas et al. (2015):

- Water quality is an important aspect, as the water draining from pavement surfaces carries pollutants accumulated from vehicles, deicers, and other sources. Water draining from a pavement surface is often warmer that of local streams. When runoff from a pavement enters the stream, the temperature of the stream water can be increased, thus affecting the aquatic life.
- Air quality can be degraded by the usage of vehicles on the pavement, since these vehicles release CO_2 as well as other particles that are smaller than 0.01mm into the atmosphere. It can also be effected by the machinery used for raw materials processing and construction of the pavements.
- Construction of roads can sometimes lead to deforestation which can result in habitat loss and migration of wildlife. This can have an effect on the ecological balance of the planet.
- Pavements are typically impervious, preventing stormwater infiltration and impacting the hydrological cycle.
- Construction and maintenance of pavements requires a significant amount of energy consumption, causing an increased amount of GHG to be released into the atmosphere.

- Construction of pavements requires a significant amount of raw materials, including earthen materials and fossil fuels, all of which are non-renewable.

The sustainability performance of a pavement, or of pavement designs under consideration, can be quantified by different methods. The four most preferred methods for measuring sustainability are performance assessment, life cycle cost analysis (LCCA), life cycle assessment (LCA), and sustainability rating systems (Thomas et al., 2015). LCA is a technique which can be used to quantify environmental impacts of the pavement, whereas LCCA is a technique in which all the costs associated with each alternative are analyzed over the required period but does not specifically address the environmental issues (Thomas et al., 2015). Sustainability rating systems are often used to compare and contrast projects based on a scoring system, and ultimately provide a level of recognition for the stakeholders (Van Dam et al., 2015).

2.2 Overview of Portland Limestone Cement (PLC)

Portland cement can be defined as a hydraulic cement which can set, harden, and stay stable even under water. Ordinary portland cement (OPC) consists two-third of calcareous materials and one-third of argillaceous (containing clay as a significant secondary component) materials (Mehta, 1999). The standards for OPC in United States of America are ASTM C150 and AASHTO M85. In general, a portland cement contains limestone up to 5% by mass. More recently, a modified type of cement has become more commonly utilized, called portland limestone cement (PLC). In PLC, the limestone content is increased to contents ranging from 6% - 35% by mass. The maximum amount of limestone currently used is 35% by mass, with PLCs containing this content utilized mostly in Europe (Hooton, 2002). In Canada the maximum amount used is 15% by mass of limestone (Hooton, 2002). Previously, United States standards allowed only up to 5% by mass of limestone, but due to the increasing desirability of environmental benefits associated with use of PLC (discussed subsequently in this literature review), ASTM C595 and ASHTO M240 accepted PLC in the year 2012 (Hooton, 2002).

PLCs were developed in Europe several decades ago (Lothenbach et al, 2008). Germany was the first nation to use PLC in 1965, with a standard accepting limestone content of up to 20%. In 1979, French standards accepted PLC at a similar limit of 20%. The use of limestone in Portland cement was common and an accepted practice in France in the 1980's (Hawthorn, 1989), whereas British Standards did not allow addition of limestone until 1991. A British Research Establishment (BRE) Working Party was formed to examine the effect of limestone on the performance of cement and concrete (Matthews, 1989). A comprehensive testing program was initiated by the members of the Working Party to determine the effect of limestone at levels of 5% and 25% on the performance of concrete. A paper reporting the 5-year data (Matthews, 1994) concluded that the "performance of cements containing 5% limestone is, overall, indistinguishable from that of Ordinary Portland Cement (OPC) without additions, vindicating the decision to permit such additions under British Standards." In 1992, United Kingdom (UK) standards accepted PLC with up to 20% limestone replacement.

By 1990, Germany began using PLC with $15\pm5\%$ limestone content. Recently, in 2000, European standard EN 197-1 has classified PLC into two categories, CEM II/A-L with 6-20% limestone and CEM II/B-L with 21-35% limestone (Tsivilis et al, 2003). In the European Standard, EN 197-1 Cement – Part 1: Composition, specifications and conformity criteria for common cements, all 27 common cement products defined are permitted to contain up to 5% of minor additional constituents (macs) which can include limestone. In addition to permitting limestone as a mac in other types of cement, EN 197-1 also covers portland-limestone cement, which may contain up to 20% limestone when designated as a CEM II/A cement or up to 35% limestone as a CEM II/B cement. It is not permitted to use limestone as a minor additional constituent in portland-limestone cement (Lothenbach et al., 2008).

The European Standard for concrete, EN 206-1 Concrete. Part 1: Specification, performance, production and conformity, does not specify the types of cement that are permitted in various classes of chemical (sulfate) exposure. Instead, this standard simply refers to "sulfate-resisting cement," which is intended to cover all cement types recognized as being sulfate resistant. However, as of 2002, no European Standard for sulfate-resisting cements existed, as it has not been possible to achieve consensus among the member countries regarding the cement types to be included (Hooton et al., 2002). This issue is therefore dealt with on a national basis. In the UK, blast furnace cements, CEM III/B, with 66-80% slag, portland-fly ash cements, CEM II/B-V, with more than 25% fly ash, and pozzolanic cements, CEM IV/B, with no more than 40% fly ash, are all permitted in the most severe sulfate class, although fly ash cements are excluded in some situations where the magnesium ion concentration in the groundwater exceeds 1 g/L. The use of minor additional constituents (≤ 5%) is permitted in the manufacture of all these cement types. Sulfate-resisting Portland cement (SRPC) is also permitted in this exposure class. In the U.K. the governing standard for SRPC is BS 4027 (1996) specification for sulfate-resisting Portland cement, which does not permit any additional constituents. Portland-limestone cements (e.g. cements with more than 5% limestone) are only permitted for use in the lowest sulfate exposure class in Europe (Hooton et al., 2002).

As previously discussed, use of PLC in Europe has been supported by several decades of development and implementation. However, use and acceptance of PLC in North America has been slower. In North America, Canada has led the way in acceptance of PLC, with cement standards undergoing revisions over several decades to include increasing percentages of interground limestone. In the late 1970's, to evaluate the influence of 5% limestone in portland cements, the 1977 version of CSA A5-M77 was amended in November 1980 to allow "a maximum of 5% addition of limestone" to normal portland cement (CSA Type 10, equivalent to ASTM Type I). In the next revision to the standard, limestone was permitted in high-early strength cement (CSA Type 30, equivalent to ASTM Type III) (Hooton et al, 2002). Canadian standard CSA 3001 (approved in 2008) included PLC with 5%-15% limestone.

One concern that has been voiced regarding use of PLC is the potential for increased susceptibility of PLC concrete to a form of sulfate attack called thaumasite sulfate attack (TSA). Concrete in service in cold temperatures is more prone to sulfate attack due to the presence of fine calcite particles that speed up the formation of thaumasite (Ramezanianpour et al, 2013). A number of laboratory studies have been performed to investigate the potential impacts of PLC on TSA. In one study, thaumasite formation in concrete with PLC in cold laboratory conditions is increased compared to concrete where 30% to 50 % of the cement is replaced by supplementary cementitious materials (SCM). The results from this study showed that at 23^{o}C, the concrete specimen containing cements with 30% and 50% SCM showed better resistances to sulfate attack compared to cement without SCM. At 5^oC, concrete specimens containing cement with 30% and 0% SCM were prone to sulfate attack, while 50% SCM containing cement was resistant to sulfate attack. From this study we can conclude that cements with high C_3A are resistant to sulfate attack (Ramezanianpour et al, 2012). Although the focus of a number of laboratory studies, actual occurrence of TSA in field concrete is extremely rare. In fact, after 22 years of extensive use in the cold Canadian climate, which would tend to promote potential thaumasite problems, there have been no cases of TSA related to the use of limestone in cement (Ramezanianpour et al., 2013). In fact, the only reported case of TSA in Canada from concretes made since 1980 (Bickley et al, 1990) did not involve the use of cement with limestone, but rather a "sulfate-resisting" cement meeting CSA Type 50 and API Type G cement (Hooton, 2002).

Successful use of PLC in Canada has resulted in recent increased production and use of PLC in the United States, coinciding with acceptance of PLC and associated standard guidance provided in American standards ASTM C595 and ASHTO M240. Utah, Iowa, Missouri, Louisiana, Oklahoma are the states that now allow the use of PLC (Rupnow et al., 2015). In Utah and Colorado, pilot projects have been implemented where PLC is used (Laker et al., 2012).

PLC is also currently utilized in other parts of the world. The amount of limestone used in Central and South America varies from 5% to 20% by mass. Most of the cements have 10% limestone by mass. The highest content of limestone in cement is used by Argentina where limestone content of 20% by mass is used in Calcium Carbonate Modified Portland Cement. The next highest allowable limestone content in South American cements is Peru, which allows 15% of limestone by mass in Calcium Carbonate Modified

Portland Cement, then followed by Costa Rica and Brazil with limestone content of 10% by mass. The maximum amount of limestone Bolivia uses is 6% or less by mass (Tennis et al., 2011).

2.2.1 Composition

The chemical composition of PLC is similar to that of Portland cement because the clinker used is the same. The chemical composition is changed only by the quantity of limestone added during the intergrinding process. For the production of cement, limestone ($CaCO_3$) is heated to a temperature of 2700^{o}F. During this process, called as calcination, CO_2 is released and lime (CaO) is formed. This lime combines with silica and alumina products to form portland cement clinker. Clinker is then mixed with gypsum and limestone and is grinded to form powder, which is the final cement. In general, portland cement clinkers are combined with limestone of less than 5%. In the case of PLC, the limestone content varies between 5% and 35% by mass, with the additional limestone added after production of the clinker in the kiln, during the grinding phases. American Standards ASTM C595 and AASHTO M240 are allowing a limestone content of 5% to 15% and the limestone should be a minimum of 70% $CaCO_3$. Typical compositions of PLC and limestone are provided in Tables 2.1 and 2.2, below.

Table 2.1: Typical chemical composition of PLC (Tsivilis et al., 2000)

Chemical Component	Composition (%)	Mineralogy	Composition (%)
SiO_2	21.96	C_3S	61.59
AL_2O_3	5.15	C_2S	16.48
Fe_2O_3	3.78	C_3A	7.27
CaO	65.95	C_4AF	11.50
MgO	1.76	Moduli	
K_2O	0.56	LSF	94.20
Na_2O	0.12	SR	2.46
SO_3	0.52	AR	1.36
		HM	2.14

Note: LSF is the lime saturation factor. It is the ratio of CaO to Fe_2O_3, Al_2O_3, and SiO_2. SR is silica ratio, AR is the alumina ratio, and HM is the hydraulic modulus.

Table 2.2: Typical chemical composition (%) of limestone (Tsivilis et al., 2000)

Chemical Component	Composition (%)
SiO_2	0.55
AL_2O_3	0.40
Fe_2O_3	0.17
CaO	53.47
MgO	1.02
K_2O	0.03
Na_2O	0.01
LOI	43.13

2.2.2 Influence of Limestone on Hydration of Portland Cements

Cement of desired properties can be obtained with appropriate selection of source raw materials, production of quality clinker, inter grinding of quality limestone and grinding the clinker to the appropriate cement fineness. The presence of additional limestone in PLC has been shown to influence hydration of the cement. This influence, as detailed by Lothenbach (2008) can be summarized as follows. Limestone helps in formation of monocarbonate, which in turn leads to stabilization of ettringite by reducing monosulfate. The stabilization of ettringite happens in presence of calcite, which increases the total volume of the solid phase. The increase in total volume is due to low density of ettringite with respect to the larger volume per formula unit. This difference in volumes reduces permeability and improves compressive strength. Also the presence of limestone in cement accelerates hydration as an additional surface will be available for nucleation and growth of hydration products (Lothenbach et al, 2008).

PLCs with a limestone content of less than 10 percent and ground to the same fineness have been shown to produce concrete with compressive strengths similar to those obtained from concrete produced with OPC (Tsilivis et al., 1999). PLCs generally possess lower water demand compared to OPC though they possess higher fineness than the latter. This is because of wider particle distribution and lower value of uniformity factor of Rossin-Rammler distribution (Tsilivis et al., 1999).

2.2.3 Permeability of PLC Concrete

"Permeability can be defined as the property that governs the rate of flow of fluid into a porous solid (Rethaliya, 2012)." Concrete with lower permeability generally exhibits better durability performance than concrete with higher permeability (Mehta and Monteiro, 2014). PLC concrete has been shown to exhibit a higher gas permeability than OPC concrete, while the water permeability of PLC concrete has been shown to be lower than that of OPC concrete (Tennis et al., 2011). However, concrete produced using PLC with limestone content above 35% has been shown to have a lower gas permeability and as the limestone content increases water permeability decreases. In general PLC concrete exhibits lower sorptivity than OPC concrete (Tsivilis et al, 2003). Porosity can be defined as void space present in the solid. Some studies have shown that the porosity of PLC concrete is same as that of the corresponding OPC concrete if the percentage of limestone in the PLC is up to 15%. However, if the limestone replacement percentage is increased above 15%, in limestone content, the porosity of PLC concrete has been shown to increase (Tsivilis et al, 2003).

2.3 Thaumasite Sulfate Attack (TSA)

Ettringite is one of the products formed during hydration of cement along with C-S-H and portlandite (Ramezanianpour et al., 2013). After the hardening of the concrete, an external sulfate source, such as those from groundwater, seawater, or other sources, can facilitate a reaction with the existing hydration products obtained after hydration. The sulfate reacts with C-S-H and portlandite. This reaction leads to a change in pH (lowers pH) and expansion of concrete takes place (Ramezanianpour et al., 2013). As discussed previously, this is called thaumasite attack, which has been shown to vary with temperature. This type of attack is generally observed in extreme cold conditions (Hartshorn et al., 1999).

As detailed previously, a key study was conducted by University of Toronto on TSA in portland cement and PLC mortars exposed to sulfate solution. The mortar bars for this study were placed in two different temperatures, 5ºC and 23ºC. This study concluded that mortars containing PLC were more prone to sulfate attack at lower temperatures (such as 5°C) than mortars containing OPC. The initial expansion in mortar bars was due to ettringite formation and gypsum present in cement preceded thaumasite formation. Formation of the thaumasite crystals was confirmed by X-ray Diffraction (Ramezanianpour et al., 2013). From this study it can be understood that the study of TSA is required when concrete construction is done at places which experience low temperatures and areas where mobile water is present as TSA formation converts concrete into a friable material which can easily be broken. TSA can greatly affect dams and bridges over water and thus may lead to greater disaster. In general scenario occurrence of TSA is nearly negligible (Hooton and Thomas, 2002).

2.4 Methods of Project Assessment

Several tools to support evaluation of the economic and sustainable benefits of highway materials and projects are typically used. They are Cost-Benefit Analysis (CBA) which compares the overall costs to the benefits, Life-Cycle Cost Analysis (LCCA) which compares costs to performance achieved over a specified duration, and Life-Cycle Assessment (LCA) which is used to evaluate sustainability benefits.

In general, any assessment program is performed by dividing the project into different phases in order to facilitate the study of the effects of the project at different levels. This facilitates an understanding of the impacts of a project at the beginning, at a midpoint and at the end. Assessment of a pavement is typically performed by dividing the entire life of the pavement phases, starting from the manufacturing of materials and proceeding to the disposal of the pavement. The life cycle of a pavement is often divided into 6 phases, as outlined by Muench et al. (2012). They are:

1. *Material production*: Life of any finished material depends on the treatment which it undergoes during production and manufacturing. Hence study of materials used in construction of pavement is a necessary aspect. The quality in which materials are produced reflects in lifetime and benefits of pavements.
2. *Pavement design*: Any construction project depends on the surrounding environment for sustaining. A pavement generally extends from one region to another. During the design phase of pavements, the study of soil, climate, and traffic

load are important considerations. A suitable design that considers these factors helps to improve a pavement life. Hence this phase is important to study for LCA.

3. *Construction*: Design and construction procedure of a pavement reflects in its total life. The kind of instruments used, the method of construction used, and the time of curing are considered in this phase of study. In addition to the impacts of the initial construction of the pavement, the maintenance of the pavement over the years and rehabilitation plans are also considered in the assessment.
4. *Use*: Once constructed, pavement is used by the public for transportation. This leads to interaction of vehicles with pavement. For this purpose factors such as deflection, texture, roughness, and heat capacity are studied in this phase.
5. *Maintenance*: In this phase, treatments method which will help in slowing the deterioration of pavement are studied along with identification of factors which might lead to damage of the pavement.
6. *Disposal*: in this phase, materials which are of no use to the pavement and materials which are to be replaced are studied. Recycling of materials is also done in this phase.

2.4.1 Cost-Benefit Analysis (CBA)

According to the definition of Prest and Turvey (1965), the goal of cost-benefit analysis is to “maximize the present value of all the benefits less than that of all costs, subject to specified constraints.” Though costs and benefits are often compared, in the CBA technique the main problem lies in which costs are to be considered and what are the benefits that are to be taken in to consideration, at what interest rates are they to be discounted, and what are the relevant constraints. Costs and benefits are project specific.

In general, the benefits which can be calculated in financial terms are considered. In a conventional CBA, other sustainability measures, such as social and environmental impacts are not considered, as these are not typically calculated in financial terms. A method of analysis that does include social benefits exists, and is called a social CBA. This technique, is often utilized on projects which has major impact on society and on projects carried out by the government (Pande 2014).

The use of CBA in support of construction decisions is increasing. However, the usefulness and fidelity of CBA is dependent on the available data. According to Mehta, in 1991, there were relatively few publications on costs of materials and construction (Mehta, 1991). Mehta indicated that he felt that to perform CBA, the required data needed to be collected from unpublished papers, as costs of materials and construction will vary from state to state. Local assessment was required in order to collect all the information (Mehta, 1991). Increased attention to the benefits of CBA since that time have resulted in them being a more commonly utilized assessment technique.

Recently, the Puget Sound Regional Council (PSRC) developed a methodology for CBA for the transportation sector. The steps involved in this methodology are (Outwater et al., 2011):

1. The alternatives to be considered are defined, and a pavement design is selected as base design. The remaining alternatives are compared to the base pavement design.
2. The required data to support the CBA (cost of materials, labor, construction costs, alternatives designs, and benefits that are to be compared) are identified.
3. User cost factors, such as vehicle unit operating costs, time values, accident rate and costs are identified and supporting data gathered.

4. Economic factors such as discount rate, inflation rates, time period or analysis period are selected.
5. For the given period, traffic parameters related to pavement performance are identified and supporting data obtained.
6. User costs are computed for each alternative.
7. User benefits are calculated for each alternative.
8. Benefits over the pavement lifetime are computed.
9. The net present value of benefits and costs are determined for each alternative and compared to aid in project selection.

A pavement can be considered as economically viable if the overall cost is less than the selected other alternatives. Some of the major factors that are to be considered for obtaining greater benefits with respect to the costs are (Cheneviere and Ramdas, 2006):

1. Initial construction costs
2. Costs associated with maintenance and rehabilitation
3. User costs
4. Residual value after the life of the pavement
5. Costs associated with deterioration of the pavement which may lead to loss in budget of the project.
6. Costs associated with surrounding environment maintenance and safeguard.

Cost-benefit analyses can also be utilized for analysis of specific aspects of pavement performance. For example, Gerwick (1994) made an attempt to compare relative mitigation measures for 38 different concretes to avoid corrosion of concrete due to steel. From this study, a number of conclusions associated with concrete mixtures and construction techniques were identified, such as: replacement of some part of cement with fly ash might lead to a decrease in project cost, cost may increase by 2% by reducing the water-cement ratio and adding superplasticizer, addition of silica fume might increase the cost by 5%, usage of epoxy or corrosion resistant admixtures might lead to an increase costs about 8%, and by external coating such as cathode project might result in increase in cost by 20% to 30% (Gerwick 1994).

2.4.2 Life Cycle Cost Analysis (LCCA)

LCCA can be defined as a procedure used for comparing different alternatives with respect to tradeoffs in cost and performance (Mack et al. 2012). LCCA can be considered as an improvised version of LCA that does not directly consider the environmental impact metrics in the analysis (Thomas et al. 2015). FHWA has made a policy in order to promote LCCA through Intermodal Surface Transportation Equity ACT of 1991 for transportation investment decisions. A Demonstration Project 115 named Life-cycle Analysis in Pavement Design was initiated under technology transfer effort by FHWA in the fall of 1996 and was delivered to more than 40 State transportation agencies. By the year 1998, FHWA issued an Interim Technical Bulletin on LCCA entitled "Life-Cycle Cost Analysis in Pavement Design (FHWA, 2002). For an LCCA, all costs are taken as net present value. Performance, rehabilitation activities, user cost, maintenance cost, environmental costs are included in the analysis to facilitate identification of design and construction alternatives that produce lower costs and lessen the environmental impacts of pavement design (Mack et al, 2012).

LCCA is conducted in 5 stages (Nayab et al., 2011). These stages are summarized as:

1. Identify and develop different alternatives for the same purpose.
2. Develop a schedule for initial construction, maintenance, material costs, and end of life for each alternative.
3. Determine the estimated costs associated with construction, maintenance, materials costs, and labor costs.
4. Evaluate all costs in net present value (discounting).
5. Perform the analysis, by correlating costs to performance.

Some of the important factors that are to be considered when performing LCCA are the alternatives that are to be compared, analysis time period, anticipated scheduling of maintenance and rehabilitation, agency costs, user costs, service life of each alternative, discount rate, and the risk involved in material production and construction of the project (Nayab et al., 2011).

Recently, a LCCA study was performed for municipal pavements in Southern and Eastern Ontario. This study used pavements designed using Mechanistic-Empirical Pavement Design Guide (MEPDG), facilitating relative equivalent thickness design and the development of maintenance and rehabilitation plans. After completion of LCCA on the selected alternatives it was found that concrete rigid pavements had lower initial costs and life cycle costs compared to the flexible pavement alternatives (Holt et al., 2011).

Michigan Department of Transportation (MDOT) conducted research to review its existing LCCA method. For the purpose of this research, ten pavements were selected in the state of Michigan and studied. The results revealed that the estimated costs and actual construction costs of the pavements were lower than the values calculated in LCCA. The reason for this is that MDOT LCCA methodology was not site-specific. Other findings from this study indicated that road maintenance schedules did not match those estimated in the LCCA. This research has limitations due to the fact that though two alternatives were selected for analysis, one pavement was actually constructed, while the other one was just designed for the purpose of evaluation in the LCCA. The sample size taken for this study is also relatively small as only ten pavements from the entire state were considered (Chan et al., 2008).

Texas Department of Transportation (TxDOT) conducted research to develop methodology for LCCA for pavements across the state. Among the alternatives considered in this analysis, it was determined that a 9" continuously reinforced concrete pavement (CRCP) has higher initial costs but lower user costs and lower maintenance costs than 8" CRCP for the selected constraints. Thus, the overall cost of 9" CRCP was shown to be less than 8" CRCP. These researchers asserted that lower initial costs can be justified if cost savings are obtained in the long term. Another alternative considered in this research was 10" jointed reinforced concrete pavement (JRCP) pavement. It was found that 10" JRCP had higher initial costs, maintenance costs, and user costs compared to 8" and 9" CRCP pavements, with agency costs of the 10" JRCP pavement about 16% higher than that of 8" CRCP pavement during the 30 year span of the analysis (Wilde et al, 1999).

2.4.3 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a means of assessment aimed at quantifying the materials and energy input and output flows of a project in order to assess its impacts on environment (Harvey et al, 2014). This process includes means of assessing the relative impacts of a project related to social, economic and environmental. LCA helps in selecting the best option among different alternatives for the same project and also helps in improving the environmental performance of a pavement in its complete life span. Indicators are categorized into three types: social, environmental and economic. Indicators such as income, government tax, and injury are categorized under “social indicators” while GHG emissions, energy consumption, water footprint, and hazardous waste generation are categorized under “environmental indicators.” Economic indicators include foreign purchase, business profit, and gross domestic product.

LCA was developed in 1960 by the scientific community, and later in the year 1969 Harry E. Teasley Jr. conceived the first analytical model of the modern LCA methodology for Coca-Cola Company (Hunt and Franklin, 1996). Developers of the LCA aimed to incorporate the analysis of the three main elements of earth (air, land, and water) into the analysis, as these each are subjected to degradation due to human impacts (Harvey et al., 2014). By the start of the new millennium in 2000, LCA was typically broadened to include energy, use of available resources, and GHG emissions (Harvey et al., 2014). In recent years, the LCA process has been standardized by the International Standardization Organization (ISO) standardized assessment methods, and is detailed in ISO 14040 and ISO 14044. Some of the key issues in LCA include identification of the required data, standardization of data collected, and updating and understanding impact assessment methodology (Meunch et al., 2012).

For evaluation of the environmental impacts of construction and use of pavements (and other types of infrastructure), LCA is a quantitative approach to compare alternatives and acts as a tool to identify chances which helps to improve a pavement life cycle (Harvey et al., 2014). Utilizing an LCA to evaluate pavement alternatives and to guide construction decisions helps in reducing waste, GHG emissions, and usage of natural resources (Harvey et al., 2014). Due to the detailed nature of the information required to support this type of analysis, LCA results are generally project specific and hence cannot be generalized for all the pavement projects around the country (Van Dam et al., 2015). By utilizing LCA, however, an agency can become aware of the impact of a project on the surrounding environment, compare alternatives, and make design and construction decisions aimed at lessening a project's impact on the existing environment. For example, LCA of a pavement evaluates the impact of construction of pavement on the environment and also considers factors such as raw material production, impact of the construction phase, impacts during use of the pavement, and the impact of the end use of the pavement. Therefore, the results of an LCA can be used to guide decisions impacting each of these areas during the pavements service life, as well as provide a tool to guide initial decision making during design.

As mentioned previously, the International Standard Organization (ISO) developed a methodology for life cycle assessment in the year 1997. As per ISO 14040 LCA is divided into three important phases: goal and scope, life cycle inventory assessment, and impact assessment (ISO 14040, 2006).

1. *Goal and Scope*: This is the first phase where the goal of project is decided. The goal is generally set considering environmental impacts, costs, and the required output. The scope defines the boundaries for analysis (Harvey et al., 2014).
2. *Life Cycle Inventory Assessment (LCIA)*: In this phase all the required inputs regarding materials, energy, resources, waste outlet, and pollution are collected. This information is typically obtained from sources such as US Bureau of Economic Analysis, Federal Highway Administration, US Environmental

Protection Agency, US Department of Energy, and the US Energy Information Administration (Harvey et al., 2014). Information from Environment Product Declaration (EPD) can be used in LCA, and preparation of these EPDs are in accordance with ISO 14025. An EPD does not indicate any environment and social performances that are to be met but it compliments LCA as LCAs do not address site specific environment impacts and human health toxicity (Locks, 2016).

3. *Impact assessment*: Environmental impacts which occur in LCIA phase due to environmental flows are studied in impact assessment phase. As described in Harvey et al. (2014), three things are generally studied in this phase, they are impact on people, impact on ecosystem, and depletion of resources. Impact on people may be in type of loss of land due to construction, health of surrounding communities due to emissions from project construction and usage, and distribution of population. Impact on ecology might be due to deforestation and which further might affect the wildlife, and pollution of natural water resources by hazardous materials and lack of sewage. Raw materials and energy sources are required for material extraction and construction of project which might lead in depletion of non-renewable resources (Harvey et al., 2014). For this purpose, the most widely used methodology worldwide is the methodology proposed by the Center of Environmental Science of Leiden University (CML). In the United States, the Environmental Protection Agency (EPA) has developed a methodology which is used by Tool for the Reduction and

Assessment of Chemical and other Environmental Impacts (TRACI) of United States (Harvey et al., 2014).

Concrete is the one of the most consumed products on earth. An increase in need of concrete also increases the need for production of cement. Cement production requires calcination of limestone, and as stated previously, during this process (calcination) a significant amount of carbon dioxide is released into the atmosphere. As discussed previously, energy is required for calcination is often obtained by the burning of fossil fuels, which in turn releases about 5% carbon dioxide (Huntzinger et al., 2009). Hence the cement industry is a major producer of greenhouse gases. Nearly 5% of total GHG is released by the cement manufacturing industry (Huntzinger et al, 2008), and as such, LCA has been shown to be a valuable tool to allow stakeholders to quantify the environmental impact of cement and concrete production, as well as projects containing concrete.

For example, from a study performed by the Athena Sustainable Materials Institute for the Cement Association of Canada, it was observed that addition of limestone in Portland cement reduces greenhouse emissions by about 9.6% (Athena, 2005). This study also showed that production of PLC not only reduces greenhouse emissions but also supports improved industry performance across other environmental impact metrics, including reductions in ozone depletion potential and lower smog potential (Athena, 2005). As a result of this study, the researchers suggested that agencies in the United States support the increase in the allowable percentage of limestone in cement from 15% to 35%. This allowable percentage of limestone inclusion would be similar to European standards, promoting reduction in environmental impacts. This recommended increase would be a marked change in American standards, which prior to the study, had restricted limestone content to up to 5%, primarily citing perceived reductions in the strength of the concrete as the reason for this relatively low limit (Athena, 2005).

A quantitative assessment of environmental impacts on the lifecycle of highways was performed in Korea using LCA methodology. This study was done for highways in which asphalt cement concrete (ACC) was used. This assessment was performed considering four stages of a pavement lifecycle, including manufacturing of construction materials, the construction stage, the maintenance and rehabilitation stage, and the demolition stage. A lifecycle period of 20 years was considered for the pavement in this study. Energy consumed in each stage was quantified. From the research conducted it was understood that the maximum energy is consumed in manufacturing the required materials (about 1,525.80 tons of oil equivalent per 1 km of four lane highway). Results for other impacts showed that the amount of NOx, SO_2, and CO_2 emissions per 1km of 4 lane highway are 17.1 tons, 62.1 tons, and 2,438.5 tons respectively (Park et al., 2003). This was a generalized evaluation and as such, the findings could not be directly applied to projects with other environmental and traffic conditions.

An LCA study was done by Roudebush (1996) comparing PCC and ACC pavements. The research was done in 10 phases, from formation of resources to manufacturing materials, construction, and demolition of the pavement. This study showed that for the conditions studied, the impact of PCC pavement on the environment is 47.6% less than the impact of the ACC pavement system based on comparison of emergy input data (Roudebush, 1996). Emergy can be defined as “universal measure of wealth of the work and society on common basis” (Odum et al., 2000). These environmental impacts account for the usage of renewable and non-renewable resources, fuel energy, equipment, tools, materials, and labor (Roudebush, 1996).

A study was conducted on LCA of pavements in Florida in the year 2012. For the purpose of this research, three different methods of performing an overlay rehabilitation project for a pavement were considered. The three overlays considered in this study were Portland cement concrete (PCC), Hot-Mix Asphalt (HMA), and crack, seat overlay (CSOL). The LCA model was built in a manner that allowed consideration of the environmental impacts of each of the three proposed overlays due to materials, construction, traffic congestion, usage, and end of life of pavements. For purpose of this LCA study, the base course and subgrade layers were considered to be structurally sound. The existing pavement has a PCC overlay of 225 mm and a crushed base and subgrade course of 250 mm. Three alternatives were considered for the rehabilitation. The first alternative was to remove the existing 225mm PCC overlay and replace it with a new 250mm PCC overlay. The second alternative was to remove old 225mm PCC overlay and replace it with a new 225mm thick HMA overlay. The third alternative that was considered was to crack and seal the existing 225mm PCC overlay and fill it with 125mm thick HMA. A 1 km length of a four-lane pavement was considered with traffic in both directions with design life of about 40 years. The results from this study showed that energy consumption are in increasing order for PCC, CSOL, and HMA if materials, traffic congestion, and usage phases are considered. If the usage phase was eliminated from LCA then energy consumption was reduced up to 40% for PCC overlay, 50% for HMA overlay, and 44% for CSOL. The results from this study indicated that if LCA was performed considering material production and transportation, traffic congestion, and usage phase of the pavement then the pavement with HMA overlay would consume the least amount of energy followed by CSOL overlay pavement. The PCC overlay pavement had the highest energy consumption among the three alternatives. If the usage phase of pavement was excluded from study then results show that energy consumption was reduced up to 40% for pavement with the PCC overlay, 50% for HMA overlay pavement, and 44% for CSOL overlay pavement. This study also showed that GHG emissions are higher in the usage phase stage for HMA and CSOL compared to PCC overlay. The lower albedo of the lighter colored concrete adds an advantage to PCC compared to that of HMA and CSOL (Bin Yu et al., 2012).

A research team at the Massachusetts Institute of Technology (MIT) conducted an LCA study on concrete pavements in 2011. Twelve concrete pavements serving a range of uses (from rural roads to urban interstates) were considered. Pavements in the study were designed using 1993 AASHTO Design Method for design of pavements. For each of the pavements, the global warming potential (GWP) for each phase of pavement lifecycle was determined. Results from this study show that the GWP of concrete pavements ranged from 600 tons CO_2 per mile (for rural roads) to 11,000 tons CO_2 per mile for urban interstates per annum. The production phase for most of the pavements constituted a large portion of overall GHG emissions, as cement production was associated with 45% of GHG emissions for urban interstates and 72% of GHG emissions for rural roads. Another important contributor of GWP for all pavements was fuel consumption, which is linked to roughness of pavements. Findings from this study show that addition of fly ash (at replacement rates of about 10% to 30%) will reduce GWP of about 15% for urban interstates and 36% for rural roads. According to Santero et al. (2011), emissions due to rehabilitation activities are greater than fuel consumption due to roughness of roads if the daily traffic on road is approximately less than 2,500 vehicles. Hence rehabilitation strategies may increase GWP of rural roads by 10% and reduce about 13% for urban interstates. This study also shows that GWP in rural roads can be reduced up to 17% by using AASHTO MEPDG for design, rather than the 1993 AASHTO Design Method. By following the above strategies GWP can be reduced to about 38% for urban interstates and 58% for urban roads (Santero et al., 2011).

One of the most valuable ways of using LCA is to consider two design alternatives for a specific project. LCA of a roadway was performed by Swedish Environmental Research Institute (IVL) with support of the Swedish National Road Administration was performed in order to evaluate design alternatives: a concrete surface and two asphalt surfaces (asphalt, hot method and asphalt, cold method). As a part of this research a complete lifecycle of the roadway was studied from extraction of materials, production of materials, construction, usage, maintenance, and disposal and reuse of road. The total energy consumed during the construction, maintenance and operation phase of a 1 km road with a life period of 40 years was calculated. Traffic in the entire life of the road was not considered as this study mainly focuses on energy consumed for raw material production and construction of pavement. LCA in this study followed recommendations from the Society of Environmental Toxicology and Chemistry (SETAC). Two alternatives of vehicles and machines used for construction and material production process were considered, conventional diesel engines and modern low emission diesel engines. Results of the LCA indicated that approximately 23 TJ of energy would be consumed for construction of the road if surfaced with asphalt and 27TJ for concrete roads (Stripple, 2001).

A similar LCA was also conducted on a reconstruction project for an interstate road in Northern Illinois. For this study, the material production phase and construction phases were considered, but not the use and end of life phases as scope of this study include energy consumption and GHG emissions during the material production phase and construction phase. For the purpose of this study, data was collected from local processing plants and contractors by preparing a confidential questionnaires. This questionnaire was prepared for seven types of materials. They were: reclaimed asphalt (HMA), recycled asphalt shingles (RAS), reclaimed asphalt pavement (RAP), portland cement, coarse aggregate, fine aggregate, and ready-mixed concrete. This project studied included the reconstruction of 7.6 mi full depth HMA asphalt pavement. The mixture design for new pavement was developed by Illinois Tollway department. The new pavement design consisted of a 2 in surface layer, 3 in binder layer, and two 3.5 in binder layers. The new pavement design depth was 15 in, and no surface coating was considered for the pavement. To account for traffic delay, three scenarios were considered. They were:

1. 7.6 mi road was divided into four equal 1.9 mi zones. In order to avoid traffic delay emissions the pavement was closed from 9 p.m to 5 a.m.
2. 7.6 mi road was divided into two equal halves i.e, 3.8 mi each zone. A 16 hour closure period is taken from 10 p.m to 2 p.m.
3. 7.6 mi road is constructed at once keeping a closure period of 32 hours.

The results showed that the material production phase has more impact associated with energy use than the construction phase. The energy consumption during the material production phase ranged between 60% and 90%, while the energy consumption during the construction phase ranged from 11% to 40%. The CO_2 emissions for material phase ranged between 60% and 87% while ranging between 5% and 16% during construction phase. The GWP in the material production phase was found to be 19 to 29 times greater than the construction phase while energy consumption in the material phase was 21 to 34 times greater than the construction phase (Kang et al., 2008).

2.5 Need for Research

In these times of increased effort to mitigate the environmental impact of infrastructure, as well as to responsibly utilize the limited amount of funds available for infrastructure maintenance and construction, there is great need for research to aid in decisions regarding pavement design, construction, and maintenance. To date, the cement used in rigid pavements in North Carolina is OPC. Considering the substantial amount of transportation infrastructure projects pending in North Carolina, an alternative to OPC that reduces environmental impact could be welcomed if acceptable performance is confirmed. As outlined in this literature review, the findings of studies in other countries and in the United States indicate that PLC requires less clinker for production of cement, energy can be preserved, raw materials can be saved, and fuel use can be reduced. It has also been shown that PLC concrete can provide equivalent performance to OPC concrete (Rupnow and Icenogle, 2015), although this has not been confirmed using materials locally available for concrete produced in North Carolina.

Based on the literature review, the CBA, LCCA, and LCA tools can be beneficial in evaluating the impacts and benefits of pavement alternatives. Specifically, the LCA tool is useful in identifying and quantifying the environmental impacts of a construction material or project. Although previous studies by various researchers have proven that this tool is useful in comparing pavement alternatives, there have been no previous studies on pavements having North Carolina's location-specific materials, particularly comparing PLC concrete and OPC concrete. Additionally, most of the research studies on quantitative assessment of pavements performed in the United States focused on assessment of already existing pavements. Assessment of the potential environmental impacts (or benefits) of use of PLC concrete in North Carolina concrete pavements is needed.

CHAPTER 3: EXPERIMENTAL METHODOLOGY

This chapter provides an overview of materials used to produce the North Carolina concrete pavement mixtures produced as part of this research project, an overview of batching and test specimen preparation, and laboratory test procedures.

3.1 Concrete Mixture Designs

Concrete mixtures prepared for this research study were typical mixtures used for North Carolina pavement concrete. For the purposes of investigating the influence of materials in the performance of the concrete, a single base mixture was developed, and subsequent modified versions of this mixture were produced to evaluate variables of interest. In addition to evaluation of the performance of PLC concrete compared to similar OPC concrete mixtures, variables of interest included source of coarse aggregate (Piedmont, Coastal, or Mountain region of North Carolina), type of fine aggregate (natural or manufactured sand), and use of fly ash (from two North Carolina-based sources).

Concrete pavements require concrete mixtures with low slump (as they are placed with slipform paving equipment), adequate air content to withstand freezing and thawing, adequate strength and other mechanical properties, and adequate durability. Ultimately, paving mixtures need to be economical as well. The following mixture design parameters were identified by NCDOT for the base mixture for this research project:

- 550 lb. of cement per cubic yard
- Water cement ratio of 0.48

- A target slump of 1.5 inches
- Air content: 5% to 6%
- A minimum flexural strength of 650 psi at 28 days
- A minimum compressive strength of 4,500 psi at 28 days
- Cement content of the mix design can be reduced up to 20% and replaced that amount with fly ash at a rate of 1.2 lb per pound of cement.

Figure 3.1 shows the matrix of mixture designs used for this project. For the purpose of this study, three cements were considered: two types of OPC and one PLC prepared with the same clinker as one of the OPC. The orange color blocks in the Figure 3.1 represent base mixture designs where the coarse aggregate is changed, but remaining materials and proportions were kept constant. Mixtures in orange blocks utilized manufactured sand as fine aggregate. The blue color blocks in Figure 3.1 represent mixtures where natural sand was used instead of manufactured sand. For each of the mixtures where natural sand was used, Piedmont coarse aggregate was used. Two different fly ashes were used for this study, and in Figure 1, each fly ash mixture was assigned a different color (yellow color for fly ash A and green color for fly ash B). For each of the fly ash mixtures, the Piedmont coarse aggregate and manufactured sand were used. Additional details, including the sources and characteristics of materials utilized, are provided in the subsequent sections of this chapter.

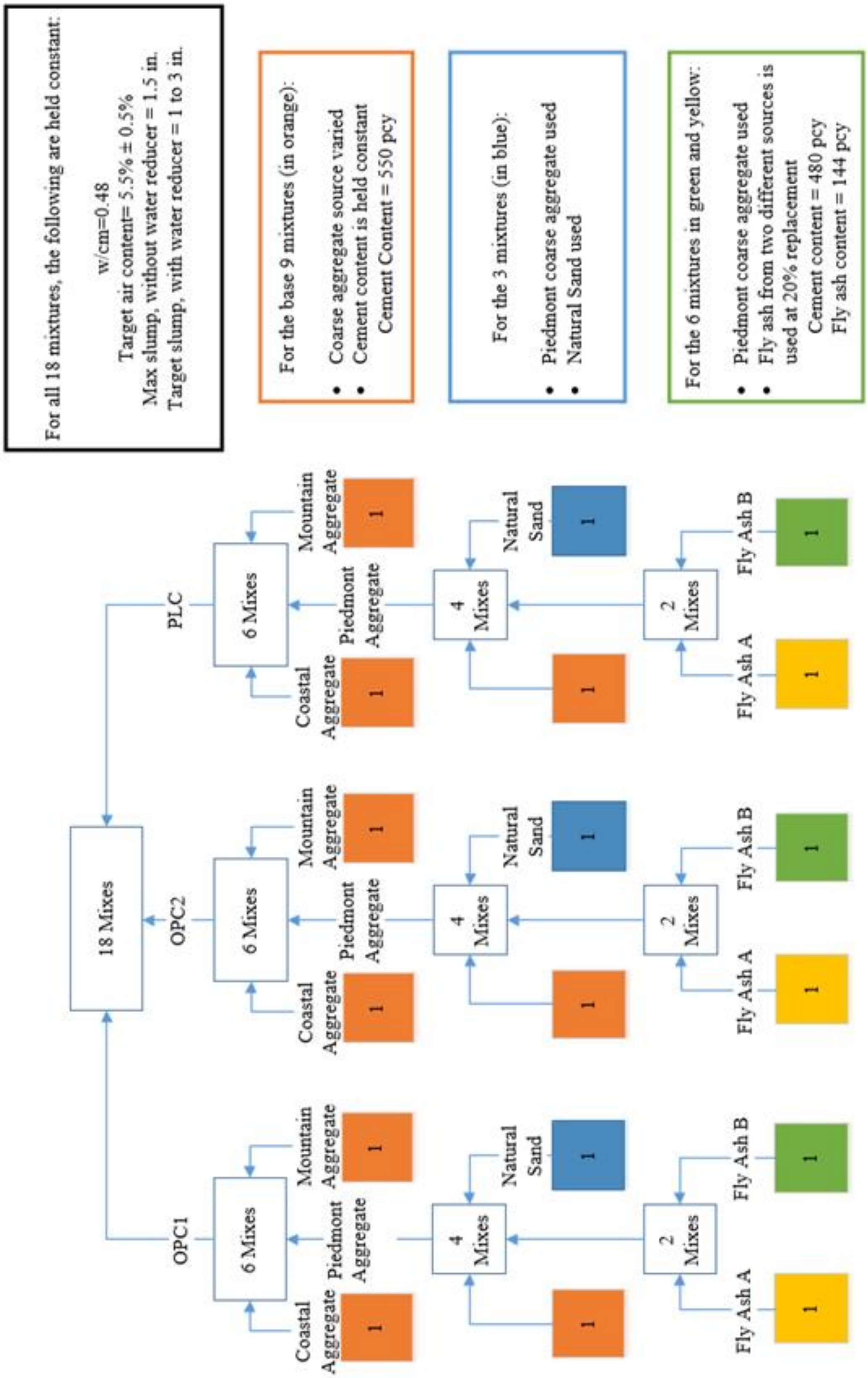

Figure: 3.1: Concrete mixture matrix

For the purpose of evaluating the susceptibility of the PLC concrete to thaumasite attack, a series of mortar mixtures were also made. All the mortar mixture compositions are tabulated in Table 3.1. For all mortar mixtures, a water-cement ratio of 0.485 was used. Each mixture contained 5.18 lb of cement, 14.26 lb of sand, and 2.51 lb of water. Mortar mixtures were made with either manufactured sand or natural sand, as shown in Table 3.1. For the fly ash mixtures, 20% of the mass of cement was replaced with fly ash, keeping the sand and water quantities constant.

Table 3.1: Composition of mortar mixtures

Mixture ID	**Cement**	**Fine Aggregate**	**Fly ash**
A.N	OPC 1	Manufactured Sand	No fly ash
B.N	OPC 2	Manufactured Sand	No fly ash
BL.N	PLC	Manufactured Sand	No fly ash
A.N.N	OPC 1	Natural Sand	No fly ash
B.N.N	OPC 2	Natural Sand	No fly ash
BL.N.N	PLC	Natural Sand	No fly ash
A.A	OPC 1	Manufactured Sand	Fly ash A
B.A	OPC 2	Manufactured Sand	Fly ash A
BL.A	PLC	Manufactured Sand	Fly ash A
A.B	OPC 1	Manufactured Sand	Fly ash B
B.B	OPC 2	Manufactured Sand	Fly ash B
BL.B	PLC	Manufactured Sand	Fly ash B

3.2 Materials Description and Characterization

For the purpose of this research two different OPCs, one PLC, two different Class F fly ashes, three different coarse aggregates, and two different fine aggregates were utilized. Material sources were selected as they represented typical sources of materials utilized in concrete mixtures approved for use in existing concrete pavements in North Carolina. Admixtures, including an air entraining admixture and a water reducer, were also used to achieve the targeted slump and air content. A description of the materials utilized for this study is provided in the subsequent sections.

3.2.1 Cementitious Materials

Cementitious materials used in this research consist of Type I/II portland cement (OPC), PLC produced using one of the OPC, and fly ash. A brief description of each is provided below, with supporting information provided in Appendix A.

3.2.1.1 Portland Cement

Two different ordinary portland cements (both Type I/II) were used for this research study. One cement was produced by a manufacturing plant located in Tennessee. This cement source was selected as it is a cement typically utilized in concrete produced in the Mountain region of North Carolina. The second OPC was produced by another plant located in South Carolina. This cement source was selected because it is commonly utilized in concrete mixtures in the Piedmont and Mountain regions of North Carolina. Mill reports for both OPCs are provided in Appendix A in Figure A.1 and Figure A.2, and both cements meet the requirements of ASTM C150 and AASHTO M85.

3.2.1.2 Portland Limestone Cement

The PLC used for this research was manufactured at the same South Carolina plant as one of the Type I/II OPCs used for this study. The PLC used for this study was produced using the same clinker as the OPC. The mill report for the PLC is provided in Appendix A in Figure A.2. The chemical composition of cement met the requirements of ASTM C595 and AASHTO M240.

3.2.1.3 Fly Ash

Several concrete mixtures in this study were prepared using fly ash as a replacement for 20% of cement by mass, in accordance with North Carolina Standard Specifications. Two different fly ashes were used, both Type F fly ashes. One fly ash was sourced from the Belews Creek power plant in Belews Creek, North Carolina, and the other fly ash was sourced from the Hyco power plant in Semora, North Carolina. Test reports of both the fly ashes are provided in Appendix A in Figures A.3 and A.4.

3.2.2 Fine Aggregates

Concrete pavement mixtures produced in North Carolina currently utilize both natural sand and manufactured sand as fine aggregates, with some pavement mixtures including blends of the two types of sand. For this study, concrete mixtures were prepared with both types of sand, manufactured (meeting 2MS gradation requirements) and natural (sourced from a naturally deposited pit). Of the 18 mixtures prepared for this study, 15 were produced using manufactured sand and 3 were produced using the natural sand. For evaluation of the PLC concrete's susceptibility to thaumasite attack, three mortars were made with manufactured sand and one with natural sand, as outlined in Table 3.1.

3.2.2.1 Manufactured Sand

Manufactured sand was selected for use in most (15 of 18) of the mixes due to NCDOT's forecast that it will be increasingly utilized in future concrete pavements due to the reduced availability of natural sand, as well as for economic reasons. The manufactured sand was produced by a quarry in the Charlotte, North Carolina, metropolitan area which is centrally located in the Piedmont region of North Carolina. The manufactured sand met the requirement of 2MS. The specific gravity, absorption, and average fineness modulus for this sand are 2.81, 0.3%, and 2.54 respectively. Sieve analysis of manufactured sand is provided in Table A.4 of Appendix A.

3.2.2.2 Natural Sand

Natural sand meeting ASTM C33 was utilized for used for several (3 of 18 total) mixes. The natural sand was obtained from a pit supplying the Charlotte, North Carolina metropolitan area. The bulk specific gravity, SSD specific gravity, apparent specific gravity of the sand are 2.64, 2.66, and 2.69 respectively. The absorption and average fineness modulus of the sand are 0.74% and 2.73 respectively. Sieve analysis of natural sand is provided in Table A.5 of Appendix A.

3.2.3 Coarse Aggregates

Three different kinds of coarse aggregates were used for this study, one selected to represent each region of North Carolina: Piedmont, Mountain, and Coastal. The quarries supplying each of the coarse aggregates were selected due to being commonly utilized in North Carolina concrete pavement mixtures. A description of the aggregates, along with the relevant engineering properties are provided below.

3.2.3.1 Piedmont Aggregate

The Piedmont aggregate used for this research study was a granitic gneiss supplied by a quarry located near Raleigh, North Carolina. This aggregate, a crushed granite, meets a No. 67 gradation. The specific gravity of this aggregate is 2.663 is determined by ASTM C127 test method, and the absorption is 0.8%. Sieve analysis of aggregate is provided in Table A.1 of Appendix A.

3.1.3.2 Mountain Aggregate

The Mountain aggregate used in this project is a granitic gneiss supplied by a quarry near Ashville, North Carolina. This aggregate is a granite meeting No. 67 gradation. The specific gravity and absorption of the aggregate are 2.62, and 1.1% respectively. Sieve analysis of aggregate is provided in Table A.2 of Appendix A.

3.1.3.3 Costal Aggregate

The Coastal aggregate (a coastal limestone) used in this project is supplied by a quarry located near Wilmington, North Carolina. This marine limestone meets No. 67 gradation. The bulk SSD specific gravity, bulk dry specific gravity, absorption, and dry rodded unit weight are 2.391, 2.338, 2.26%, and 82.1 lb/cf respectively. Sieve analysis of aggregate is provided in Table A.3 of Appendix A.

3.2.4 Admixtures

Two admixtures were used for this research to achieve the target entrained air content and slump. To ensure consistency in test results, as well as to help ensure that changes in concrete performance could be linked to changes in materials (not differences in air content), a tight air content tolerance of 5.0% to 6.0% was utilized. Batches not meeting this air content range were discarded. The target slump for each mixture was 1.5 inches (typical for slip-form paving mixtures), but varied from 1 to 2.5 inches, as cement content and water to cementitious materials ratio was held constant.

An air entraining admixture and a mid-range water reducing admixture were used in all mixtures. The air entraining admixture and water reducing admixture used for this research were MasterAir AE 200 and Master Polyheed 997, respectively. Both of the admixtures are manufactured by BASF. The dosage of air entraining admixture recommended by manufacturer is 0.125 to 1.5 fluid oz/cwt. The actual required dosage of air entraining admixture varied between 0.48 fluid oz/cwt to 12.6 fluid oz/cwt to maintain the specified 5.0% to 6.0% air content utilized for this project. Lower dosages of air entraining admixture were required for mixtures containing natural sand, where no water reducing admixture was required. Higher dosages of air entraining admixture were required for mixtures containing fly ash. The dosage of mid-range water reducer recommended by the manufacturer was 3 to 15 fluid oz/cwt. The actual dosages of mid-range water reducer required ranged between 3.9 fluid oz/cwt and 17.3 fluid oz/cwt as to achieve the desired slump of about 1.5. Lower dosages of mid-range water reducing admixture were required for mixtures containing fly ash and higher dosages were required for concrete mixtures where Coastal coarse aggregate was used.

3.3 Laboratory Testing Program

The overall testing program for this project is shown in Table 3.2. It is noted that although a number of tests were performed as part of this work, only those utilized in the analytical portion of this thesis are discussed here. Information on other tests will be presented in the project report and in other publications (Blanchard, 2016 and Medlin, 2016).

Table 3.2: Tests performed for this study

	Test	Protocol	Age(s) in days	Replicates
Fresh	Air content	Pressure meter (ASTM C231)	Fresh	1 each batch
	Slump	ASTM C143	Fresh	1
	Fresh density (unit weight)	ASTM C138	Fresh	1
	Temperature	AASHTO T309	Fresh	1
Hardened	Compressive strength	ASTM C39	3, 7, 28, 90	3 each age
	Resistivity	AASHTO TP95-11	3, 7, 28, 90	3 each age
	Modulus of rupture	ASTM C78	28	2
	Modulus of elasticity and Poisson's ratio	ASTM C469	28	2
	Shrinkage	ASTM C157	per standard	3
	Cracking potential	ASTM C1581	per standard	3
	Rapid chloride permeability	ASTM C1202	28	2
	Thaumasite attack	CSA A3004-C8	per standard	6

3.4 Batching and Mixing Procedure

As shown in Table 3.2, this research study required the evaluation of fresh concrete properties, mechanical properties of hardened concrete and thermal properties of hardened concrete. Hence a relatively large amount of concrete was required to batch all testing specimens. Considering that batching had to be done in a laboratory using a six cubic foot portable concrete mixer, each mixture design shown in Figure 1 was prepared in four batches, so that optimum sized batches (approximately 2 to 2.5 cubic feet) could be produced for each batch. Concrete prepared in Batch 1 was used to prepare specimens for the rapid chloride ion penetration test and the cracking potential test. Batch 2 concrete was used to prepare specimens for freeze-thaw testing. Batch 3 concrete was used to prepare specimens for testing to determine the modulus of elasticity, drying shrinkage potential, heat capacity, and thermal conductivity. Batch 4 concrete was used to prepare specimens for testing for modulus of rupture and coefficient of thermal expansion.

3.5. Preparation and Curing of Test Specimens

Batching of concrete was done in accordance with the ASTM C685 standard, "Standard Specification for Concrete made by Volumetric Batching and Continuous Mixing." Each of the four batches was used to prepare specimens for specific tests, as outlined above. To ensure consistency in test specimen preparation, the same individual prepared specimens for each test. Also, to ensure consistency between batches prepared for the same mixture, additional 4" by 8" cylinders were prepared and tested for compressive strength. For thaumasite attack testing, mortar bars were prepared using a small stand-type mortar mixer in laboratory. As per the standard, after demolding, mortar bars were stored in lime water for 14 days and later transferred into sulfate solution.

3.6 Laboratory Testing

3.6.1 Testing of Fresh Concrete Properties

3.6.1.1 Air Content

Total air content was measured in accordance with ASTM C231 standard, "Standard Test method for Air Content of Freshly Mixed Concrete by the Pressure method." using a Type B meter.

3.6.1.2 Slump Test

Slump testing is a traditional method of evaluating the potential workability of a concrete mixture. The test was performed in accordance with ASTM C143, "Standard Test Method for Slump of Hydraulic-Cement Concrete." The desired slump for the project was 1.5 inches, since these mixtures represent concrete to be placed with a slipform paver (concrete needs to be stiff enough to hold an edge as the paver moves on). However, in order to maintain consistency of the w/cm ratio, slump values ranging between 1 and 2 inches were considered acceptable.

Despite maintaining a constant w/cm ratio, slump values fluctuated slightly due to changes in materials. Water reducing admixture dosages were adjusted as needed to obtain slumps within the acceptable range. Of note, mixtures that utilized the natural fine aggregate had slump values greater than 2 inches. Although this is greater than typically utilized for paving mixtures, the goal of the project warranted that the w/cm remain constant, and these mixtures were utilized at these higher slumps to accomplish project goals.

3.6.1.3 Fresh Density (Unit weight)

This test was performed according to standard ASTM C138, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete." This test was performed to ensure constancy in batching. Fresh density was performed with the same equipment as the air content using the pressure method, utilizing a container of known volume.

3.6.1.4 Temperature

This test was utilized to determine the temperature of freshly mixed concrete, and was performed within five minutes of batching of the concrete mixture. The test was performed according to the standard AASHTO T309, "Temperature of Freshly Mixed Portland Cement Concrete."

3.6.2 Mechanical Properties

3.6.2.1 Compressive Strength

This test was performed according to the standard ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." The size of cylinders that were used for this tests were 4"x8" cylinders. Compressive strength tests were performed at 3 days, 7 days, 28 days and 90 days of age using a total of three Specimens at each age. In order to check the consistency of concrete strength, four 4"x8" specimens were prepared for all the batches of concrete made for other tests and compressive strength was determined on 3^{rd} and 28^{th} day ages of concrete.

3.4.2.2 Modulus of Rupture

This test was performed according to standard ASTM C78, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." This test was used to determine the modulus of rupture or flexural strength of the concrete by use of simple beam with third point loading. This test was conducted at 28 days of age on two specimens prepared from each mixture. Specimens were moist cured and were tested immediately after taking them out as drying them may result in reduction of measured flexural strength.

3.6.2.3 Modulus of Elasticity and Poisson's Ratio

This test was performed according to standard ASTM C469, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." This test determines the modulus of elasticity and Poisson's ratio of concrete cylinders under longitudinal compressive stress conditions. This test was conducted at 28 days age, using 6"x12" cylinders. A total of two specimens were tested per mixture.

3.6.3 Durability Performance

3.6.3.1 Resistivity

Surface resistivity tests were performed according to the standard AASHTO TP95-11, "Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration." This test was used for determination of the electrical resistivity of water saturated concrete to provide a rapid indication of resistance to chloride ion penetration. For this test, 4"x8" cylinders were used, and the test was conducted using the Proceq surface resistivity meter. This test was conducted at ages of 3 days, 7 days, 28 days and 90 days from batching, on a total of three specimens per age.

3.6.3.2 Rapid Chloride Permeability

Rapid chloride permeability tests are utilized to provide an indication of the resistance of concrete to the penetration of chloride ions. This test was performed according to the standard ASTM C1202, “Standard Test Method for Electrical Indication of Concrete’s Ability to Resist Chloride Ion Penetration.” The test specimens were prepared from cylinders of 4”x8” size, with two specimens tested from each mix design at each test age. Prior to the test date 2” thick disk specimens were cut from each of the two cylinders: a 2” disk from the end (bottom surface) of the cylinder and another specimen from the next two inches of the cylinder. The concrete specimens were tested at 28 days and 90 days of age. One day before the test date specimens were vacuum saturated per the ASTM C1202 standard.

3.6.3.3 Thaumasite Attack

This test was performed according to Canadian standard CSA 3004-C8, “Test Method for Determination of Sulphate Resistance of Mortar Bars Exposed to Sulphate Solution,” which is similar to ASTM C1012, “Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution.” Mortar mixtures prepared are as shown in Table 3.1. After batching in a small stand mixer, test specimens were prepared in accordance with CSA A3004-C5, “Test Method for Determination of Expansion of Hydraulic Cement Mortar Bars due to Internal Sulfate Attack.” For each mortar mixture prepared for testing, six mortar bars were cast from the same batch of mortar. Test specimens used were bars of size 25x25x160 mm with an effective gage length of 110 mm.

The specimens were removed from the molds after 22 to 23 hours of curing in a moist environment. The initial specimen lengths were measured after placing the specimen in saturated lime water at 23±2 °C for at least 30 minutes. For each mortar mixtures 9 mortar cubes were batched to test compressive strength on 3 days, 7 days, and 28 days to check if it meets the standard for performing thaumasite. Specimens were again stored in the saturated lime water, and a second measurement was taken at 14 days of age. Then, specimens were transferred into storage containers with a 50 g/L sodium sulfate solution, with the volumetric proportion of solution to bars kept within the range of 4 to 1). For each mixture, three of the six specimens were placed in sulfate solution kept at 5^{o}C temperature, and the other three specimens were placed in sulfate solution in 23^{o}C temperature. The storage requirements of the standard were adhered to, with specimens stored with at least 6mm clearance on all sides. Changes in length were determined after 1 week, 2 weeks, 3 weeks, 4 weeks, 8 weeks, 15 weeks, and 6 months of immersion in the solution and storage at the specified temperature.

CHAPTER 4: RESULTS

This chapter presents the results of tests that were performed in this study. The results are divided into three different sections: fresh concrete properties, mechanical properties of hardened concrete, and durability performance of hardened concrete. Results are presented in tabular form for ease of comparison. In this chapter, the summary (average) results are presented, while the raw data for tests is presented in Appendix B. The first column of each table provides a code that represents the batch ID. The first letter of the ID represents the type of coarse aggregate utilized in the mixture (P- Piedmont, C- Coastal, and M- Mountain). The second letter represents the type of cement used in the mixture (A- OPC1, B- OPC2, and BL- PLC). The third letter represents the type of fly ash used in the mixture (N- no fly ash, A- fly ash 1, and B- fly ash 2). Finally, the fourth letter represents the type of fine aggregate used in the mixture (M- manufactured sand, N- natural sand).

4.1 Fresh Concrete Properties

Fresh concrete properties for the mixtures batched as part of this work are summarized below in Table 4.1. Additional details regarding each test are presented in the subsequent sections.

Table 4.1: Test results for fresh concrete properties

Mixture ID	Slump (in)	Air Content (%)	Unit Wt. (pcf)
P.A.N.M	1.4	5.4	145
P.B.N.M	1.9	6.0	143
P.BL.N.M	2.2	5.6	144
C.A.N.M	1.1	5.8	138
C.B.N.M	1.4	5.6	139
C.BL.N.M	1.1	5.5	139
M.A.N.M	1.6	5.3	146
M.B.N.M	2.0	5.2	145
M.BL.N.M	2.3	5.2	145
P.A.A.M	2.8	5.7	141
P.B.A.M	2.2	5.2	143
P.BL.A.M	2.5	5.2	142
P.A.B.M	2.1	5.6	141
P.B.B.M	2.3	5.7	141
P.BL.B.M	2.3	5.6	141
P.A.N.N	2.1	5.4	142
P.B.N.N	3.8	5.6	142
P.BL.N.N	2.9	5.4	141

4.1.1 Slump

As discussed previously in Chapter 3, the slump test was performed in accordance with ASTM C143, and was performed immediately after batching the concrete mixture. This test was performed on all 18 mixtures to evaluate the workability of the concrete, and ensure that each batch had a consistency within the desired range for paving concrete. As shown in Table 4.1, the average slump values for the mixtures ranged between 1.1 inches to 3.3 inches. Slump value of all the batches is provided in Appendix B in Table B.1. From the results it can be observed that fly ash mixtures and natural sand mixtures had a higher slump value than manufactured sand mixtures. Higher slump was observed in mixtures where natural sand was used as fine aggregate. For this study the desired slump value was 1.5 inches but mixtures which exhibited a higher slump value were considered in order to maintain the water-cement ratio constant. As discussed previously, this study is focused on comparison between the performance of mixtures utilizing OPC, PLC, OPC with fly ash, and PLC with fly ash. From this perspective, it can be observed from the results that keeping water-cement ratio constant, the workability of concrete with fly ash is higher compared to that of concrete mixtures with manufactured sand. Typically, additional water reducing admixture was not required for mixtures containing PLC.

4.2.2 Air Content

For each batch, the air content was determined according to ASTM C231 using a Type B meter. The desired air content for this project was 5% to 6%, a very tight tolerance (tighter than NCDOT specifications), in order to have the best odds of attributing changes in test results to changes in materials rather than difference in air content. In order to obtain the desired value of air content, air entraining admixture was added to the concrete mixture. Overall, the air entraining admixture required for mixtures ranged between 0.5 oz/cwt and 12.6 oz/cwt which was not within the recommended dosage range recommended by the manufacturer. The air content value for all mixtures ranged between 5.2% and 6.0%. The results are tabulated in Table 4.1. Air content of all the batches is provided in Appendix B in Table B.2.

Concrete mixtures containing natural sand required less air entraining admixture than the concrete mixtures containing manufactured sand. Concrete mixtures containing fly ash required higher air entraining admixture doses than non-fly ash mixtures in order to reach the desired air content. PLC concrete mixtures (with the exception of the one containing for Piedmont with manufactured sand) tended to require slightly more air entraining admixture than the companion OPC mixtures, but it was not a large difference in dosage rate.

4.2.3 Unit Weight

The unit weight of each batch of concrete was test was tested in accordance with ASTM C138. These results are also tabulated in Table 4.1. The results ranged between 138 pcf and 145 pcf for the mixtures. Lower unit weights were observed in mixtures with Coastal coarse aggregate, which is as expected due to the slightly lower specific gravity of this somewhat more porous marine limestone aggregate. Fly ash mixtures and natural sand mixtures tended to have slightly lower unit weights than those of the mixtures containing the Mountain coarse aggregate and Piedmont coarse aggregate with manufactured sand. Unit weight of all the batches is provided in Appendix B in Table B.3.

4.2 Mechanical Properties

4.2.1 Compressive Strength

Compressive strength tests were performed on 4” by 8” cylinders per standard ASTM C39. For each mixture, tests were performed on three specimens at 3 days, 7 days, 28 days, and 90 days of age. The average results are tabulated in Table 4.2, and all test results are provided in Appendix B in Table B.4. The average compressive strength at 3 days of age ranged between 2,040 psi and 4,340 psi. From the results it can observed that mixtures with manufactured sand and no fly ash exhibited higher early-age strength than mixtures with no fly ash and mixtures with natural sand as fine aggregate. Changes in the type of coarse aggregate appeared to have less of an influence on early-age compressive strength than the type of fine aggregate used and whether or not fly ash was used. The average compressive strength test results at 7 days ranged between 2,390 psi and 5,960 psi.

The influence of materials on strengths at this age appears similar to that observed with the 3-day compressive strength test results.

At 28 days, as per NCDOT Standard Specifications (2012), the strength of concrete should be 4,500 psi for a pavement mixture. All mixtures met this requirement, with the exception of the mixtures containing fly ash and mixture containing natural sand (P.B.N.N). This slower strength gain of the fly ash mixtures is as expected based on the known hydration characteristics of fly ash. Each of these mixtures met the 4,500 psi compressive strength requirement by 90 days, with the exception of mixtures P.B.A.M, P.B.B.M, and P.BL.B.M, all three being fly ash mixtures. Ultimately, in a production setting, modifications to the mixture proportions for these mixture (including use of high-range water reducers to lower the w/cm ratio) would be performed to achieve the required 28-day strengths. However, as the goal of this research project was to elucidate the effects of different materials on the same base mixture, and some deviation from specified was anticipated as an artifact of this research approach.

Overall, the results show that compressive strengths of concrete mixtures produced with OPC (designated B in the Mixture ID) and the compressive strengths of concrete mixtures produced with the companion PLC (BL in the Mixture ID) are typically similar. To facilitate comparison, these mixtures are highlighted in yellow, below in Table 4.2. In general, early age (3-day and 7-day) strengths of the OPC (cement B) and PLC mixtures (limestone interground with cement B) were very similar, with the exception of two instances (7-day compressive strengths of P.B.N.M and P.BL.N.M, and 7-day compressive strengths of P.B.N.N and P.BL.N.N). A few notable exceptions occur at later ages (such as the 90-day compressive strengths of P.B.N.M and P.BL.N.M).

Table 4.2: Compressive strength test results

Mixture ID	Average Compressive Strength (psi)			
	3 Days	**7 Days**	**28 Days**	**90 Days**
P.A.N.M	3,370	4,020	5,020	5,230
P.B.N.M	3,660	3,960	4,850	5,500
P.BL.N.M	3,720	4,340	5,020	6,170
C.A.N.M	3,650	4,890	5,360	6,010
C.B.N.M	4,340	4,770	5,960	5,690
C.BL.N.M	4,290	4,850	5,560	5,610
M.A.N.M	3,060	3,930	5,030	5,530
M.B.N.M	3,800	4,130	5,100	5,390
M.BL.N.M	3,670	4,130	4,790	5,530
P.A.A.M	2,620	3,550	4,270	5,560
P.B.A.M	2,460	3,050	4,050	4,380
P.BL.A.M	2,210	2,960	3,750	4,620
P.A.B.M	2,130	2,390	3,780	5,490
P.B.B.M	2,040	2,410	3,140	4,340
P.BL.B.M	2,330	2,500	3,780	4,370
P.A.N.N	2,720	4,080	5,400	6,060
P.B.N.N	3,010	3,420	4,390	5,450
P.BL.N.N	3,270	3,930	5,190	5,800

4.2.2 Modulus of Rupture (MOR)

Tests to determine the modulus or rupture (flexural strength) of the concrete were conducted according to ASTM C78, with two specimens per mixture tested at 28 days age of concrete. Average test results for all mixtures are tabulated in Table 4.3, and test results for all specimens are presented in Appendix B in Table B.5. According to NCDOT Standard Specifications (2012), the minimum value of MOR at 28 days age of concrete is 650 psi for mixtures used for concrete pavements. The average value of MOR for the 18 mixtures batched as part of this study ranged from 540 psi and 750 psi. As discussed previously, in a production setting, modifications to the mixture proportions for mixtures not meeting the specification (including use of high-range water reducers to lower the w/cm ratio) would be performed to achieve the required 28-day MOR values. However, as the goal of this research project was to elucidate the effects of different materials on the same base mixture, and some deviation from specified was anticipated as an artifact of this research approach.

Table 4.3: Modulus of rupture test results

Mixture ID	Average Modulus of Rupture, MOR (Psi)
P.A.N.M	680
P.B.N.M	670
P.BL.N.M	660
C.A.N.M	730
C.B.N.M	750
C.BL.N.M	680
M.A.N.M	570
M.B.N.M	640
M.BL.N.M	610
P.A.A.M	650
P.B.A.M	540
P.BL.A.M	650
P.A.B.M	570
P.B.B.M	620
P.BL.B.M	560
P.A.N.N	740
P.B.N.N	720
P.BL.N.N	750

The influence of fine aggregate type is readily evident in the results shown in Table 4.3. Mixtures that utilized the natural sand (P.A.N.N, P.B.N.N and P.BL.N.N) had the highest MOR values, exceeding the requirement by almost 100 psi. For mixtures without fly ash, all mixtures that included manufactured sand had average MOR values exceeding the 650 psi requirement, with the exception of the mixtures that included Mountain coarse aggregate. With the exception of two mixtures (P.A.A.M and P.BL.A.M), all mixtures containing fly ash did not meet the required MOR of 650 psi at 28-days. This is consistent with the slower strength gain of fly ash mixtures.

Of key interest in this study is the performance of OPC mixtures with cement type B (indicated with B in the Mixture ID), and the companion PLC mixtures (indicated with BL in the Mixture ID). These pairs are again highlighted in yellow in Table 4.3. MOR test results for these pairs tended to vary somewhat, but a general trend (OPC having higher MOR than PLC or vice versa) is not readily evident from the test results. For example, for mixtures containing the Piedmont and Coastal coarse aggregate without fly ash, the OPC mixture had a higher MOR than the companion PLC mixture. In the case of mixtures containing fly ash from source A, the PLC mixture had a higher MOR than the companion OPC mixtures. The opposite results were observed in the test results for the OPC and PLC mixture pair that included fly ash from source B. For the natural sand mixtures, the concrete made with PLC had a higher MOR than the companion OPC mixture. However, for mixtures containing the Mountain coarse aggregate, both the OPC and PLC mixtures had similar values of MOR. This may indicate that the use of PLC was not a key factor in MOR test results.

4.2.3 Modulus of Elasticity (MOE) and Poisson’s Ratio

Tests to determine the modulus of elasticity and Poisson’s ratio were performed according to standard ASTM C469. A summary of the averages of test results are tabulated in Table 4.4, and test results for all specimens are provided in Appendix B in Table B.6 and B.7. These tests were conducted at 28 days age, and each average shown in Table 4.4 represents the average of two samples.

Table 4.4: Modulus of elasticity and Poisson’s ratio test results

Mixture ID	**Modulus of Elasticity, MOE (psi)**	**Poisson’s Ratio**
P.A.N.M	2,920,000	0.20
P.B.N.M	3,340,000	0.20
P.BL.N.M	2,430,000	0.18
C.A.N.M	3,730,000	0.22
C.B.N.M	3,490,000	0.21
C.BL.N.M	3,690,000	0.22
M.A.N.M	2,540,000	0.18
M.B.N.M	2,760,000	0.20
M.BL.N.M	3,020,000	0.20
P.A.A.M	3,220,000	0.23
P.B.A.M	2,700,000	0.21
P.BL.A.M	2,690,000	0.16
P.A.B.M	2,840,000	0.22
P.B.B.M	2,510,000	0.18
P.BL.B.M	2,720,000	0.19
P.A.N.N	3,400,000	0.15
P.B.N.N	3,510,000	0.19
P.BL.N.N	3,040,000	0.15

As can be seen in Table 4.4, the average MOE values for the 18 mixtures ranged from 2,510,000 to 3,730,000 psi, and some general trends were evident. For mixtures without fly ash, mixtures containing Coastal coarse aggregates typically had higher MOE values than mixtures containing Mountain or Piedmont coarse aggregates. Concrete mixtures containing fly ash had lower MOE values compared to other mixtures that did not contain fly ash. This is consistent with the lower rate of hydration and strength gain typically observed in fly ash mixtures. Two of three natural sand mixtures (which did not have fly ash) also had higher MOE values, particularly higher than the companion Piedmont coarse aggregate mixtures with manufactured sand.

As stated previously, the performance of OPC mixtures with cement type B (indicated with B in the Mixture ID), and the companion PLC mixtures (indicated with BL in the Mixture ID) is a focus of this study. These pairs are again highlighted in yellow in Table 4.4. MOE test results for these pairs tended to vary somewhat, but a general trend (OPC having higher MOE than PLC or vice versa) is not readily evident from the test results. In case of mixtures with manufactured sand and no fly ash, PLC concrete mixtures had higher MOE values compared to that of OPC mixtures with Mountain aggregate, but vice versa for mixtures containing the Piedmont coarse aggregate. In the case of mixtures containing Coastal coarse aggregate, the OPC and PLC mixtures had similar MOE test results. Comparing the natural sand mixtures, the PLC mixture had a lower MOE value than both OPC mixtures. In case of fly ash mixtures with fly ash A, the value of the PLC mixture was close to the companion OPC mixture. For mixtures containing fly ash B, the PLC mixture had a higher MOE than the companion OPC mixture. Similar to the findings for the MOR test results in the previous section, this may indicate that the use of PLC was not a key factor in MOE test results.

Poisson’s ratio values are also shown in Table 4.4. The average Poisson’s ratio values ranged between 0.15 and 0.23. From Table 4.4, it can observed that for mixtures containing Piedmont coarse aggregate and Mountain coarse aggregate with manufactured sand, Poisson’s ratio was between 0.18 and 0.20. A number of other mixtures tended to have Poisson’s ratios between 0.18 and 0.22. A few mixtures had lower Poisson’s ratios, but a trend is not readily evident. Similar to the results for MOR and MOE, an overall trend in Poisson’s ratio between the PLC and OPC (companion cement type B) is not evident from Table 4.4, where the pairs are highlighted in yellow to facilitate comparison.

4.3 Durability Performance

4.3.1 Surface Resistivity

Surface resistivity tests were performed in accordance with AASHTO TP95-11. Tests were performed on cylinder specimens of size 4” by 8”, which were the same specimens used for compressive strength tests. Surface resistivity measurements were obtained at concrete ages of 3 days, 7 days, 28 days, and 90 days. For each age, three specimens were tested for each mixture. The average surface resistivity measurements are tabulated in Table 4.5, and all measurements are provided in Appendix B in Table B.8.

Table 4.5: Surface resistivity test results

Mixture ID	**Surface Resistivity (KiloOhm-cm)**			
	3 Days	**7 Days**	**28 Days**	**90 Days**
P.A.N.M	3.57	4.27	6.90	8.90
P.B.N.M	4.81	5.23	7.32	9.29
P.BL.N.M	4.98	5.36	7.59	9.13
C.A.N.M	4.06	4.85	6.73	9.80
C.B.N.M	4.52	5.52	7.02	8.72
C.BL.N.M	4.83	5.53	6.64	8.08
M.A.N.M	3.05	3.68	5.98	7.75
M.B.N.M	4.47	4.71	6.65	7.78
M.BL.N.M	5.85	6.15	7.59	8.53
P.A.A.M	3.12	3.62	7.76	26.61
P.B.A.M	4.98	5.36	10.45	32.86
P.BL.A.M	4.60	5.56	12.61	37.35
P.A.B.M	3.45	3.62	7.51	24.28
P.B.B.M	5.01	5.38	9.83	26.60
P.BL.B.M	4.83	5.56	12.54	35.25
P.A.N.N	4.56	5.42	7.46	9.64
P.B.N.N	7.99	8.73	10.67	10.80
P.BL.N.N	7.05	7.96	9.49	10.33

Of use in evaluating the results shown in Table 4.7 is the correlation between surface resistivity and chloride ion penetration (ASTM C1202) provided in AASHTO TP95-11. This table is shown below as Table 4.6.

Table 4.6: Relationship between surface resistivity and chloride ion penetration from AASHTO TP95-11.

Chloride Ion Penetration	**Surface Resistivity (KiloOhm-cm)**
High	<12
Moderate	12-21
Low	21-37
Very Low	37-254
Negligible	>254

For early ages (3-day and 7-day) the surface resistivity measurements for all mixtures indicated a high susceptibility to chloride ion penetration. By 28 days of age, mixtures containing fly ash began to show higher surface resistivity (and therefore potentially lower chloride ion penetration) than the non-fly ash mixtures. However, at 28 days, all mixtures had surface resistivity measurements that indicated moderate to high susceptibility to chloride ion penetration. By 90 days, the effects of the fly ash in increasing surface resistivity (and therefore decreasing potential chloride ion penetration) are readily evident. For mixtures that did not contain fly ash, the OPC (cement type B) and PLC mixtures did not show a notable difference in performance. However, for the fly ash mixtures, the PLC mixture showed notably higher surface resistivity (indicating potentially better durability performance) than the OPC (cement type B). This may indicate that pairing a PLC with fly ash results in a denser microstructure, increased resistivity, and potentially lower chloride permeability.

4.3.2 Rapid Chloride Penetration Test

The rapid chloride ion penetration tests were conducted according to standard ASTM C1202 on 28 days and 90 days age of the concrete. Test specimens of 4” diameter by 2” thick that were cut from 4” by 8” cylinders. As detailed in Chapter 3, care was taken to cut the two specimens from the same locations on the cylinders (from the bottom two inches of a cylinder) for all tests. Specimens were vacuum saturated per ASTM C1202 prior to testing, and a 60 V potential was applied to the specimens.

Per the ASTM C1202 standard, the charge passed through the specimens after six hours can be related to relative susceptibility to chloride ion penetration per Table 4.7. A summary of the average rapid chloride ion test results for all mixtures is shown in Table 4.10.

Table 4.7: Chloride ion penetrability based on charge passed (from ASTM C1202)

Charge Passed (Coulombs)	**Chloride Ion Penetrability**
>4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very Low
<100	Negligible

Table 4.8: Rapid chloride ion permeability test results

Mixture ID	Charge Passed (Coulombs)	
	28 Days	90 days
P.A.N.M	7,170	5,300
P.B.N.M	6,860	5,120
P.BL.N.M	6,550	4,540
C.A.N.M	6,720	4,782
C.B.N.M	6,021	4,629
C.BL.N.M	6,769	5,433
M.A.N.M	6,828	5,240
M.B.N.M	6,056	5,286
M.BL.N.M	6,504	4,985
P.A.A.M	6,401	1,773
P.B.A.M	4,591	1,980
P.BL.A.M	3,682	1,331
P.A.B.M	6,134	1,562
P.B.B.M	5,225	1,651
P.BL.B.M	4,337	1,323
P.A.N.N	4,881	3,471
P.B.N.N	4,394	3,227
P.BL.N.N	4,330	3,449

As can be seen in Table 4.8, for the 28-day tests, results ranged from 3,682 Coulombs to 7,170 Coulombs. With the exception of mixture P.BL.A.M (a fly ash mixture) all mixtures had results indicating that the concrete is highly permeable to chloride ion penetration, while P.BL.A.M concrete is moderately permeable to chloride ion penetration. This may be a function of the relatively high w/cm ratio (0.48) required to obtain adequate workability with the manufactured sand. The charge passed through specimen prepared with manufactured sand and no fly ash is typically higher than the charge passed through mixtures with containing fly ash mixtures and natural sand mixtures. When all other materials are kept constant except cement, we can observe that the current passed through PLC concrete is less than that of OPC except in the case of Coastal coarse aggregate mixtures. Additionally, PLC concrete with fly ash tends to show the lowest chloride ion permeability, which indicates that PLC concrete containing fly ash concrete can provide enhanced durability performance.

By 90 days of age, test results show a decrease in amount of current passed for each specimen, as expected. Test results for 90 days ranged from 1,323 Coulombs to 5,433 Coulombs. However, the effects of fly ash in lowering chloride permeability are even more evident, likely corresponding to the slower rate of hydration of the fly ash. From Table 4.8, it can be observed that mixtures with manufactured sand and no fly ash are still highly permeable to chloride ion penetration, mixtures with natural sand are moderately permeable to chloride ion penetration, and mixtures with fly ash exhibit low permeability. Similar to the 28 day results (but even more pronounced), the 90 day test results show that PLC concretes that include fly ash tend to allow significantly lower charge passed compared to other mixtures with the OPC cements. In fact, the two mixtures containing PLC and fly ash exhibited the lowest charge passed (and therefore highest resistance to chloride ion penetration) of all mixtures. These results are similar to the results from surface resistivity, where PLC mixtures that included fly ash showed the potential for improved durability performance.

4.3.3 Shrinkage

Testing to evaluate the potential shrinkage of mixtures was performed according to the ASTM C157 standard. The average results for each mixture are tabulated in Table 4.9, with the raw data presented in Appendix B in Table B.9. Rows highlighted with yellow color are the results of tests on specimens prepared from cement B and PLC, which are to be compared in this study. Per ASTM C157, the specimens were cured for 28 days prior to placement in the environmental chamber. Discussed below are the shrinkages at durations of section are 2 weeks, 4 week, 8 week, and 32 weeks.

Table 4.9: Percentage length change due to shrinkage

	Length change due to shrinkage (%)			
Mixture ID	4 Weeks	8 Weeks	32 Weeks	64 Weeks
P.A.N.M	0.0300	0.0436	0.0533	0.0569
P.B.N.M	0.0345	0.0466	0.0545	0.0600
P.BL.N.M	0.0384	0.0500	0.0575	0.0606
C.A.N.M	0.0266	0.0418	0.0518	0.0569
C.B.N.M	0.0287	0.0409	0.0472	0.0509
C.BL.N.M	0.0284	0.0372	0.0433	0.0460
M.A.N.M	0.0290	0.0412	0.0512	0.0569
M.B.N.M	0.0318	0.0430	0.0527	0.0572
M.BL.N.M	0.0363	0.0487	0.0566	0.0624
P.A.A.M	0.0281	0.0409	0.0457	0.0530
P.B.A.M	0.0239	0.0333	0.0393	0.0533
P.BL.A.M	0.0303	0.0409	0.0478	0.0557
P.A.B.M	0.0254	0.0381	0.0454	0.0530
P.B.B.M	0.0257	0.0357	0.0457	0.0539
P.BL.B.M	0.0306	0.0415	0.0500	0.0584
P.A.N.N	0.0263	0.0336	0.0448	0.0530
P.B.N.N	0.0181	0.0245	0.0321	0.0433
P.BL.N.N	0.0203	0.0272	0.0360	0.0460

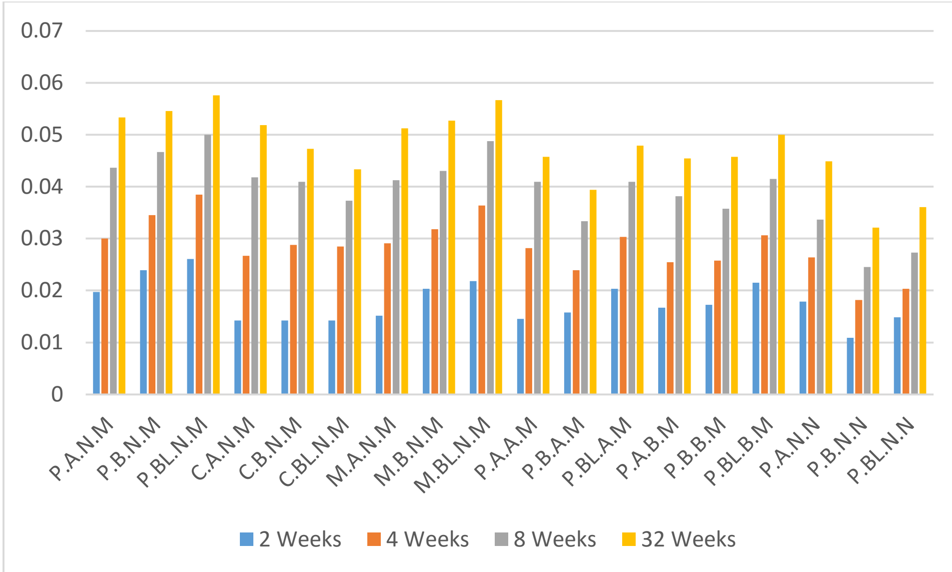

Figure 4.1: Percentage length change due to shrinkage

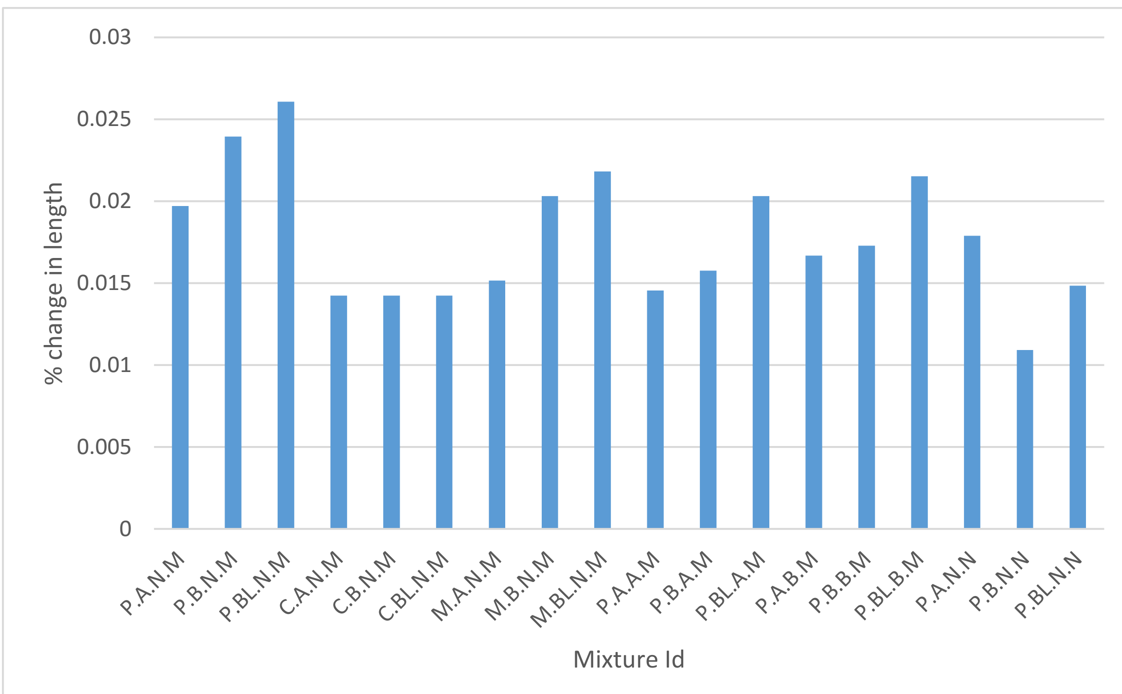

Figure 4.2: Percentage length change due to shrinkage after 14 days

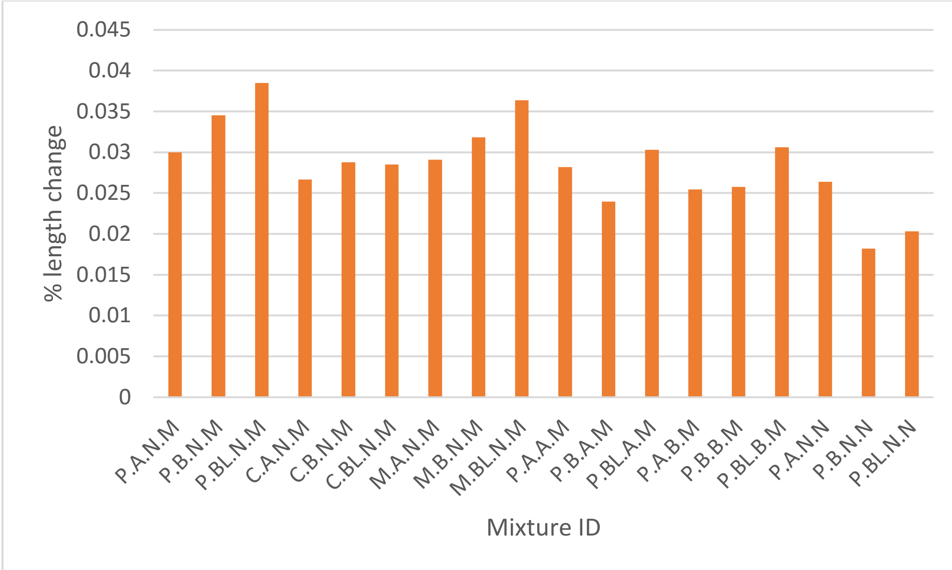

Figure 4.3: Percentage length change due to shrinkage after 4 weeks

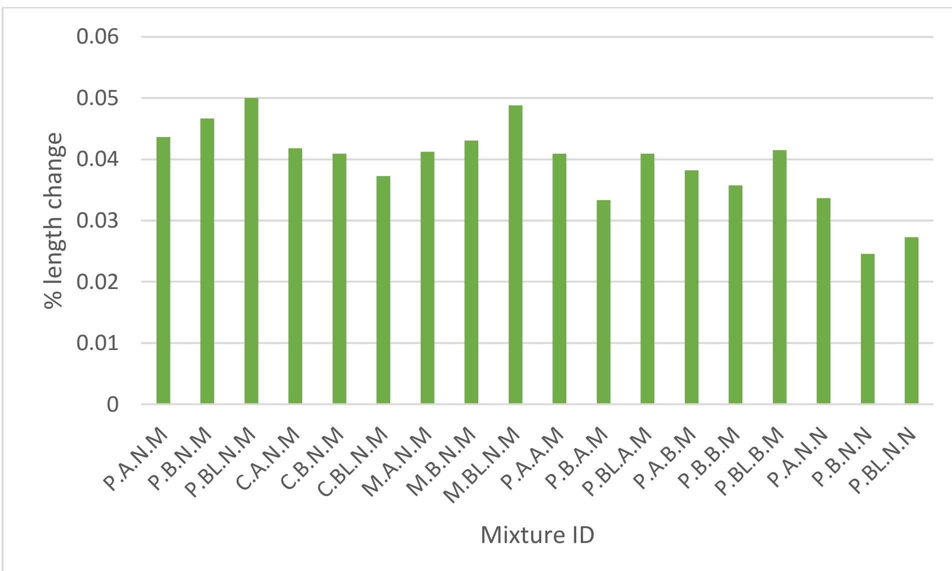

Figure 4.4: Percentage length change due to shrinkage after 8 weeks

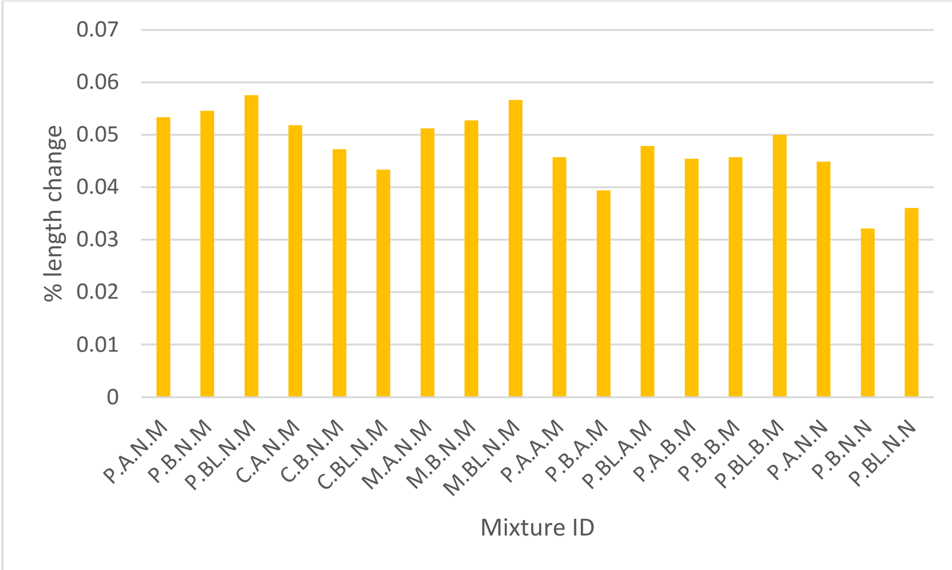

Figure 4.5: Percentage length change due to shrinkage after 16 weeks

Figures 4.2 to 4.5 show the shrinkage (% change in length) at the 2 week, 4 week, 8 week, and 16 week durations in the environmental chamber. From Figure 4.2 it can be observed that at 2 weeks, the PLC mixtures had a greater change in length compared to OPC mixtures except for the mixtures that included Coastal coarse aggregates where the shrinkage of OPC and PLC mixture were almost the same. For mixtures with natural sand OPC 1 (cement A) had greater change in length than the companion PLC and OPC 2 (cement B) mixtures. From Figure 4.3, the 4 week results, a change can be observed in Coastal aggregates mixtures, where OPC mixtures had greater change in length compared to PLC mixtures, while other mixtures repeated a trend similar to the 2 week result. From Figure 4.4 it can be seen after 8 weeks in the environmental chamber, PLC specimens for all mixtures (except the mixture with the Coastal coarse aggregate) had greater expansion than the companion OPC mixtures.

Figure 4.5 shows results from the 32 week measurement. For mixtures with manufactured sand, trends in change of length due to shrinkage were similar to the trends observed in the 8 week result. Overall, it can observed that PLC mixture had greater shrinkage than cement B in each case, with the exception of the Coastal aggregate mixtures. However, the differences in the amount of drying shrinkage observed between the PLC and OPC mixtures is judged to be very minimal. In almost all cases, at 32 weeks, the difference in drying shrinkage between the PLC mixtures and the OPC 2 (cement B) mixtures is 0.01% or less.

4.3.3 Thaumasite Attack

As described in Chapter 3, this test was performed on mortar bars of size 1" by 1" by 11", exposed to a sulfate solution and stored at two different temperatures (5^{o}C and 23^{o}C). Per the CSA 3004-C8 standard, six specimens for each mixture were prepared, of which three were stored at 5^{o}C (Procedure B) and three were stored at 23^{o}C (Procedure A). Readings of length change were taken after 1 week, 2 weeks, 3 weeks, 4 weeks, 8 weeks, 15 weeks, and after 6 months (24 weeks) period of storing the specimens in sulfate solution. The percent change of length was computed for each bar, and the average percent length change of three bars was determined. The average percent change in length for bars stored at 23^{o}C is shown in Table 4.10, and the average percent change in length for bars stored at 5^{o}C are shown in Table 4.11. Raw data is presented in Appendix B in Table B.10 and B.11. In both tables, the first column provides the Mixture ID. The first letter represents type of cement (A-OPC 1, B-OPC 2, and BL-PLC), the second letter represents the type of fly ash (N-no fly ash, A- fly ash A, and B-fly ash B), and in case of natural sand mixtures, the third letter N denotes natural sand.

Table 4.10: Percentage change in length of mortar bars at 23°C

Mixture ID	Average Expansion (%)					
	2 weeks	**3 Weeks**	**4 Weeks**	**8 Weeks**	**15 Weeks**	**24 Weeks**
A.N	0.0021	0.0033	0.0057	0.0072	0.0093	0.0163
B.N	0.0012	0.0039	0.0054	0.0103	0.0136	0.0190
BL.N	0.0024	0.0033	0.0015	0.0075	0.0106	0.0178
A.N.N	0.0049	0.0073	0.0073	0.0128	0.0190	0.0364
B.N.N	0.0003	0.0027	0.0039	0.0072	0.0115	0.0160
BL.N.N	0.0021	0.0015	0.0027	0.0075	0.0157	0.0430
A.A	0.0018	0.0033	0.0030	0.0084	0.0100	0.0109
B.A	0.0021	0.0041	0.0053	0.0094	0.0129	0.0278
BL.A	0.0018	0.0033	0.0039	0.0072	0.0000	0.0145
A.B	0.0057	0.0087	0.0103	0.0181	0.0303	0.0584
B.B	0.0012	0.0027	0.0042	0.0090	0.0166	0.0387
BL.B	0.0018	0.0036	0.0060	0.0081	0.0115	0.0196

Table 4.11: Percentage change in length of mortar bars stored at 5°C

Mixture ID	Average Expansion (%)					
	2 weeks	**3 Weeks**	**4 Weeks**	**8 Weeks**	**15 Weeks**	**24 Weeks**
A.N	0.0000	0.0021	0.0021	0.0084	0.0112	0.0193
B.N	0.0009	0.0009	0.0042	0.0069	0.0090	0.0172
BL.N	0.0006	0.003	0.0051	0.0042	0.0078	0.0142
A.N.N	0.0049	0.0073	0.0073	0.0128	0.0190	0.0364
B.N.N	0.0003	0.0027	0.0039	0.0072	0.0115	0.0160
BL.N.N	0.0021	0.0015	0.0027	0.0075	0.0157	0.0430
A.A	0.0018	0.0033	0.003	0.0084	0.0100	0.0109
B.A	0.0003	0.0021	0.0024	0.0045	0.0063	0.0075
BL.A	0.0018	0.0033	0.0039	0.0072	0.0000	0.0145
A.B	0.0036	0.0048	0.0060	0.0157	0.0372	0.0945
B.B	0.0069	0.0045	0.0084	0.0118	0.0184	0.0369
BL.B	0.0024	0.0033	0.0054	0.0069	0.0151	0.0306

Most importantly, from Table 4.10 it can be observed that all mixtures stored at both 23°C (CSA A3004-C8 Procedure A) and 5°C (CSA A3004-C8 Procedure B) exhibited an average expansion less than 0.10% at six months. Therefore these mixtures can be considered to have “passed” as sulfate resistant per the CSA 3004-C8 standard. Additional testing (for a duration of 18 months or longer) is required to determine whether the mixtures are considered to have high sulfate resistance.

Further discussion on the relative performance of mortar bars stored at 23°C and 5°C is presented subsequently. To help facilitate comparison, graphs showing the average percentage length change of the mortar bars were also prepared, and are shown in Figure 4.6 (for specimens stored at 23°C) and Figure 4.7 (for specimens stored at 5°C). The series of graphs following (Figures 4.8 through 4.13) show the relative average expansions during the course of the six months of testing that has transpired to date.

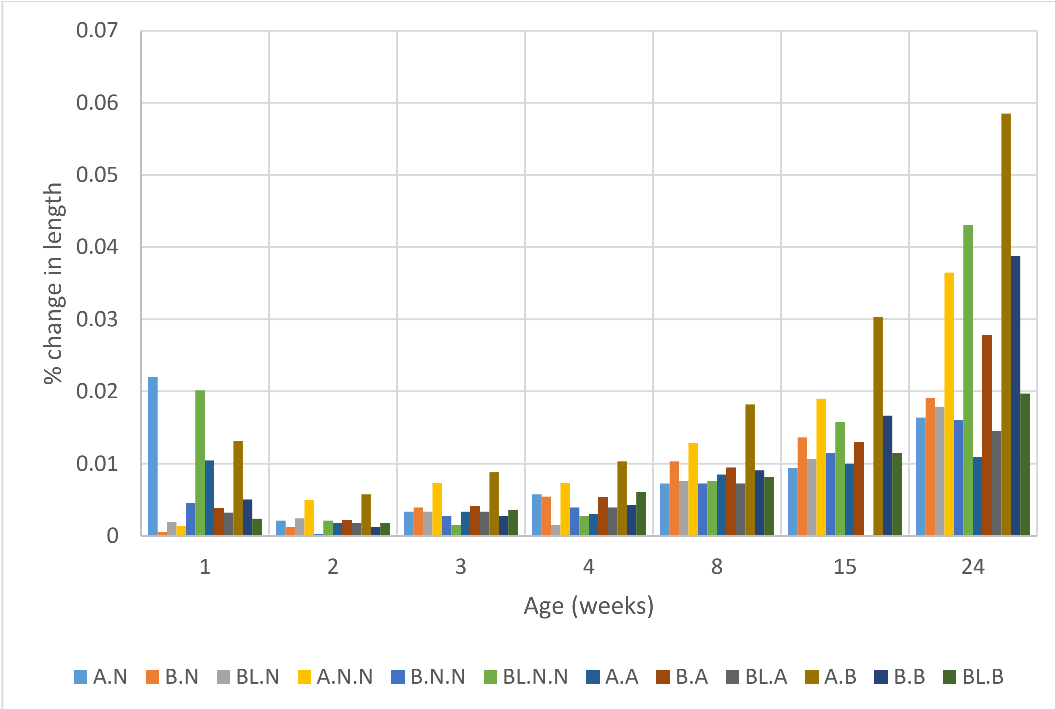

Figure 4.6: Percentage length change of mortar bars at 23^{o}C

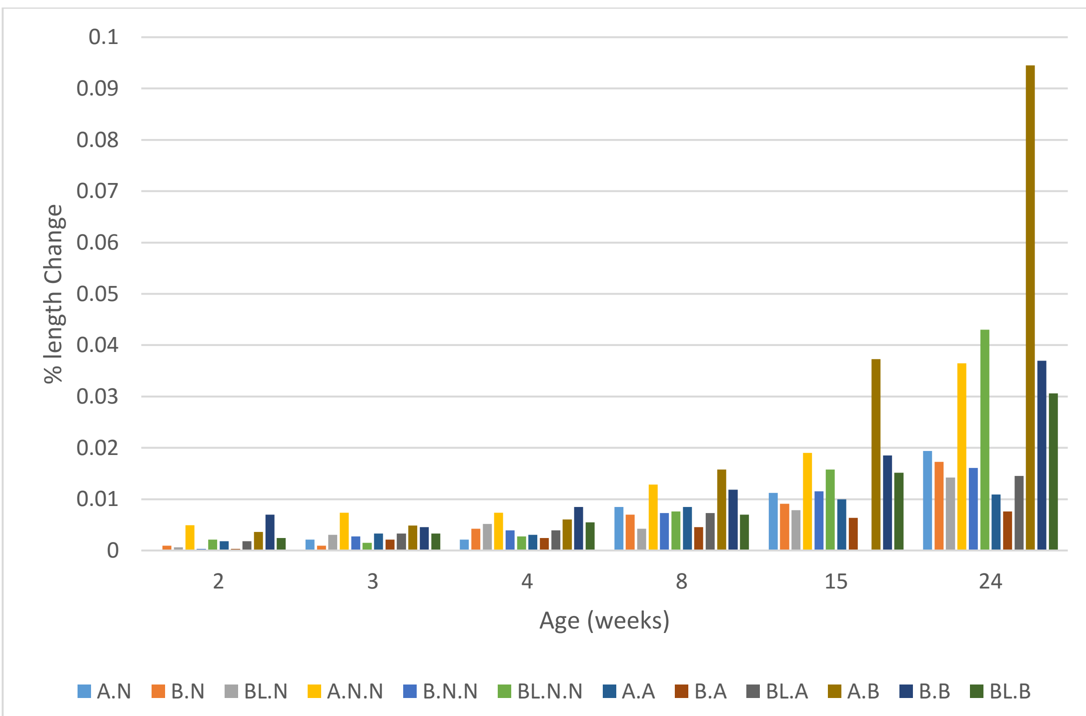

Figure 4.7: Percentage length change of mortar bars at 5^{o}C

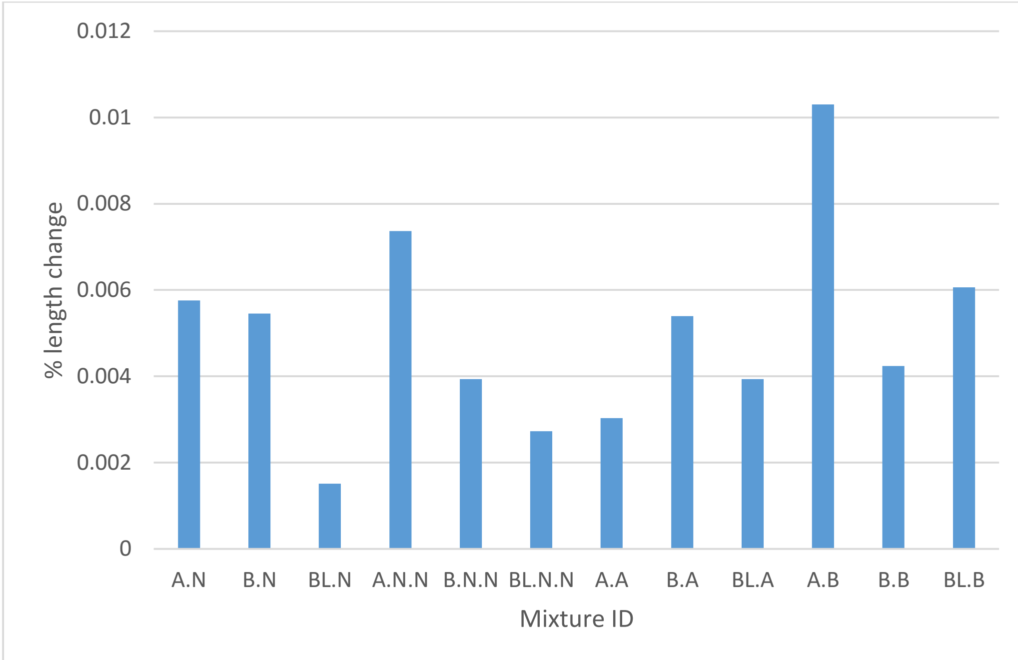

Figure 4.8: Percentage length change of mortar bars at 23°C after 4 weeks

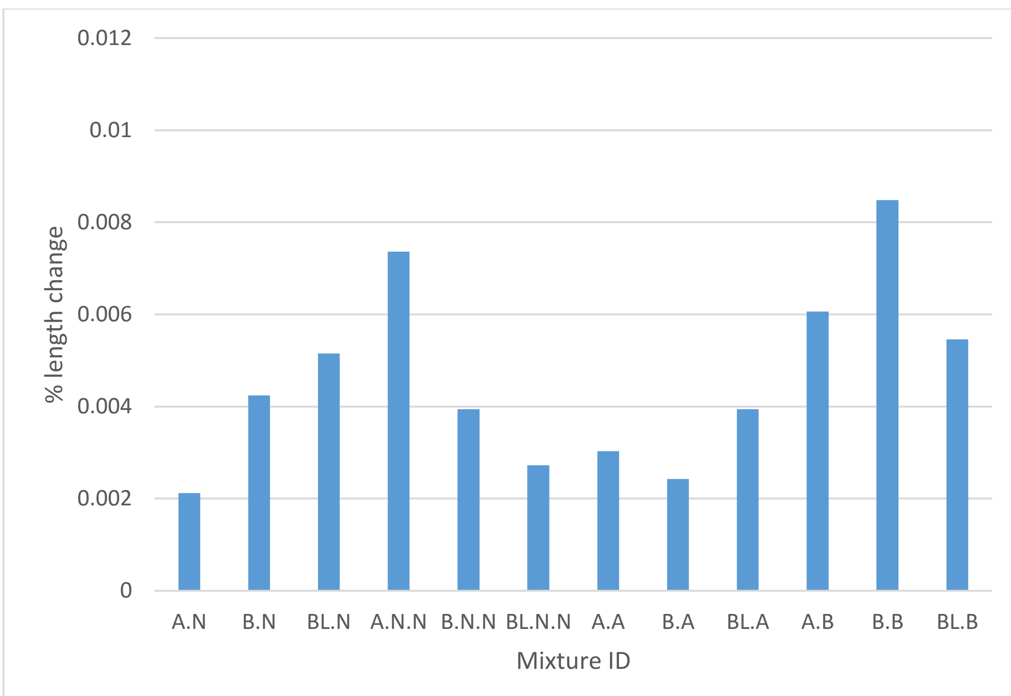

Figure 4.9: Percentage length change of mortar bars at 5°C after 4 weeks

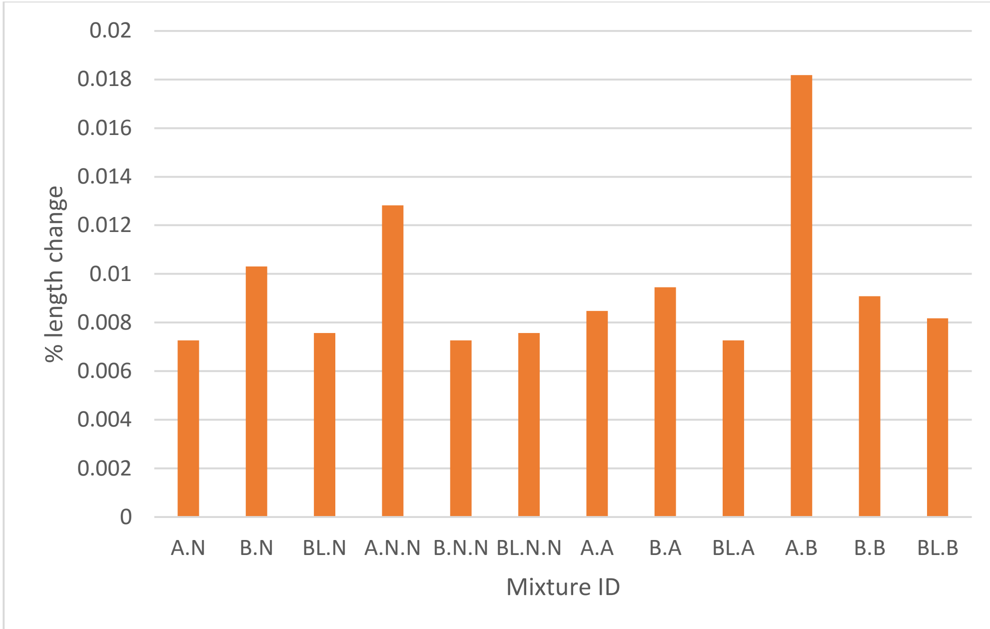

Figure 4.10: Percentage length change of mortar bars at 23ºC after 8 weeks

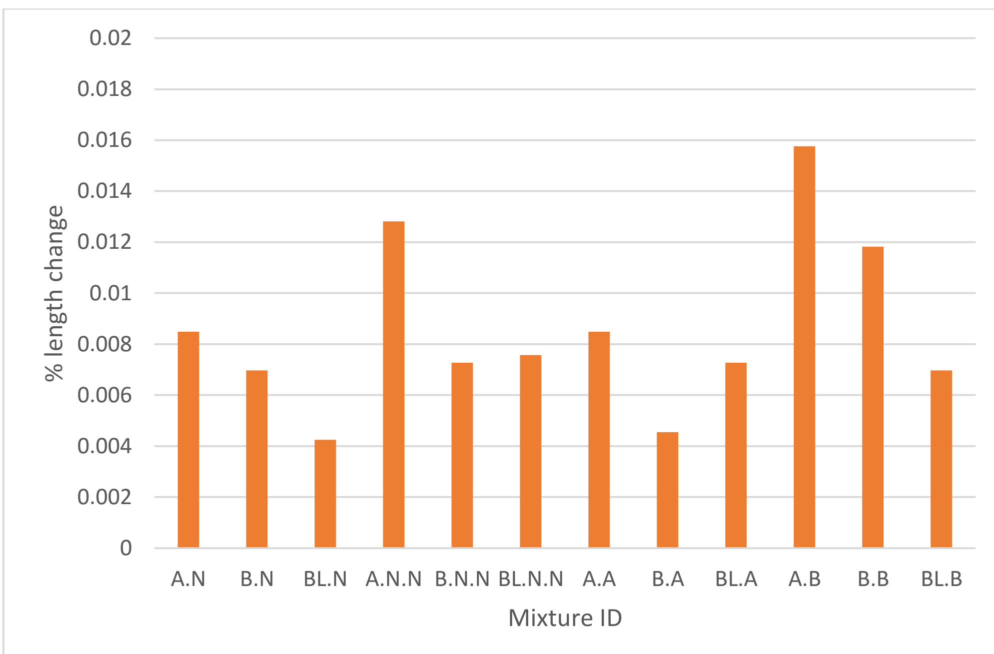

Figure 4.11: Percentage length change of mortar bars at 5ºC after 8 weeks

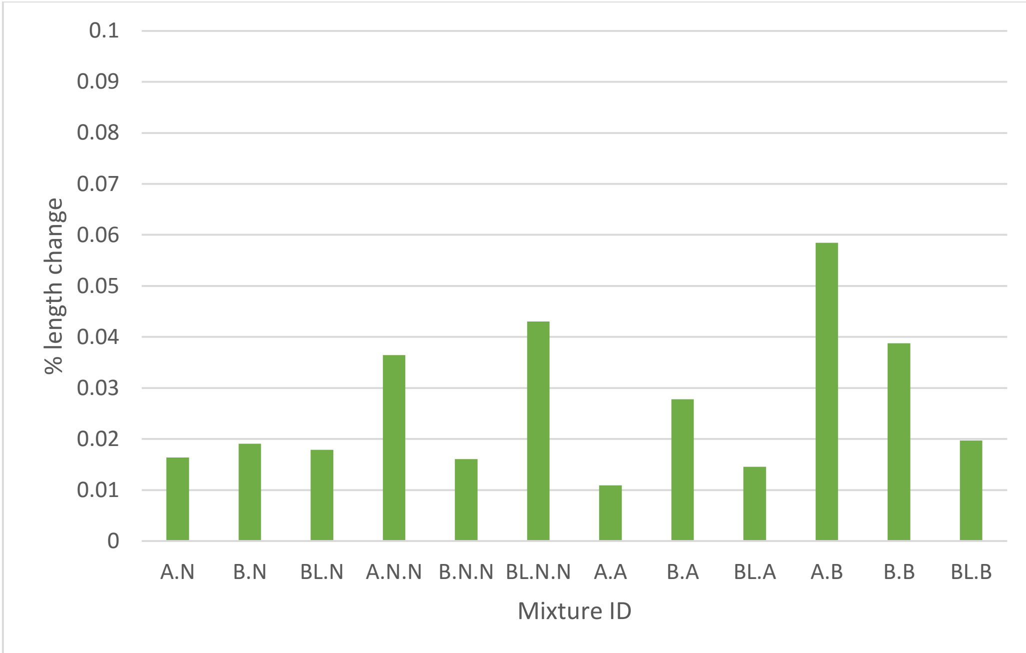

Figure 4.12: Percentage length change of mortar bars at 23°C after 24 weeks

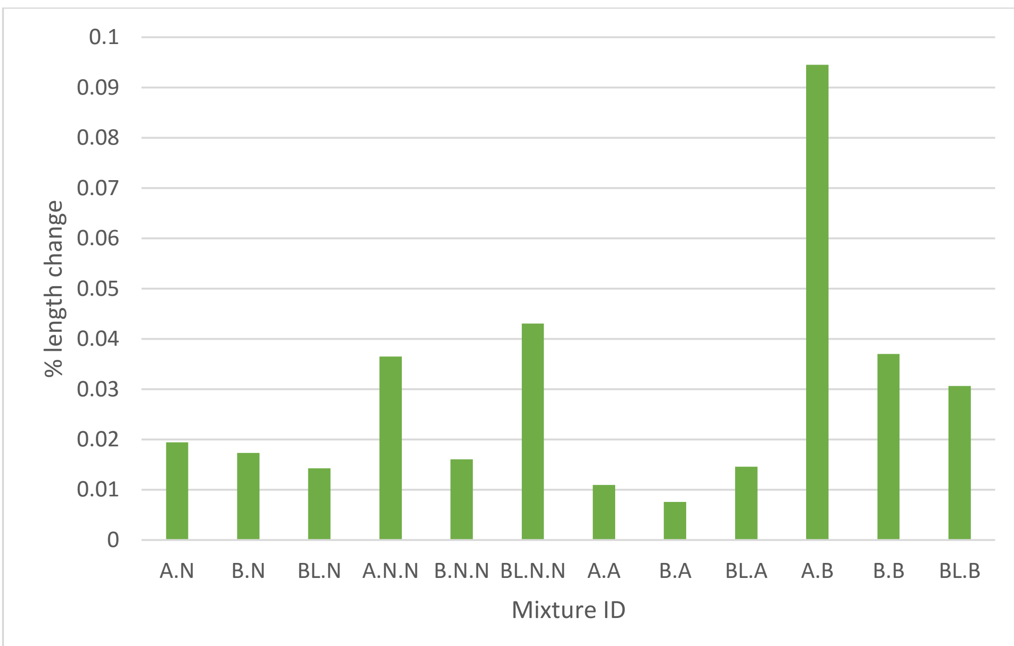

Figure 4.13: Percentage length change of mortar bars at 5°C after 24 weeks

From Table 4.10 and Figure 4.6 it can be observed that, with the exception of mortars containing natural sand, PLC mortar bars exhibited less expansion than OPC 2 (cement B) mortars at 23°C. From Figure 4.8, the week 4 results show a similar trend.

From Figure 4.10, week 8 results show that the PLC mortar with natural sand had slightly greater expansion than the companion cement B mortar, while all in other mortars expansion was more in mortars containing cement B than mortars containing PLC. From Figure 4.12, the 24th week results, it can be seen that at 23°C, PLC mixtures exhibited more expansion than cement B (OPC) when used with manufactured sand and natural sand. In the case of fly ash mixtures at 24 weeks of age, PLC mortars exhibited less expansion than OPC mortars for fly ash A mortars, while it was vice-versa for mortars containing fly ash B.

From Table 4.11 and Figure 4.7, the percentage change in length of mortar bars at 5^{o}C is shown. As stated previously, from Table 4.10 it can be observed that all mixtures stored at 5°C exhibited an average expansion less than 0.10% at six months. Therefore these mixtures can be considered to have "passed" as sulfate resistant per the CSA 3004-C8 standard. Additional testing (for a duration of 18 months or longer) is required to determine whether the mixtures are considered to have high sulfate resistance. Further discussion on the relative performance of mortar bars stored at 23°C is presented subsequently.

From Figure 4.9, the 4 week results, it can observed that for mortars with no fly ash and manufactured sand, PLC mortars exhibited greater expansion than mortar containing cement B. For natural sand mortars, cement B mortars exhibited greater expansion than PLC mortars. In the case of mortars containing fly ash, PLC mortars had greater expansion than mortars containing cement B paired with fly ash A. The opposite trend was observed for mortars containing fly ash B. Mixed results are observed after 8 weeks of exposure (shown in Figure 4.11). However, at 24 weeks, PLC mortars typically had lower expansions than cement B mortars.

To facilitate comparison, mortar bars were averaged by cementitious materials content (grouping as OPC, PLC, OPC with fly ash, and PLC with fly ash), and the 4, 8, and 24 week expansions are shown in Figure 4.16 (bars stored at 23°C) and Figure 4.17 (bars stored at 5°C). The 8 week expansions were all relatively low (passing the CSA 3004-C8 standard requirements at 6 months, as stated previously), but the influence of the relatively high expansion of cement A paired with fly ash B at 8 weeks (at both temperatures) is evident. At this time it is unclear whether this is an anomaly or not. Future expansion measurements should provide more insight.

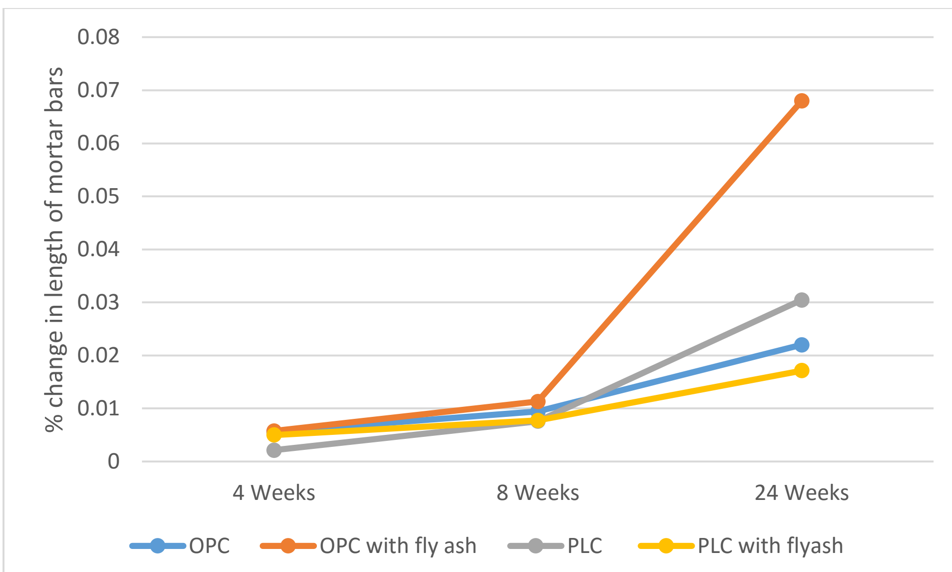

Figure 4.16: Expansions in OPC and PLC at 4, 8, and 24 weeks at 23°C

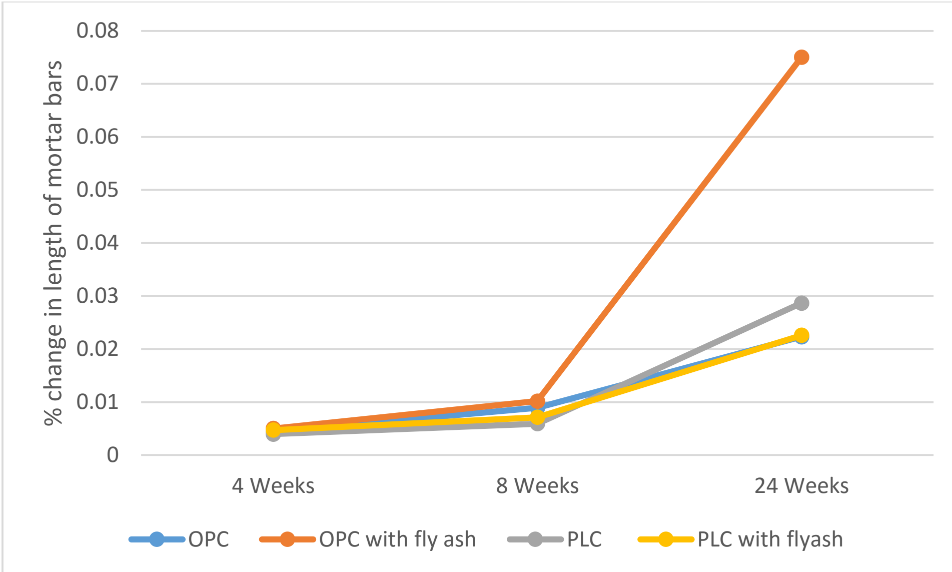

Figure 4.17: Expansions in OPC and PLC at 4, 8, and 24 weeks at 5°C

4.4. Summary of Results

From the mechanical property test results, PLC concretes tended to perform very similarly to the OPC concrete mixtures. Compressive strength, modulus of rupture, modulus of elasticity, and Poisson's ratio test results for the PLC concrete and the companion OPC (Cement B) mixtures, are similar. Fly ash mixtures had lower initial strength compared to non-fly ash mixtures, which is as expected. However, strengths gradually increased with age, regardless of the OPC or PLC cement the fly ash was paired with.

Durability performance test results showed several key results. For surface resistivity testing and RCPT tests, PLC and OPC mixtures (without fly ash) showed similar performance. However, a trend can clearly be observed between fly ash and non-fly ash mixtures. The non-fly ash mixtures were highly permeable to chloride ion penetration, whereas non-fly ash mixtures exhibited low permeability to chloride ion penetration, particularly at the 90 day tests. Overall, the PLC mixtures tended to exhibit slightly greater shrinkage than cement B in a number of mixtures. However, the differences in the amount of drying shrinkage observed between the PLC and OPC mixtures is judged to be very minimal. In almost all cases, at 32 weeks, the difference in drying shrinkage between the PLC mixtures and the OPC 2 (cement B) mixtures is 0.01% or less. From the results of the thaumasite attack testing, the specimens cast from PLC mixtures did not exhibit excessive length changes after the durations of exposure to sulfate solution for six months. Ongoing tests (up to 18 months) will reveal more about the sulfate resistance of these mortars. Overall, it was determined that minimal differences in performance were observed between the PLC and OPC concretes and mortars.

CHAPTER 5: LIFE CYCLE ASSESSMENT (LCA)

5.1 Introduction to Green Concrete LCA tool

To quantify the sustainability benefits that may be associated with use of PLC, a LCA analysis was performed. In this study a web-based LCA tool, Green Concrete, was identified as an appropriate LCA analytical framework. Green Concrete was developed at University of California at Berkeley by researchers including Dr. Petek Gursel. This tool was specially designed for cement and concrete manufacturers in order to quantify and compare environmental impacts of the products they produce. This tool can also be used to help the industry stakeholders evaluate the environmental impacts of materials and technologies utilized in concrete construction, and make choices based on the potential environmental impacts of the considered alternatives (Green Concrete 2016).

The Green Concrete web tool is based on MS-Excel operations. The web tool consists of user inputs and results, where one can give the available inputs or otherwise use the default values and run the analysis. These two sections are connected with reference data pool and processes & calculation. The reference data pool consists of four LCI data sets. They are the electricity grid mix LCI data, transportation LCI data, facilities operation data, and fuel (pre-combustion and combustion) LCI data. This LCI of materials, fuels, and electricity are organized in each material production phase in the process and calculation section.

Analyses performed using the Green Concrete LCA tool consider the environmental impacts due to production of concrete, cement, aggregates, admixtures, and SCMs. The units used are meters and kilometers for distance and volumes. The tool allows the user to utilize US averages or state averages for electricity inputs. The results from LCI include resources use, primary energy use, water consumption, and air emissions. Air emissions include global warming potential (GWP) in CO_2 equivalents (CO_2-eq) for production of concrete, cement, and admixtures. Air emissions also include air pollutants released during production process such as CO, NO_X, lead, PM_{10}, SO_2, and volatile organic compounds (VOC). Total criteria air pollutant emissions (as computed by Green Concrete) will be the focus of this LCA study, as a more robust LCA is planned in the future using more specific inputs that may facilitate a better quantification of GWP in CO_2-eq.

5.2 Intent and Goal of Analysis

The intent and goal of this analysis is to quantify the environmental impact, as measured by total criteria air pollutant emissions, associated with production of concrete made cement of different limestone contents (0%, 5%, 10%, 12%, 15%, and 20%), Additionally, the impact of changes in technology for finish milling and change energy source in electricity grid were also analyzed. Analyses were also performed on concrete produced using fly ash (and companion mixtures without fly ash) in order to evaluate the reduction in environmental impacts associated with addition of fly ash in the concrete mixtures. This LCA analysis will aid in justifying the use of PLC (in lieu of OPC) with respect to sustainability in future pavement projects in North Carolina.

5.3 Scope

The scope of the LCA analysis performed by the Green Concrete web tool can be explained by description of the functional unit and system boundaries. The scope of this analysis is to evaluate the environmental impacts due to production of cement, aggregates, fly ash, admixtures, and concrete along with impacts due to energy generation required for all the processing and transportation of products. Five different alternatives of cement were evaluated with varying limestone content (two 0%, 5%, 10%, 12%, 15%, and 20% of limestone). In regards to the cement plant configuration, fuel sources, distance commuted for materials delivery and in-plant hauling, and technology used in plant operations (with the exception of finish milling) were held constant. Values utilized in this analysis were obtained from a cement manufacturer through a confidential survey. Inputs held constant are described subsequently in this chapter.

5.4 Functional Unit

The functional unit in the Green Concrete tool can be defined as the unit volume of ready-mix concrete exiting the concrete plant. This concrete is produced from cement, SCMs, admixtures, and aggregates. The unit volume of concrete is expressed in the International system of units, cubic meter (m^3). For this analysis, the amount of concrete considered for comparison between alternatives is 1 m^3 of concrete produced.

5.5 System Boundary

The system boundary utilized by the Green Concrete LCA tool is shown in Figures 5.1 and 5.2. Within the system boundary is included the production of cement, SCMs, and aggregates along with energy sources like fuels for energy and transportation. The system boundary excludes burdens from the work force such as accidents, infrastructure, and human resources. The analysis also excludes the energy required to produce the fuels that are needed to produce cement, admixtures, aggregates, SCMs, and concrete.

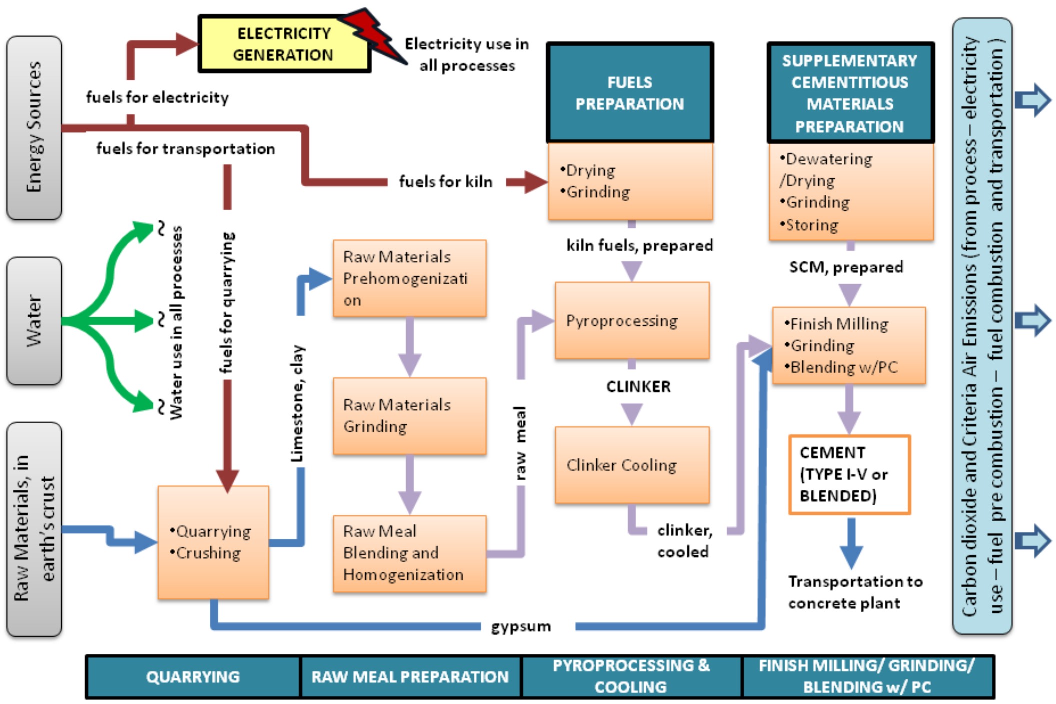

Figure 5.1: Cement production processes (from Green Concrete Web tool)

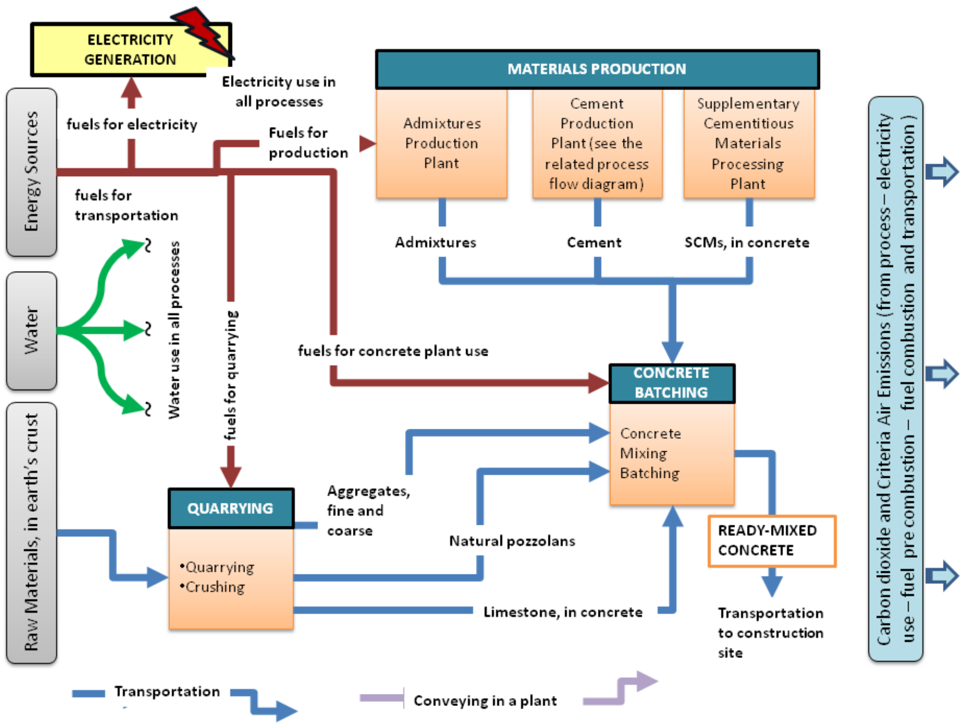

Figure 5.2: Concrete production processes (from Green Concrete Web tool)

5.6 Data Sources

5.6.1 Raw Materials:

Data on raw materials in production of cement were collected from a manufacturer using a confidential survey. This data included information on the amount of cement clinker, gypsum, and mode of transportation to the plant. Data on raw materials for concrete production were collected from the laboratory testing performed as part of this work and from available data from Green Concrete web tool. Green Concrete has data from various resources which are provided in Appendix C.

5.6.2 Fuel and Electricity

The Green Concrete web tool provided default information on fuel and electricity usage (along with supporting data used in the analysis) which was collected from various resources. Information on these resources used for Green Concrete web tool are provided in Appendix C. Modes of fuel and electricity sources available for use in the Green Concrete web tool include: bituminous coal, lignite coal, distillate fuel oil, petroleum coke, residual fuel oil, natural gas, waste oil, waste solvent, waste tire (whole), waste tire (shredded), non-hazardous waste, waste paper, waste plastic, waste sewage sludge, and hazardous waste. Data used for fuels used for pyro processing of was clinker collected from a regional manufacturer supplying concrete to North Carolina through a confidential survey.

Electricity data for the concrete production plant was obtained from the Green Concrete web tool. For the purposes of this comparative analysis, the US average and respective state averages (North Carolina and South Carolina) were chosen depending on the location of the typical production of locally-utilized cements (South Carolina) and concrete batching plants (North Carolina). Electricity data for cement production, operation of the quarry, and concrete batch plant location were taken from default values provided in the tool. Data on pre-combustion fuel, combustion fuel and electricity were collected from various resources such as National Renewable Energy Laboratory, U.S. energy Information Administration (2011b), (2011c), U.S. Environmental Protection agency (1993), (1998a), etc. by the Green Concrete web tool designer. Additional information regarding data resources is provided in Appendix C.

5.6.3 Transportation

The Green Concrete web tool provided default modes of transportation (along with supporting data used in the analysis) which was collected from various resources. Information on these resources used for Green Concrete web tool are provided in Appendix C. Modes of transportation of raw materials available for use in the Green Concrete web tool include: truck class 8b (model 2005), truck class 5 (model 2005), truck class 2b (model 2005), rail, and water (inland barge). Transportation inputs for the transfer of raw materials to the cement plant and for the conveying distance of raw materials within the cement plant were collected from manufacturers through a confidential survey.

5.6.4 Technology

Technologies used in processing and handling of raw materials for cement production available for use in the Green Concrete web tool include: dry process raw storing (non-preblending), dry process raw storing preblending, wet process raw storing dry raw grinding (ball mill, tube mill, and vertical roller mill), wet raw grinding (tube mill and wash mill) raw meal homogenization (blending and storing), slurry blending homogenization and storing, preheater/precalciner kiln, wet kiln, long dry kiln, preheater kiln, US average kiln, rotary cooler, planetary cooler, reciprocating grate cooler (modern), reciprocating grate cooler (conventional), vertical gravity cooler with planetary cooler, grate cooler (recirculating excess air), ball mill, tube mill, vertical roller mill, roller press, and horizontal roller mill. Data used in selecting the technology for each phase of cement production and clinker cooling particulate matter (PM) control technology were obtained from manufacturers through a confidential survey.

5.6.5 Emissions

Emission are calculated in Green Concrete based on the other inputs such as raw materials, fuel and electricity, transportation, and technology used. Data required to support this analysis in Green Concrete were collected by the web tool designer from various sources. Additional information regarding the data sources used by the web tool is provided in Appendix C.

5.7 Cement Production Technologies and Plant Operation Assumptions

The Green Concrete web tool allows the user to select technology for production of cement and batching of concrete. For the purposes of the web tool analytical framework, cement production is performed in six phases. Each phase utilizes different technologies in order for the final product to be produced in that respective phase. The six phases considered in the Green Concrete web tool are raw materials prehomogenization, raw materials grinding, raw material blending/homogenization, pyroprocessing, clinker cooling, and finish milling/grinding/ blending with PC. A brief description of each phase is provided below, along with the technologies selected to be held constant for this analysis based on the results of a confidential survey of a local cement producer.

1. Raw materials prehomogenization: The end product in this phase is raw meal. The Green Concrete web tool allows the user to select one technology from three provided. The provided technologies are dry process raw storing (non-preblending), dry process raw storing (preblending), and wet process raw storing. Among these three alternatives dry process raw storing, non-preblending was utilized in this analysis.
2. Raw materials grinding: The end product in this phase is ground meal. The Green Concrete web tool provided five alternative technologies. They are: dry raw grinding (ball mill), dry raw grinding (tube mill), dry raw grinding (vertical roller mill), wet raw grinding (tube mill), and wet raw grinding (wash mill). Based on the results of the confidential survey, the technology selected for this phase (held constant for the analysis) was dry raw grinding, ball mill.

3. Raw meal blending/homogenization: The end product of this phase is blended meal. The alternatives provided by the Green Concrete web tool for this technology are raw meal homogenization (blending and storage), and slurry homogenization storage. Based on the results of the confidential survey, the technology utilized for this analysis (held constant) was homogenization, blending, and storage.
4. Pyroprocessing: The end product of this phase is clinker. Four technologies are provided in the Green Concrete web tool for the clinker production phase. These alternatives are preheater/precalciner kiln, wet kiln, long dry kiln, pre heater kiln. Based on the response to the confidential survey, the technology selected for use in this analysis was pre heater/ precalciner kiln.
5. Clinker cooling: The end product of this phase is cooled clinker. The Green Concrete web tool provides six alternative technologies for this phase. They are reciprocating grate cooler (modern), reciprocating grate cooler (conventional), rotary cooler, planetary cooler, vertical gravity cooler with planetary cooler, grate cooler (recirculating excess air). For this analysis, the technology used for this phase was again selected through the confidential survey. The technology held constant for this phase was the reciprocating grate cooler (conventional).
6. Finish milling/grinding/blending with PC: The end product of this phase is blended/traditional portland cement. The Green Concrete web tool provides five alternative technologies for this phase. These alternative technologies are ball mill, tube mill, vertical roller mill, roller press, and horizontal roller mill. Since production of PLC is highly dependent on the finish milling/grinding/blending of the limestone with the cement clinker, this technology was varied in the analysis.

The purpose of varying this technology was to explore the environmental impact of the finish process used to produce the PLC. As part of this LCA, the five finish milling/grinding/blending technologies were varied.

Conveying of each product in the above phases can also be done using different technologies. The technologies available in Green Concrete web tool include conveyance by screw pump, airlift, dense phase pump, and bucket elevator. Based on the response to the confidential survey, an appropriate technology was used for different product, and was held constant through this LCA analysis.

1. Raw meal: This is the product from raw meal prehomogenization phase. The selected technology for conveyance was a bucket elevator, and the conveyance distance was held constant at 25 meters.
2. Ground meal: This is the product from the raw materials grinding phase. The selected conveyance technology and distance was selected to be a bucket elevator and 25 meters, respectively.
3. Blended meal: This is the end product from the raw material blending/homogenization phase. The conveyance mode and distance utilized in this analysis are the dense phase pump and 100 meters, respectively.
4. Clinker: This is the end product from the pyroprocessing phase. The technology used for conveyance is the bucket elevator, and the conveyance distance selected was 25 meters.
5. Clinker cooled: This is the end product from the clinker cooling phase. The conveyance technology used was the bucket elevator, and the conveyance distance used was 50 meters.

6. Blended/traditional portland cement: This is the final product in cement production, and is produced in finish milling/grinding/blending with portland cement (PC) phase. The conveyance technology used was a dense phase pump, and the conveyance distance considered in the analysis was 75 meters.

Two technologies are available in the Green Concrete webtool for clinker cooling and particulate matter (PM) control. They are fabric filter and electrostatic precipitators. Based on the confidential survey results, the technology selected for this analysis was fabric filter. The two alternatives that were provided in the Green Concrete web tool are controlled with fabric filter and uncontrolled. For this analysis, an uncontrolled PM emissions was utilized and held constant. Two alternative options were provided for mixing and plant loading were provided in the web tool. Mixer loading (central mix) and truck loading (truck mix) are the options. Mixer loading (central mix) was selected for the purpose of this analysis. Ultimately, the system boundary at the end of production is the gate of the concrete plant, with the truck ready to transport a batch of concrete to a jobsite (Celik et al. 2015).

5.8 Calculations and Methodology

Green Concrete web tool consists of a user input section and a results section. These two sections of the web tool are supported by two other sections, which are not visible in the web tool. These are the reference data pool and the process & calculation sections. The reference data pool in the Green Concrete web tool consists of life cycle inventories (LCI) of the electricity grid mix, freight transportation, and fuel pre-combustion and combustion database taken from various sources which are provided in Appendix C. The process and calculation sections are supported by LCI data for of electricity, fuel, and materials at each phase. Emission factors from the reference data pool worksheets are multiplied by phase inventories and final total phase impacts are calculated and displayed in the results section.

Calculations and methodology of LCA analysis in Green Concrete can be explained by observing Figure 5.5. The user input page consists of concrete mix proportions inputs, quarry/plant input, operational input, transportation input, transportation input, technology input, and run analysis option. A description of each section of the web tool follows Figure 5.3.

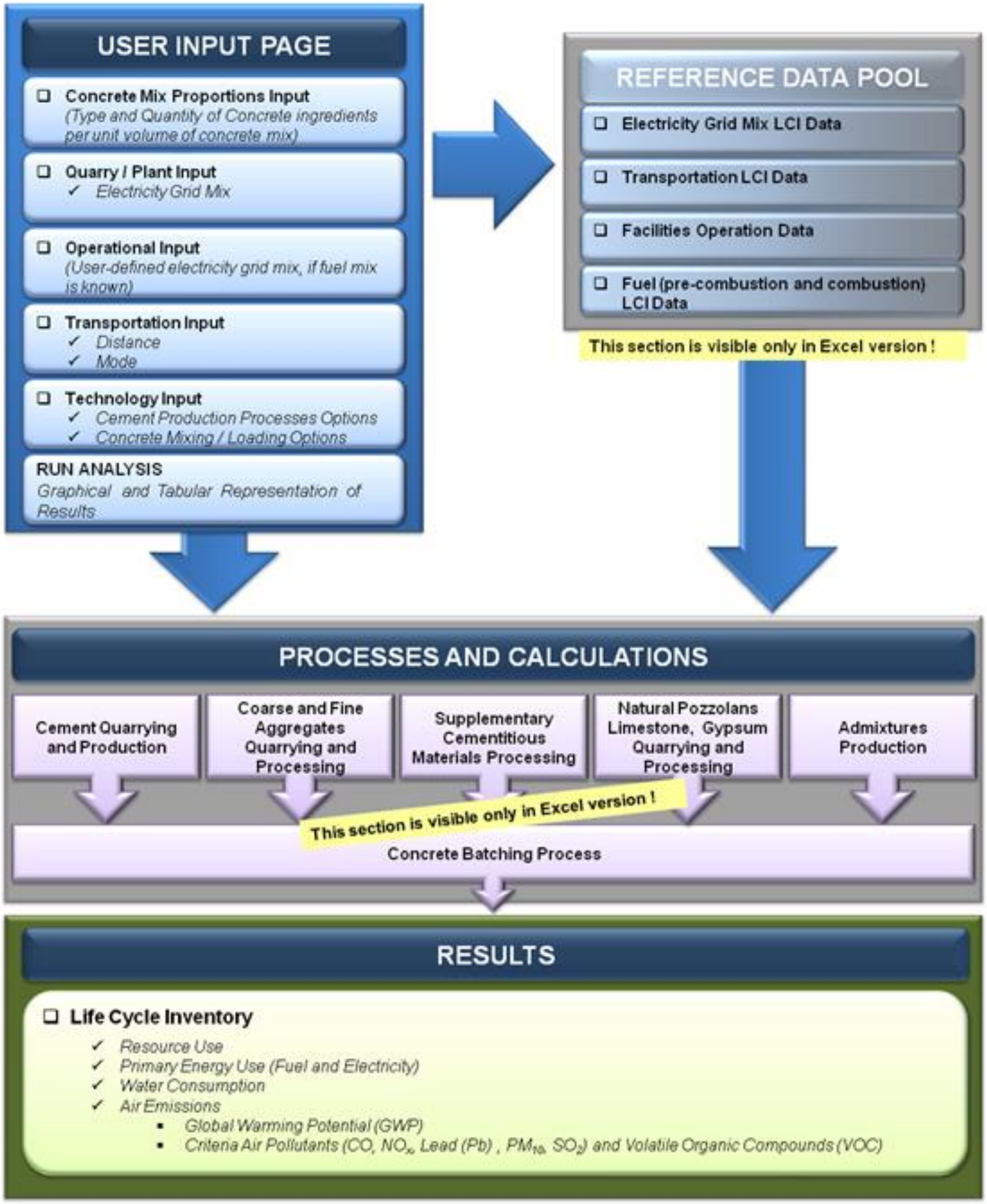

Figure 5.3: LCA structure of Green Concrete tool (from Green Concrete)

The results section consists of graphs showing energy consumed and GWP at each phase along with a table consisting of air pollutants released at each phase in the units of kilogram (although it is noted that these results are based on one m^3 of concrete). A sample of output results from a Green Concrete webtool analysis is shown in Figure 5.4 and Figure 5.5 to further clarify how the Green Concrete webtool computes.

Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.011	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.010	0.000	0.004	0.000	0.009	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	99.090	0.015	0.949	0.026	0.722	0.012
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.019	0.000	0.007	0.000	0.016	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure 5.4: Sample table of criteria air emissions from Green Concrete analysis (from Green Concrete web tool)

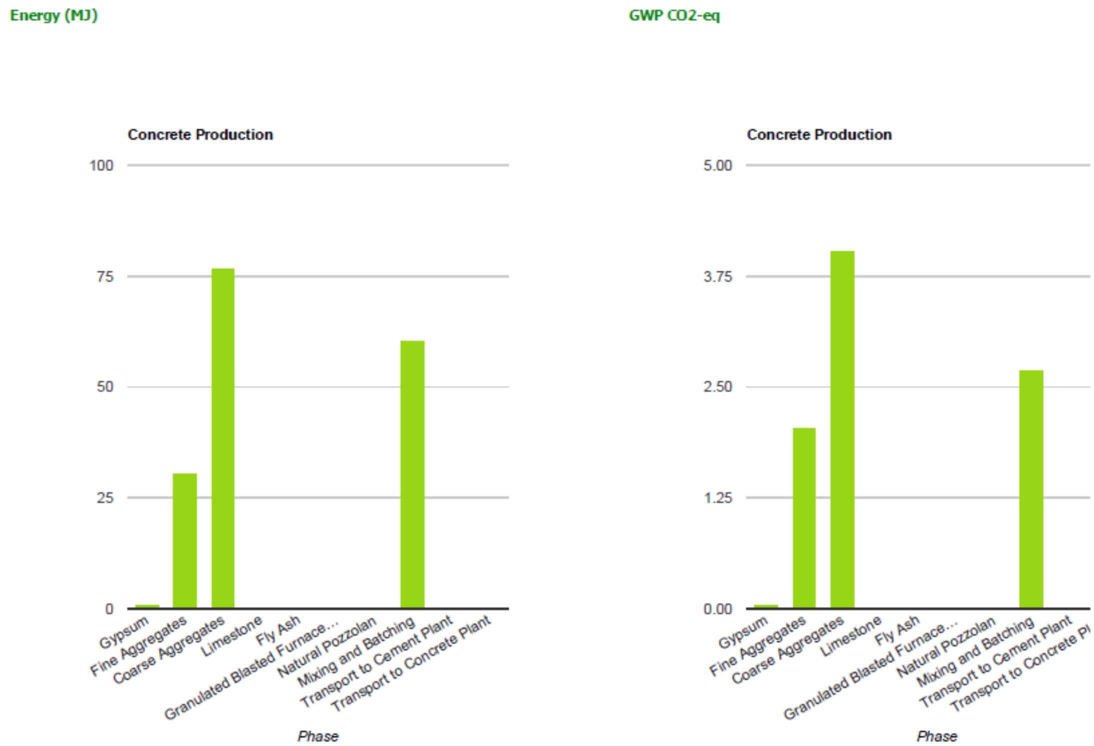

Figure 5.5: Sample graph of energy and GWP (in CO_2-eq) from Green Concrete analysis (from Green Concrete web tool)

5.9 Analysis

For this study, LCA analysis was performed by running sequential analyses with the Green Concrete LCA web tool using different percentages of limestone in the cement. Additionally, the type of finish milling was varied between the five options available in the Green Concrete web tool, and the source energy mix for the electricity grid was varied to include a decrease in fossil fuels and (and an increase in nuclear power).

1. Concrete mix proportions: In this section the unit used for concrete volume is m^3. Components of the concrete considered in the analysis, including cement, SCMs, aggregates, water, and admixtures are input in kg/m^3. The quantity of cement and limestone used for analysis are provided in Table 5.1 and 5.2. Based on the mixture design used for this study, the amount of coarse aggregate, fine aggregate, water,

water reducing admixture, and air entraining admixture used for analysis are 1067.69 kg, 746.61 kg, 172.61 kg, 3.077 kg, and 0.77 kg respectively. The type of cement selected for analysis was portland cement moderate sulfate resistance, type II. The cement type and amount of raw materials utilized in the production of the cement was calculated by web tool based on quantity of inputs given in material quantities section.

Table 5.1: Quantity of cement per cubic meter of concrete (kg)

Cement	Quantity (kg)
0% limestone without fly ash	326.30
0% limestone with fly ash	261.04
5% limestone without fly ash	309.98
5% limestone with fly ash	247.98
10% limestone without fly ash	293.67
10% limestone with fly ash	234.93
12% limestone without fly ash	287.14
12% limestone with fly ash	229.71
15% limestone without fly ash	277.35
15% limestone with fly ash	221.88
20% limestone without fly ash	261.04
20% limestone with fly ash	208.83

Table 5.2: Quantity of limestone per cubic meter of concrete (kg)

Cement	Quantity (kg)
0% limestone	0.00
5% limestone	16.01
10% limestone	32.63
12% limestone	39.15
15% limestone	48.94
20% limestone	65.26

2. Quarry and plant location, grid mix information: For the quarry and plant location, the electricity grid mix information US average was utilized in the analysis. This section of inputs consists of the electricity source (mix) proportions for raw materials mining, electricity mix for cement plant, electricity mix for gypsum

quarrying and processing, electricity mix for fine and coarse aggregate quarrying and processing, electricity mix for limestone quarrying and processing, electricity mix for natural pozzolan quarrying and processing, electricity mix for fly ash processing plant, electricity mix for granulated blast furnace slag processing plant, and electricity grid mix for concrete batching plant.

3. Operation electricity mix: Alternatives were made in this section in order to check changes in emissions and GWP by reduction non-renewable fossil fuels. In this section, four different grid electricity alternatives were considered. The first (base) analysis was performed by running the analysis with default values. The second analysis option included reducing fossil fuel by 3% and increasing the nuclear fuel by 3%. The third analysis option was to further reduce fossil fuel by 6% and increase nuclear fuel by 6%. The fourth analysis option was to reduce fossil fuel by 10%, and to increase nuclear fuel by 10%. Fuel options for pyroprocessing of cement were taken as 95% bituminous coal and 5% waste tire (whole) through information from survey.
4. Transportation input: In this section, distance travelled from raw materials to the cement plant were considered. Units for distance were taken as kilometer. For this analysis, the distance travelled from the cement raw materials to cement plant and the gypsum to cement plant were considered. The information about the distance travelled were again collected through a confidential survey from manufacturers. The distance travelled from cement raw materials to cement plant was taken as 241.402 km (150 miles) and the distance travelled from the gypsum source to the

cement plant was considered to be 0.4672 km (50 miles). The mode of transportation considered for both of them was Truck Class 8b (model 2005).

5. Technology input: In this section, inputs regarding technology used for different phases of cement production, conveyance distance, and conveyance mode were input into the Green Concrete LCA web tool based on confidential surveys and assumptions. Details regarding this section have been explained in Section 5.7, cement production technologies and plant operation assumptions above.
6. Run analysis: Once all the inputs are provided in the respective sections run analysis option is selected, the Green Concrete web tool analysis is performed, and the output graphs and table of emissions are displayed. The LCA results consist of resources use, energy usage, water consumption, and air emissions such as global warming potential (GWP) and air pollutants (CO, NO_X, Lead, PM_{10}, SO_2, and volatile organic compounds (VOC)).

The results of the LCA analysis, in terms of the environmental impacts as computed by the Green Concrete LCA web tool, are described in sections below.

5.9.1 Impacts of increase in limestone content in PLC

Analysis was performed using values as mentioned in the above sections on cements with 0%, 5%, 10%, 12%, 15%, and 20% limestone content. The technology used for finish milling was ball mill for all cements. The results from the analysis are provided in Appendix C in Table C.1, with each criteria air pollutant (CO, lead, NOx, PM_{10}, SO_2, VOC, and total) quantified in kg per one m^3 of concrete produced. From the results it can be observed that as the percentage of limestone is increased the total amount of criteria air pollutant emissions decreases by up to 20% for the 20% limestone addition. Addition of fly ash also further reduces the total criteria air pollutants by about 20%. Figure 5.6 illustrates the results showing a difference between fly ash and non-fly ash mixtures. Criteria air pollutant emissions from each phase of cement and concrete production are provided in Appendix C.

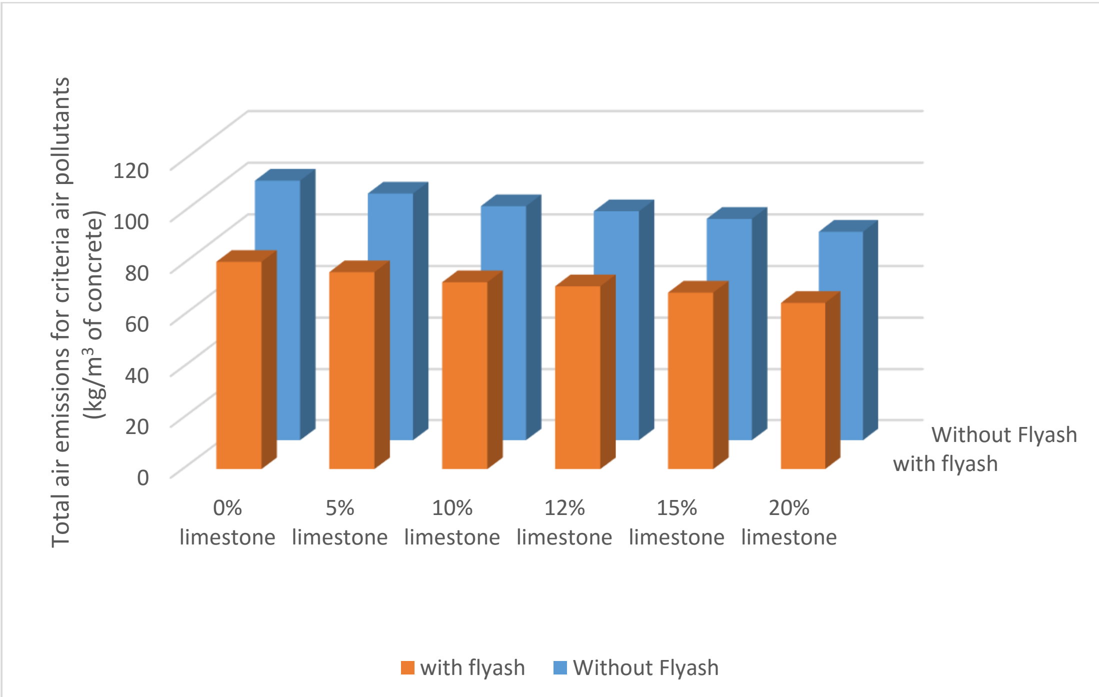

Figure 5.6: Air emissions from LCI with and without fly ash

5.9.2 Impact of changes in finish milling technology

The LCA analysis was again conducted on cements with 0%, 5%, 10%, 15%, and 20% limestone using the Green Concrete web tool, but the changing technology used for blending/milling/grinding with PC was changed. This facilitated the investigation of the impact of use of more and less modern technologies on the environmental impacts associated with the production of PLC. The results of total criteria air pollutant emissions tallied by the LCA webtool are provided in Appendix C in Table C.2, and are also shown in Figure 5.7. The amount of pollutants released is from production of cement, aggregates, and admixtures that are required to produce 1m^3 of concrete. The total amount of criteria air emissions are reported in kg per one m^3 of concrete produced. From Figure 5.7, it can be observed overall, it does not appear that the finishing milling technology used had a significant impact on the criteria air pollutant emissions for PLC concrete. Additional information is provided in Appendix C.

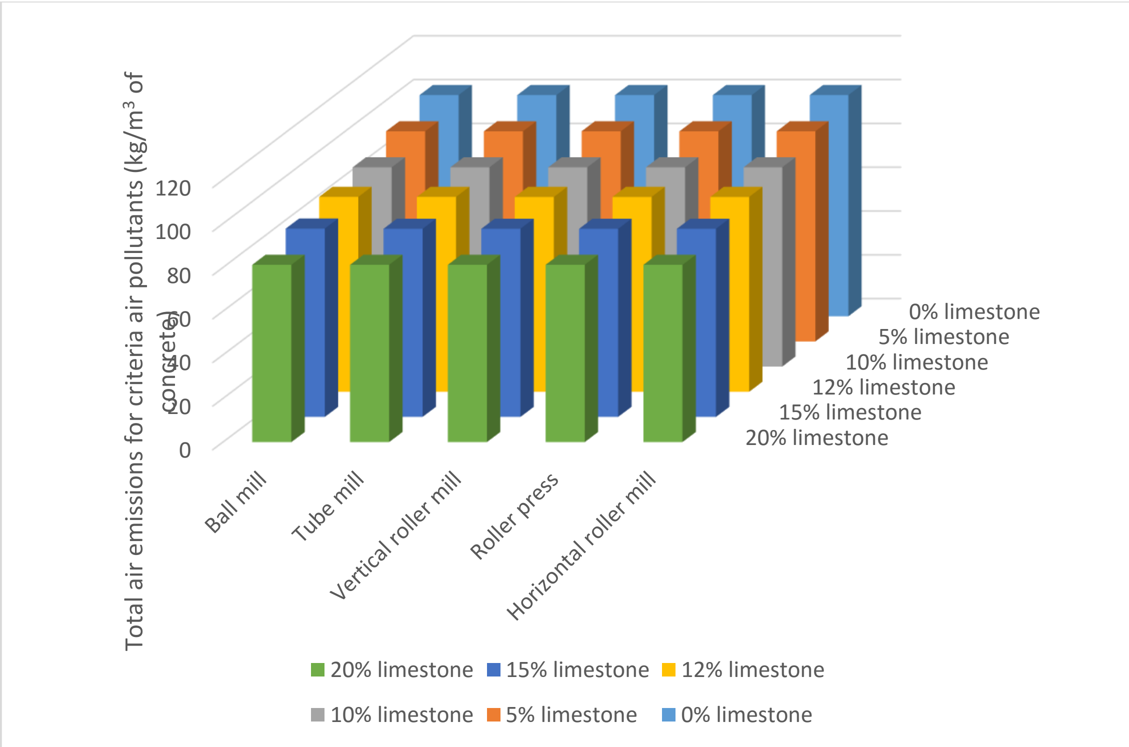

Figure 5.7: Air emissions by change in finish milling technology

5.9.3 Impact of energy source

The impact of the electricity grid source mix was assessed using the Green Concrete LCA analysis web tool. The LCA analysis was conducted on cements with 0%, 5%, 10%, 12%, 15%, and 20% limestone using Green Concrete LCA web tool by varying the electricity grid using the following four options.

1. By taking US averages.
2. By decreasing fossil fuel by 3% and increasing nuclear fuel by 3%.
3. By decreasing fossil fuel by 6% and increasing nuclear fuel by 6%.
4. By decreasing fossil fuel by 10 % and increasing nuclear fuel by 10%.

For each of these analyses, ball mill technology was considered for grinding/milling/blending of portland cement. Results are provided in Table C.3. The total criteria air pollutant emissions were computed in units of kg per one m^3 of concrete produced. From Figure 5.8, it can be observed that overall, changes in the energy grid did not appear to have a significant effect on the total criteria air pollutant emissions associated with the types of concretes analyzed. Additional data is provided in Appendix C.

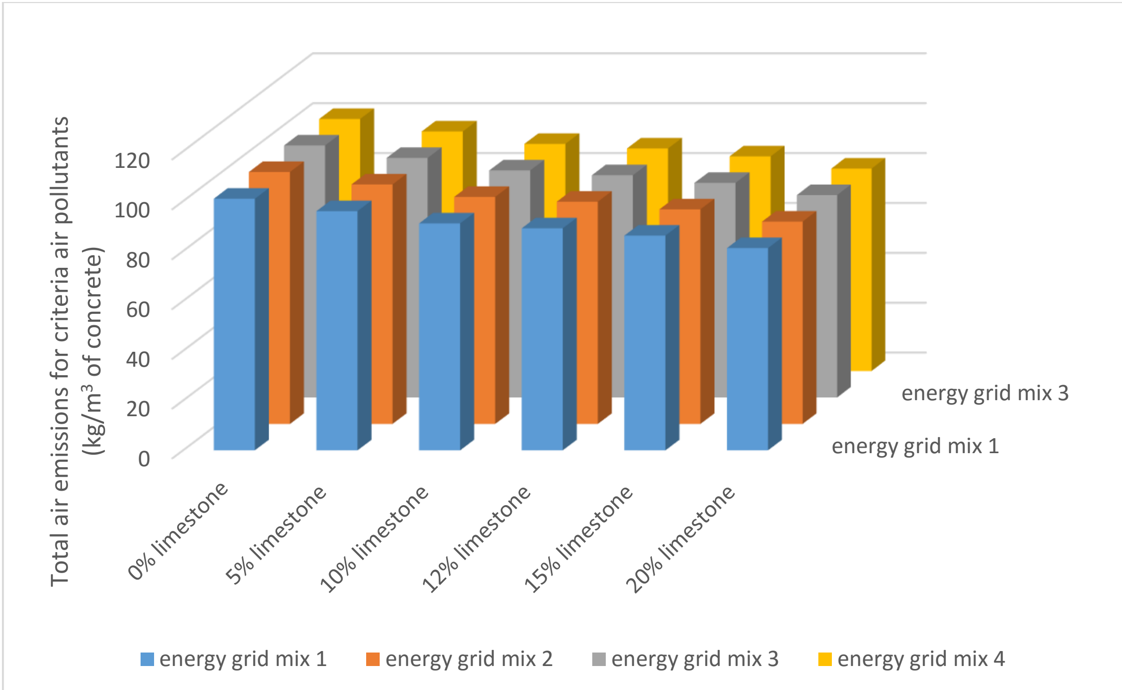

Figure 5.8: Air emissions with change in energy source

5.10 Conclusions

From the LCA analysis using the Green Concrete LCA analysis web tool, it can be observed that as the percentage of limestone included in PLC increases, the associated criteria air pollutant emissions associated with cement production (and therefore concrete production) decrease. When analysis has been performed by replacing cement content by 20% of fly ash by weight it has been observed that addition of fly ash reduced total criteria air pollutant emissions by about 20%. In each analysis case, it was observed that use of cement with fly ash and a higher limestone content in concrete will produce lower emissions, lessening the environmental impact of a cubic yard of concrete. Based on the analyses above, the alternative with the lowest environmental impact would be the concrete produced with PLC with 20% limestone content and fly ash, using an energy source close to the US average (as provided by Green Concrete), with tube mill technology for finish milling of the limestone with PC.

A change in a particular technology of finish milling of PLC is predicted to have different, but minimal, effects on the emissions associated with concrete cements with different percentages of limestone. For 0% limestone in cement (OPC) a ball mill provides lower emissions. For production of 5%, 10%, and 12% limestone PLCs, vertical, horizontal roller mill, and roller press provide the lowest emissions. For 15% and 20% limestone PLCs, a tube mill is the alternative that provides the lowest predicted emissions. Although there is a predicted increase in emissions associated with increased usage of nuclear fuel, the difference is predicted to be very small.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

This study was performed in order to make a quantitative assessment of the potential impact of use of PLC in North Carolina concrete pavements. For the purpose of this study, laboratory tests were conducted on 18 different concrete mixtures utilizing two types of OPC and one type of PLC (produced using one of the OPC clinkers). The laboratory testing program included tests to evaluate and compare the mechanical properties and durability performance of hardened concrete. Along with many traditional tests to evaluate the hardened mechanical properties and durability performance of concrete, a thaumasite attack test was conducted on mortar bars in order to determine whether mortars prepared from the cements (particularly the PLC) were sulfate resistant. Based on the results of laboratory testing, the following conclusions are offered:

1. Fresh concrete properties did not seem to be adversely affected by use of PLC instead of OPC. Use of PLC required a similar admixture dosage to companion concrete mixtures using OPC.
2. Use of PLC in concrete with North Carolina materials did not significantly affect the mechanical properties of the concrete.
3. Concrete mixtures containing PLC and flyash exhibited lower permeability than concrete mixtures containing OPC and fly ash, indicating potential durability benefits.

4. The thaumasite test results showed both PLC and OPC cements are moderately sulfate resistant.
5. The addition of fly ash to both OPC and PLC mixtures significantly reduced the rapid chloride permeability of the concrete and significantly increased the surface resistivity. When fly ash is added to a PLC concrete, the reduction in permeability increases, particularly at late ages.

An LCA analysis was performed using the Green Concrete web tool developed by the University of California at Berkeley in order to quantify the emissions associated with use of PLC at differing limestone percentages, and compare these to OPC concrete. The LCA analysis was conducted on cements with 0%, 5%, 10%, 12%, 15%, and 20% limestone. The impact of addition of fly ash to the same base concrete mixture was explored in the LCA analysis, along with the potential changes in criteria air pollutant emissions associated with changes in finish milling technology and selected changes in energy grid source mix. It is noted that the PLC used in this study contained approximately 12% interground limestone.

The key findings from this LCA analysis are:

1. By increasing the limestone content in cement from 0% to 20%, total criteria air pollutant emissions may be reduced up to 20%.
2. By replacing fly ash up to 20% in cement quantity, the predicted total criteria air pollutant emissions for concrete were reduced up to 20%.
3. The type of finishing mill utilized for intergrinding the limestone into the cement will have minimal impact on the potential emissions of a cubic yard of concrete.

4. By changing in source of electricity from the current SC averages to a mix that reflects a decrease in fossil fuels (and an increase in nuclear power), there was no significant influence on reduction of air pollutants emissions predicted.

The limestone content in PLC used for laboratory testing was 12%. Therefore some limitation is placed on the results of this LCA study, which have been extended to analyze cements with limestone contents up to 20% for exploratory purposes.

Following are the recommendations for future work on this study:

1. The laboratory testing program could be expanded to include additional mixtures with Coastal aggregates and Mountain aggregates along with natural sand and fly ash.
2. Laboratory testing could be expanded to include cements with higher portions of interground limestone (greater than 12%) with local materials.
3. A more robust LCA could potentially be performed using plant-specific data. This could be expanded to include use of the Athena LCA tool, or other, to provide confidence in the quantification of the sustainability benefits of use of PLC in North Carolina concrete pavements.

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APPENDIX A: SUPPLEMENTAL INFORMATION FOR CHAPTER 3

Table A.1: Sieve analysis for Piedmont aggregate

Sieve Size	Percentage passing	Percentage passing (ASTM C33)
1”	100	100
¾”	96	90-100
½”	55	-
3/8”	33	20-55
No. 4	5	0-10
No.8	2	0-5
No.200	0.3	1-1.5

Table A.2: Sieve analysis for Coastal aggregate

Sieve Size	Percentage passing	Percentage passing (ASTM C33)
1”	97.8	100
¾”	76.9	90-100
½”	38.3	-
3/8”	24.0	20-55
No. 4	5.6	0-10
No.8	1.4	0-5
No.200	0.3	1-1.5

Table A.2: Sieve analysis for Mountain aggregate

Sieve Size	Percentage passing	Percentage passing (ASTM C33)
1”	98.8	100
¾”	91.8	90-100
½”	27.9	-
3/8”	11.9	20-55
No. 4	3.5	0-10
No.8	0.8	0-5
No.200	0.4	1-1.5

Table A.4: Sieve analysis for manufactured sand

Sieve Size	Percentage passing	Percentage passing (NCDOT 2012)
3/8”	100	100
No.4	100	95-100
No.8	85	80-100
No.16	64	45-95
No.30	47	25-75
No.50	30	5-35
No.100	14	0-20
No.200	5.2	0-1

Table A.5: Sieve analysis for natural sand

Sieve Size	Percentage passing	Percentage passing (ASTM C33)
3/8”	100	100
No.4	99.9	95-100
No.8	98.8	80-100
No.16	79.5	50-85
No.30	34.9	25-60
No.50	5.6	5-30
No.100	0.9	0-10
No.200	0.3	0-3

CEMENT MILL TEST REPORT

Cement Identified as:	**Type I LA, Type II LA**	Date:	**10/1/2014**
Plant:			
Location:			
Production Dates:			
Beginning:	**10/1/2014**		
Ending:		**Silos: 14**	

CHEMICAL REQUIREMENTS (ASTM C 114)	**ASTM C 150 & AASHTO M85 SPEC'S**	**TYPE I (ASTM, AASHTO)**	**TYPE II (ASTM, AASHTO)**	**TYPE I LA (ASTM, AASHTO)**	**TEST RESULTS**
Silicon Dioxide (SiO_2), %	Minimum	----	----	----	20.3
Aluminum Oxide (Al_2O_3), %	Maximum	----	6.0	----	4.7
Ferric Oxide (Fe_2O_3), %	Maximum	----	6.0	----	3.3
Calcium Oxide (CaO), %		----	----	----	64.1
Magnesium Oxide (MgO), %	Maximum	6.0	6.0	6.0	1.2
Sulfur Trioxide (SO_3), % **	Maximum	3.5	3.0	3.5	3.0
Loss on Ignition (LOI), %	Maximum	3.0	3.0	3.0	1.6
Insoluble Residue, %	Maximum	0.75	0.75	0.75	0.30
Alkalies (Na_2O equivalent), %	Maximum			0.60	0.54
Tricalcium Silicate (C3S), %	Maximum	----	----	----	58
Tricalcium Aluminate (C3A), %	Maximum	----	8	----	7
C3S + 4.75(C3A), %	Maximum	----	100	----	92
PHYSICAL REQUIREMENTS					
(ASTM C 204) Blaine Fineness, M2/Kg	Minimum	280	280	280	4074
(ASTM C 191) Time of Setting (Vicat)					
Initial Set, minutes	Minimum	45	45	45	115
Final Set, minutes	Maximum	375	375	375	210
(ASTM C 451) False Set, %	Minimum	50	50	50	85
(ASTM C 185) Air Content, %	Maximum	12	12	12	6
(ASTM C 151) Autoclave Expansion, %	Maximum	0.80	0.80	0.80	-0.01
(ASTM C 1038) Expansion in Water, % at 3.6 SO3	Maximum	0.02	0.02	0.02	0.001
(ASTM C186) 7 day Heat of Hydration, (cal/g)					73
(ASTM C 109) Compressive Strength, psi (MPa)					
1 Day		----	----	----	2530 (17.4)
3 Day	Minimum	1740(12.0)	1450(10.0)	1740(12.0)	3560(24.5)
7 Day	Minimum	2760(19.0)	2470(17.0)	2760(19.0)	4530 (31.2)
*28 Day	Minimum	----	----	----	6370 (43.9)

*** The performance of Type I/II has proven to be improved with sulfur trioxide levels in excess of the 3.0% limit for Type II. Note D in ASTM C-150 allows for additional sulfate, provided expansion as measured by ASTM C-1038 does not exceed 0.020%.*
Satisfies the requirements of VDOT Standard Road & Bridge specification section 214
(*) Tests results for this period not available. Most recent test results provided

hereby certifies that this cement meets or exceeds the chemical and physical Specifications of:

Physical testing completed by:
Chemical testing completed by:

x ASTM C-150 for Type I
x ASTM C-150 for Type II
x ASTM C-150 for Type II M.H.
x ASTM C-150 for Type I L.A.
x AASHTO M85 for SCDOT Type I LA
x AASHTO M85 for Type I
x AASHTO M85 for Type II
x ASTM C-1157 for Type GU

By
Quality Control Manager

is not responsible for the improper use or workmanship associated with the use of this cement.

Figure A.1: Mill report of OPC 1

Samples for UNC Charlotte

	UNCC	UNCC
Sample Type	I-II	IL
Sample ID		
Date Tested at HH	1/20/2015	1/13/2015
% Limestone	3.4	10.2
Blaine	406	530
SiO2	20.33	19.83
Al2O3	4.93	4.29
Fe2O3	3.46	3.45
CaO	64.46	64.32
MgO	1.56	1.38
SO3	3.29	3.46
Na2O	0.18	0.15
K2O	0.59	0.47
NaEq	0.57	0.46
C3S	60.5	
C2S	12.7	
C3A	7.2	
C4AF	10.5	
1 Day psi	2580	2690
3 Day psi	4340	4520
7 Day psi	5250	5610
28 Day psi	6400	6590

Please Note: The Bogue phase calculations are not corrected for Limestone addition.

Figure A.2: Mill Report of OPC 2 and PLC

Date: February 10, 2016
I.D.:
Lab No.:

REPORT OF FLY ASH TESTS

Date Sampled: DS 11/23-12/11 | Start Date: November 23, 2015
Manufacturer: Roxboro | End Date: December 11, 2015
Date Received: December 16, 2015

Chemical Analysis**	Results (wt%)	Specification (Class F) ASTM C618-15	Specification (Class F) AASHTO M295-11
Silicon Dioxide (SiO_2)	**53.8**	----	----
Aluminum Oxide (Al_2O_3)	**27.5**	---	----
Iron Oxide (Fe_2O_3)	**8.05**	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide ($SiO_2+Al_2O_3+Fe_2O_3$)	**89.3**	70 % min.	70 % min.
Calcium Oxide (CaO)	**2.3**	----	----
Magnesium Oxide (MgO)	**1.0**	----	----
Sodium Oxide (Na_2O)	**0.45**	----	----
Potassium Oxide (K_2O)	**2.44**	---	----
"Sodium Oxide Equivalent ($Na_2O+0.658K_2O$)"	**2.05**	----	----
Sulfur Trioxide (SO_3)	**0.62**	5 % max.	5 % max.
Loss on Ignition	**2.1**	6 % max.	5 % max.
Moisture Content	**0.18**	3 % max.	3 % max.
Available Alkalies**			
Sodium Oxide (Na_2O) as Available Alkalies	**0.16**	----	----
Potassium Oxide (K_2O) as Available Alkalies	**0.71**	----	----
Available Alkalies as "Sodium Oxide Equivalent ($Na_2O+0.658K_2O$)"	**0.63**	----	1.5 % max.*
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	**21.9%**	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 4820; Test Average, psi: 3780	**78%**	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6100; Test Average, psi: 5190	**85%**	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242; Test, mls: 236	**98%**	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion:	**-0.03%**	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	**2.21**	----	----

† Meeting the 7 day or 28 day strength activity index will indicate specification compliance
* Optional
**Chemical Analysis performed by

Figure A.3: Test report of fly ash A

Date: January 30, 2015
Project No:
Laboratory No:

REPORT OF FLY ASH TESTS

Date Sampled: DS 12/11-12/16	Start Date:	December 11, 2014	
Manufacturer: Belews Creek	End Date:	December 16, 2014	
	Date Received:	December 22, 2014	
		Specification (Class F)	
Chemical Analysis**	**Results**	**ASTM C618-12a**	**AASHTO M295-11**
Silicon Dioxide	**53.21**	----	----
Aluminum Oxide	**28.74**	----	----
Iron Oxide	**7.64**	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide	**89.59**	70 % min.	70 % min.
Calcium Oxide	**1.74**	----	----
Magnesium Oxide	**0.92**		
Sulfur Trioxide	**0.38**	5 % max.	5 % max.
Loss on Ignition	**2.61**	6 % max.	5 % max.
Moisture Content	**0.10**	3 % max.	3 % max.
Available Alkalies as Na_2O	**0.42**	----	1.5 % max.*
Sodium Oxide	**0.11**	----	----
Potassium Oxide	**0.47**	----	----
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	**13.3%**	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 4930; Test Average, psi: 3840	**78%**	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6150; Test Average, psi: 5540	**90%**	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242; Test, mls: 236	**98%**	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion	**0.03%**	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	**2.29**	----	----

† Meeting the 7 day or 28 day strength activity index will indicate specification compliance

* Optional Requirement

**Chemical Analysis performed by

Figure A.4: Test report of fly ash B

APPENDIX B: SUPPLEMENTAL INFORMATION FOR CHAPTER 4

Table B.1: Slump

Mixture ID	Batch 1	Batch 2	Batch 3	Batch 4	Average
P.A.N.M	1.5	1.25	1.25	1.75	1.4
P.B.N.M	2	2	1.75	2	1.9
P.BL.N.M	2	2	2.25	2.5	2.2
C.A.N.M	-	0.75	1	1.5	1.1
C.B.N.M	-	1	1.5	1.75	1.4
C.BL.N.M	-	1	1	1.25	1.1
M.A.N.M	2.75	-	1.75	1.5	1.6
M.B.N.M	3.25	-	2.25	1.75	2.0
M.BL.N.M	2.25	-	2.5	2	2.3
P.A.A.M	2.5	3.5	2.25	2.5	2.8
P.B.A.M	2.5	2.5	2.25	1.75	2.2
P.BL.A.M	2.5	3.25	2	2.25	2.5
P.A.B.M	-	3	2.25	2	2.1
P.B.B.M	-	2.75	2	2	2.3
P.BL.B.M	-	2.75	2.25	2	2.3
P.A.N.N	-	1.5	2	2.25	2.1
P.B.N.N	-	2.5	3.75	3.75	3.8
P.BL.N.N	-	2.75	3	2.75	2.9

Table B.2: Air content

Mixture ID	Batch 1	Batch 2	Batch 3	Batch 4	Average
P.A.N.M	5.6	5.5	5.1	5.5	5.4
P.B.N.M	5.9	6.0	6.0	6.0	6.0
P.BL.N.M	5.0	5.8	5.6	6.0	5.6
C.A.N.M	-	5.7	5.8	6.0	5.8
C.B.N.M	-	5.4	5.7	5.8	5.6
C.BL.N.M	-	5.6	5.0	6.0	5.5
M.A.N.M	5.4	-	5.4	5.2	5.3
M.B.N.M	5.7	-	5.2	5.2	5.2
M.BL.N.M	5.0	-	5.4	5.0	5.2
P.A.A.M	5.5	5.9	5.6	5.6	5.7
P.B.A.M	5.1	5.3	5.3	5.0	5.2
P.BL.A.M	5.1	5.3	5.1	5.3	5.2
P.A.B.M	-	5.4	5.6	5.8	5.6
P.B.B.M	-	6.0	5.6	5.6	5.7
P.BL.B.M	-	5.9	5.6	5.3	5.6
P.A.N.N	-	5.0	5.3	5.5	5.4
P.B.N.N	-	5.1	5.6	5.6	5.6
P.BL.N.N	-	5.9	5.3	5.4	5.4

Table B.3: Unit weight

Mixture ID	Batch 1	Batch 2	Batch 3	Batch 4	Average
P.A.N.M	144	144	146	145	145
P.B.N.M	143	143	143	143	143
P.BL.N.M	146	143	144	142	144
C.A.N.M	-	138	138	137	138
C.B.N.M	-	138	139	138	139
C.BL.N.M	-	137	139	139	139
M.A.N.M	145	-	145	146	146
M.B.N.M	143	-	145	145	145
M.BL.N.M	146	-	144	146	145
P.A.A.M	141	139	142	142	141
P.B.A.M	142	142	142	143	143
P.BL.A.M	143	141	142	142	142
P.A.B.M	-	141	142	142	141
P.B.B.M	-	139	141	142	141
P.BL.B.M	-	140	141	142	141
P.A.N.N	-	144	142	142	142
P.B.N.N	-	143	142	142	142
P.BL.N.N	-	147	142	141	141

Table B.4: Table compressive strength (Psi) at 28 day

Mixture ID	Specimen 1	Specimen 2	Specimen 3	Average
P.A.N.M	5,130	5,207	5,338	5,220
P.B.N.M	4,899	4,783	4,856	4,850
P.BL.N.M	4,781	5,011	5,264	5,020
C.A.N.M	5,432	5,405	5,233	5,360
C.B.N.M	5,743	6,272	5,856	5,960
C.BL.N.M	5,405	5,295	5,969	5,560
M.A.N.M	5,060	5,151	4,882	5,030
M.B.N.M	4,941	5,271	5,077	5,100
M.BL.N.M	4,727	5,008	4,636	4,79
P.A.A.M	4,445	4,026	4,352	4,270
P.B.A.M	4,295	4,115	3,745	4,050
P.BL.A.M	3,693	3,915	3,635	3,750
P.A.B.M	3,911	3,732	3,702	3,780
P.B.B.M	3,138	3,222	3,045	3,140
P.BL.B.M	3,616	3,211	4,501	3,780
P.A.N.N	5,245	5,584	5,378	5,400
P.B.N.N	4,220	4,458	4,484	4,390
P.BL.N.N	5,196	5,352	5,024	5,190

Table B.5: Modulus of rupture at 28 day

Mixture ID	Specimen 1	Specimen 2	Average
P.A.N.M	674	685	680
P.B.N.M	721	620	670
P.BL.N.M	635	676	660
C.A.N.M	738	721	730
C.B.N.M	704	795	750
C.BL.N.M	686	665	680
M.A.N.M	583	565	570
M.B.N.M	632	650	640
M.BL.N.M	598	614	610
P.A.A.M	610	680	650
P.B.A.M	458	613	540
P.BL.A.M	675	621	650
P.A.B.M	562	573	570
P.B.B.M	609	622	620
P.BL.B.M	579	537	56
P.A.N.N	717	754	740
P.B.N.N	738	695	720
P.BL.N.N	728	777	750

Table B.6: Modulus of elasticity at 28 day

Mixture ID	Specimen 1	Specimen 2	Average
P.A.N.M	2,713,049	3,123,108	2,920,000
P.B.N.M	3,184,042	3,490,374	3,340,000
P.BL.N.M	2,659,514	2,203,131	2,430,000
C.A.N.M	4,085,851	3,382,608	3,730,000
C.B.N.M	3,620,150	3,366,678	3,490,000
C.BL.N.M	3,805,354	3,578,321	3,690,000
M.A.N.M	2,484,757	2,604,384	2,540,000
M.B.N.M	2,710,181	2,808,936	2,760,000
M.BL.N.M	2,923,484	3,122,951	3,020,000
P.A.A.M	3,257,785	3,190,631	3,220,000
P.B.A.M	2,205,106	3,200,277	2,700,000
P.BL.A.M	2,486,174	2,895,681	2,690,000
P.A.B.M	2,776,134	2,896,999	2,840,000
P.B.B.M	2,436,815	2,574,383	2,510,000
P.BL.B.M	2,671,917	2,773,204	2,720,000
P.A.N.N	3,620,851	3,176,120	3,400,000
P.B.N.N	2,919,988	4,109,804	3,510,000
P.BL.N.N	2,925,107	3,150,812	3,040,000

Table B.7: Poisson's ratio at 28 days

Mixture ID	Specimen 1	Specimen 2	Average
P.A.N.M	0.19	0.20	0.20
P.B.N.M	0.18	0.21	0.20
P.BL.N.M	0.18	0.18	0.18
C.A.N.M	0.22	0.23	0.22
C.B.N.M	0.21	0.20	0.21
C.BL.N.M	0.22	0.23	0.22
M.A.N.M	0.16	0.19	0.18
M.B.N.M	0.19	0.20	0.20
M.BL.N.M	0.19	0.20	0.20
P.A.A.M	0.24	0.23	0.23
P.B.A.M	0.20	0.21	0.21
P.BL.A.M	0.16	0.17	0.16
P.A.B.M	0.24	0.19	0.22
P.B.B.M	0.16	0.21	0.18
P.BL.B.M	0.19	0.20	0.19
P.A.N.N	0.17	0.13	0.15
P.B.N.N	0.18	0.20	0.19
P.BL.N.N	0.16	0.15	0.15

Table B.8: Surface resistivity results at 28 day

Mixture ID	Specimen 1	Specimen 2	Specimen 3	Average
P.A.N.M	6.4	7.4	6.7	6.9
P.B.N.M	7.3	6.9	7.7	7.3
P.BL.N.M	7.6	7.5	7.6	7.6
C.A.N.M	6.4	6.7	7.0	6.7
C.B.N.M	7.3	7.1	6.5	7.0
C.BL.N.M	7.1	6.7	5.9	6.6
M.A.N.M	5.9	5.9	6.0	5.9
M.B.N.M	6.7	6.4	6.7	6.6
M.BL.N.M	7.4	7.8	7.5	7.5
P.A.A.M	7.2	8.2	7.8	7.7
P.B.A.M	10.0	10.6	10.7	10.4
P.BL.A.M	12.0	13.3	12.4	12.6
P.A.B.M	7.6	7.3	7.5	7.5
P.B.B.M	10.7	9.2	9.5	9.8
P.BL.B.M	12.7	11.8	13.0	12.5
P.A.N.N	7.4	7.0	7.8	7.4
P.B.N.N	10.4	10.9	10.6	10.6
P.BL.N.N	9.6	9.4	9.3	9.4

Table B.9: Shrinkage raw data

Mixture Id	1	28	32	35	42	56	84	140
P.A.N.M	-0.0654	-0.0648	-0.0667	-0.0676	-0.0688	-0.0702	-0.0713	-0.0718
	-0.0279	-0.027	-0.0288	-0.03	-0.0312	-0.0325	-0.0336	-0.034
	-0.0687	-0.0672	-0.0699	-0.0709	-0.0719	-0.0737	-0.0747	-0.075
P.B.N.M	-0.0651	-0.0642	-0.0667	-0.0678	-0.069	-0.0704	-0.0714	-0.0721
	-0.0288	-0.0268	-0.0302	-0.0317	-0.0325	-0.034	-0.0347	-0.0351
	-0.0289	-0.028	-0.0306	-0.0312	-0.0327	-0.0338	-0.0347	-0.0354
P.BL.N.M	-0.097	-0.0966	-0.0992	-0.1001	-0.1014	-0.1027	-0.1036	-0.1039
	-0.0986	-0.0973	-0.1004	-0.101	-0.1024	-0.1037	-0.1045	-0.1048
	-0.0663	-0.0657	-0.0722	-0.0694	-0.0708	-0.072	-0.0728	-0.0732
C.A.N.M	-0.0351	-0.0347	-0.0367	-0.0367	-0.038	-0.0398	-0.0409	-0.0415
	-0.0685	-0.067	-0.0695	-0.0699	-0.0713	-0.073	-0.0741	-0.0747
	-0.0281	-0.0278	-0.0292	-0.0298	-0.0312	-0.0327	-0.0338	-0.0343
C.B.N.M	-0.0296	-0.0292	-0.03	-0.0314	-0.033	-0.0346	-0.0352	-0.0355
	-0.0584	-0.0576	-0.0588	-0.0596	-0.0612	-0.0624	-0.0632	-0.0637
	-0.0281	-0.0276	-0.0282	-0.0298	-0.0314	-0.0326	-0.0333	-0.0337
C.BL.N.M	-0.0642	-0.0635	-0.0652	-0.0661	-0.0677	-0.0687	-0.0695	-0.0698
	-0.0634	-0.0633	-0.0646	-0.0656	-0.0672	-0.0681	-0.0688	-0.0691
	-0.0262	-0.0246	-0.0258	-0.0268	-0.0283	-0.0293	-0.0298	-0.0301
M.A.N.M	-0.0623	-0.0592	-0.0615	-0.0627	-0.0642	-0.0655	-0.0664	-0.0672
	-0.0652	-0.0639	-0.0661	-0.0671	-0.0688	-0.0699	-0.0712	-0.0717
	-0.0357	-0.035	-0.0371	-0.0384	-0.0398	-0.0414	-0.0425	-0.0431
M.B.N.M	-0.0362	-0.0328	-0.036	-0.0364	-0.0377	-0.0388	-0.0399	-0.0403
	-0.0285	-0.028	-0.0312	-0.0317	-0.0328	-0.0341	-0.0352	-0.0358
	-0.0305	-0.0306	-0.0334	-0.0338	-0.0352	-0.0365	-0.0375	-0.038
M.BL.N.M	-0.0297	-0.029	-0.031	-0.0321	-0.0338	-0.0353	-0.0362	-0.037
	-0.0286	-0.0276	-0.0297	-0.0307	-0.0322	-0.0335	-0.0343	-0.035
	-0.0344	-0.0339	-0.0361	-0.0371	-0.0387	-0.04	-0.0409	-0.0413
P.A.A.M	-0.033	-0.0317	-0.0341	-0.0351	-0.0367	-0.0381	-0.0387	-0.0395
	-0.0644	-0.0629	-0.0654	-0.0663	-0.0677	-0.0691	-0.0696	-0.0703
	-0.033	-0.0305	-0.0328	-0.0338	-0.0353	-0.0367	-0.0372	-0.0381
P.B.A.M	-0.0555	-0.0542	-0.056	-0.0566	-0.0574	-0.0584	-0.059	-0.0605
	-0.0303	-0.0298	-0.0318	-0.0323	-0.0333	-0.0344	-0.0351	-0.0367
	-0.0259	-0.0257	-0.0274	-0.028	-0.0289	-0.0299	-0.0306	-0.0321
P.BL.A.M	-0.0447	-0.0444	-0.0464	-0.047	-0.048	-0.0492	-0.0499	-0.0508
	-0.0328	-0.0325	-0.0343	-0.0349	-0.036	-0.0372	-0.0379	-0.0388
	-0.0306	-0.0305	-0.0324	-0.0329	-0.0341	-0.0352	-0.0361	-0.0369
P.A.B.M	-0.0278	-0.027	-0.029	-0.03	-0.031	-0.0324	-0.0331	-0.0338

	-0.0253	-0.0238	-0.026	-0.027	-0.028	-0.0294	-0.0303	-0.0311
	-0.0317	-0.0303	-0.0325	-0.0333	-0.0342	-0.0356	-0.0364	-0.0374
P.B.B.M	-0.0322	-0.0317	-0.0337	-0.0342	-0.0352	-0.0363	-0.0374	-0.0382
	-0.0285	-0.0273	-0.0294	-0.03	-0.0309	-0.0319	-0.0329	-0.0338
	-0.0247	-0.0242	-0.0263	-0.0269	-0.0278	-0.029	-0.0302	-0.0312
P.BL.B.M	-0.0331	-0.033	-0.0351	-0.0357	-0.0367	-0.0378	-0.0387	-0.0398
	-0.0351	-0.0344	-0.0361	-0.0372	-0.0382	-0.0395	-0.0405	-0.0414
	-0.0687	-0.0682	-0.0705	-0.0711	-0.0721	-0.0733	-0.0742	-0.075
P.A.N.N	-0.0329	-0.0323	-0.0342	-0.0348	-0.0357	-0.0365	-0.0378	-0.0388
	-0.0322	-0.0317	-0.0338	-0.0344	-0.0353	-0.0361	-0.0375	-0.0383
	-0.0333	-0.0328	-0.0347	-0.0351	-0.0361	-0.0369	-0.0379	-0.0388
P.B.N.N	-0.0358	-0.0353	-0.0364	-0.0369	-0.0377	-0.0385	-0.0395	-0.0406
	-0.0334	-0.0329	-0.0342	-0.0347	-0.0355	-0.0361	-0.0369	-0.0383
	-0.0592	-0.0587	-0.0599	-0.0604	-0.0612	-0.0619	-0.0626	-0.0638
P.BL.N.N	-0.0314	-0.031	-0.0324	-0.033	-0.0337	-0.0344	-0.0355	-0.0366
	-0.0346	-0.0341	-0.0357	-0.0362	-0.0368	-0.0375	-0.0385	-0.0397
	-0.0319	-0.0314	-0.033	-0.0336	-0.0341	-0.035	-0.0358	-0.0368

Table B.10: Thaumasite raw data at 23^oC

Mixture ID	1	2	3	4	8	15	24
AN4	-0.0615	-0.0613	-0.0612	-0.0607	-0.0606	-0.0604	-0.0597
AN5	0.0066	0.0068	0.0069	0.007	0.0071	0.0074	0.0082
AN6	-0.0111	-0.0108	-0.0106	-0.0104	-0.0101	-0.0099	-0.0091
BN4	-0.003	-0.003	-0.0026	-0.0025	-0.002	-0.0017	-0.0013
BN5	-0.0004	-0.0002	0.0001	0.0003	0.0008	0.0012	0.0018
BN6	0.0017	0.0019	0.0021	0.0023	0.0029	0.0033	0.0041
BLN4	-0.0005	-0.0003	-0.0002	-0.0003	0.0005	0.0008	0.0012
BLN5	-0.004	-0.0038	-0.0035	-0.0039	-0.0034	-0.0031	-0.002
BLN6	-0.0011	-0.0007	-0.0008	-0.0009	-0.0002	0.0002	0.0011
ANN4	-0.0014	-0.0014	-0.0011	-0.001	-0.0005	0.0002	0.0017
ANN5	-0.0029	-0.0029	-0.0026	-0.0026	-0.0021	-0.014	0.0004
ANN6	0.00017	0.0018	0.002	0.0019	0.0027	0.0034	0.0058
BNN4	-0.003	-0.003	-0.0027	-0.0027	-0.0023	-0.0018	-0.0016
BNN5	-0.0048	-0.0049	-0.0045	-0.0043	-0.0039	-0.0035	-0.0028
BNN6	-0.0058	-0.0058	-0.0055	-0.0053	-0.005	-0.0045	-0.0039
BLNN4	-0.0012	-0.0015	-0.001	-0.0009	-0.0004	0.0003	0.0029
BLNN5	-0.051	-0.0512	-0.0508	-0.0507	-0.0501	-0.0492	-0.0463
BLNN6	-0.0083	-0.0085	-0.0082	-0.008	-0.0075	-0.0064	-0.0029
AA4	-0.0379	-0.0377	-0.0375	-0.0374	-0.037	-0.0367	-0.0368
AA5	0	0.0003	0.0005	0.0005	0.001	0.0011	0.0013
AA6	0.0065	0.0066	0.0067	0.0065	0.0074	0.0075	0.0077
BA4	-0.0004	-0.0003	-0.0002	-0.0001	0.0002	0.0003	0.0005
BA5	-0.0075	-0.0074	-0.0072	-0.0072	-0.0071	-0.0067	-0.0066
BA6	0.0068	0.0067	0.007	0.007	0.0073	0.0074	0.0075
BLA4	-0.0038	-0.0037	-0.0035	-0.0035	-0.0032	-0.0027	-0.0025
BLA5	-0.0019	-0.0018	-0.0016	-0.0016	-0.0011	-0.0007	-0.0003
BLA6	-0.0039	-0.0035	-0.0034	-0.0032	-0.0029	-0.0062	-0.002
AB4	0.0011	0.0017	0.0021	0.0022	0.003	0.0045	0.008
AB5	-0.0043	-0.0036	-0.0032	-0.003	-0.0021	-0.0009	0.0017
AB6	-0.0361	-0.0355	-0.0353	-0.0351	-0.0342	-0.0329	-0.0297
BB4	-0.0046	-0.0044	-0.0042	-0.0041	-0.0035	-0.0027	-0.0006
BB5	-0.0046	-0.0046	-0.0044	-0.0042	-0.0037	-0.0027	0.0004
BB6	-0.0059	-0.0057	-0.0056	-0.0054	-0.0049	-0.0042	-0.0021
BLB4	-0.0111	-0.0109	-0.0108	-0.0105	-0.0103	-0.01	-0.0092
BLB5	0.0072	0.0074	0.0076	0.0079	0.0082	0.0087	0.0098
BLB6	0.011	0.0112	0.0115	0.0117	0.0119	0.0122	0.013

Table B.11: Thaumasite raw data at 5^{o}C

Mixture ID	1	2	3	4	8	15	24
AN1	-0.0312	-0.0311	-0.0309	-0.0309	-0.0303	-0.0301	-0.0292
AN2	-0.0017	-0.0018	-0.0015	-0.0015	-0.0008	-0.0004	0.0005
AN3	-0.0152	-0.0152	-0.015	-0.015	-0.0142	-0.0139	-0.013
BN1	-0.0022	-0.0022	-0.0021	-0.0017	-0.0015	-0.0013	-0.0004
BN2	-0.0067	-0.0066	-0.0066	-0.0068	-0.006	-0.0057	-0.0048
BN3	-0.0058	-0.0056	-0.0057	-0.0048	-0.0049	-0.0047	-0.0038
BLN1	-0.0207	-0.0204	-0.0202	-0.0198	-0.0202	-0.0198	-0.019
BLN2	-0.0151	-0.0149	-0.0145	-0.0144	-0.0144	-0.014	-0.0134
BLN3	-0.0026	-0.0029	-0.0027	-0.0025	-0.0024	-0.002	-0.0013
ANN4	-0.0014	-0.0014	-0.0011	-0.001	-0.0005	0.0002	0.0017
ANN5	-0.0029	-0.0029	-0.0026	-0.0026	-0.0021	-0.014	0.0004
ANN6	0.00017	0.0018	0.002	0.0019	0.0027	0.0034	0.0058
BNN4	-0.003	-0.003	-0.0027	-0.0027	-0.0023	-0.0018	-0.0016
BNN5	-0.0048	-0.0049	-0.0045	-0.0043	-0.0039	-0.0035	-0.0028
BNN6	-0.0058	-0.0058	-0.0055	-0.0053	-0.005	-0.0045	-0.0039
BLNN4	-0.0012	-0.0015	-0.001	-0.0009	-0.0004	0.0003	0.0029
BLNN5	-0.051	-0.0512	-0.0508	-0.0507	-0.0501	-0.0492	-0.0463
BLNN6	-0.0083	-0.0085	-0.0082	-0.008	-0.0075	-0.0064	-0.0029
AA4	-0.0379	-0.0377	-0.0375	-0.0374	-0.037	-0.0367	-0.0368
AA5	0	0.0003	0.0005	0.0005	0.001	0.0011	0.0013
AA6	0.0065	0.0066	0.0067	0.0065	0.0074	0.0075	0.0077
BA4	-0.0004	-0.0003	-0.0002	-0.0001	0.0002	0.0003	0.0005
BA5	-0.0075	-0.0074	-0.0072	-0.0072	-0.0071	-0.0067	-0.0066
BA6	0.0068	0.0067	0.007	0.007	0.0073	0.0074	0.0075
BLA4	-0.0038	-0.0037	-0.0035	-0.0035	-0.0032	-0.0027	-0.0025
BLA5	-0.0019	-0.0018	-0.0016	-0.0016	-0.0011	-0.0007	-0.0003
BLA6	-0.0039	-0.0035	-0.0034	-0.0032	-0.0029	-0.0062	-0.002
AB1	-0.0282	-0.0279	-0.0276	-0.0274	-0.0263	-0.0239	-0.0183
AB2	-0.0021	-0.0016	-0.0015	-0.0015	0	0.0038	0.0146
AB3	-0.0009	-0.0005	-0.0005	-0.0003	0.0003	0.0012	0.0037
BB1	0.0023	0.0031	0.0029	0.0032	0.0037	0.0044	0.0067
BB2	-0.009	-0.0084	-0.0086	-0.0081	-0.0079	-0.007	-0.0055
BB3	0.0005	0.0014	0.001	0.0015	0.0019	0.0025	0.0048
BLB1	0.0038	0.0038	0.0042	0.0045	0.0046	0.0054	0.0062
BLB2	-0.0003	-0.0001	0.0002	0.0004	0.0007	0.0016	0.0036
BLB3	-0.001	-0.0004	-0.0008	-0.0006	-0.0005	0.0005	0.0028

APPENDIX C: SUPPLEMENTAL INFORMATION FOR CHAPTER 5

Table C.1: Air emissions

Cement	CO (kg/m^3)	Lead (kg/m^3)	NO_X (kg/m^3)	PM_{10} (kg/m^3)	SO_2 (kg/m^3)	VOC (kg/m^3)	Total (kg/m^3)
0% limestone (without fly ash)	99.1	0.015	0.982	0.075	0.787	0.013	101.00
0% limestone (with fly ash)	79.3	0.012	0.799	0.071	0.706	0.010	80.9
5% limestone (without fly ash)	94.2	0.014	0.933	0.074	0.779	0.086	96.0
5% limestone (with fly ash)	75.3	0.011	0.760	0.070	0.671	0.084	76.9
10% limestone (without fly ash)	89.2	0.014	0.884	0.072	0.710	0.162	91.1
10% limestone (with fly ash)	71.4	0.011	0.719	0.069	0.640	0.160	73.0
12% limestone (without fly ash)	87.2	0.013	0.849	0.072	0.738	0.192	89.1
12% limestone (with fly ash)	69.8	0.011	0.703	0.068	0.636	0.190	71.4
15% limestone (without fly ash)	84.3	0.013	0.837	0.071	0.675	0.237	86.2
15% limestone (with fly ash)	67.4	0.010	0.680	0.068	0.606	0.235	69.0
20% limestone (without fly ash)	79.3	0.012	0.788	0.069	0.637	0.380	81.2
20% limestone (with fly ash)	63.4	0.010	0.641	0.067	0.572	0.309	65.0

Table C.2: Air emissions by changing milling technology

Cement	CO (kg/m^3)	Lead (kg/m^3)	NO_X (kg/m^3)	PM_{10} (kg/m^3)	SO_2 (kg/m^3)	VOC (kg/m^3)	Total (kg/m^3)
0% limestone (Ball Mill)	99.1	0.015	0.982	0.075	0.787	0.013	101.0
0% limestone (Tube Mill)	99.1	0.015	0.963	0.075	0.832	0.013	101.0
0% limestone (Vertical Roller Mill)	99.1	0.015	0.962	0.075	0.829	0.013	101.0
0% limestone (Roller Press)	99.1	0.015	0.962	0.075	0.829	0.013	101.0
0% limestone (Horizontal Roller Mill)	99.1	0.015	0.962	0.075	0.829	0.013	101.0
5% limestone (Ball Mill)	94.2	0.014	0.933	0.074	0.779	0.086	96.0
5% limestone (Tube Mill)	94.1	0.014	0.915	0.074	0.793	0.086	96.0
5% limestone (Vertical Roller Mill)	94.2	0.014	0.914	0.074	0.789	0.086	96.0
5% limestone (Roller Press)	94.2	0.014	0.914	0.074	0.79	0.086	96.0
5% limestone (Horizontal Roller Mill)	94.2	0.014	0.914	0.074	0.79	0.086	96.0
10% limestone (Ball Mill)	89.2	0.014	0.884	0.072	0.710	0.162	91.1
10% limestone (Tube Mill)	89.2	0.014	0.868	0.072	0.751	0.162	91.1
10% limestone (Vertical Roller Mill)	89.2	0.014	0.866	0.072	0.748	0.162	91.1
10% limestone (Roller Press)	89.2	0.014	0.866	0.072	0.748	0.162	91.1
10% limestone (Horizontal Roller Mill)	89.2	0.014	0.866	0.072	0.748	0.162	91.1
12% limestone (Ball Mill)	87.2	0.013	0.849	0.072	0.738	0.192	89.1
12% limestone (Tube Mill)	87.2	0.013	0.849	0.072	0.738	0.192	89.1
12% limestone (Vertical Roller Mill)	87.2	0.013	0.844	0.072	0.735	0.192	89.1
12% limestone (Roller Press)	87.2	0.013	0.847	0.072	0.735	0.192	89.1
12% limestone (Horizontal Roller Mill)	87.2	0.013	0.847	0.072	0.735	0.192	89.1
15% limestone (Ball Mill)	84.3	0.013	0.837	0.071	0.675	0.237	86.2
15% limestone (Tube Mill)	84.2	0.013	0.82	0.071	0.713	0.237	86.1
15% limestone (Vertical Roller Mill)	84.2	0.013	0.819	0.071	0.710	0.237	86.1
15% limestone (Roller Press)	84.2	0.013	0.819	0.071	0.710	0.237	86.1
15% limestone (Horizontal Roller Mill)	84.2	0.013	0.819	0.071	0.710	0.237	86.1
20% limestone (Ball Mill)	79.3	0.012	0.788	0.069	0.637	0.380	81.2
20% limestone (Tube Mill)	79.3	0.012	0.771	0.069	0.672	0.380	81.2
20% limestone (Vertical Roller Mill)	79.3	0.012	0.773	0.069	0.67	0.380	81.2
20% limestone (Roller Press)	79.3	0.012	0.773	0.069	0.67	0.380	81.2
20% limestone (Horizontal Roller Mill)	79.3	0.012	0.773	0.069	0.67	0.380	81.2

Table C.3: Air emissions by changing change energy source for electricity

Cement	CO (kg/m^3)	Lead (kg/m^3)	NO_X (kg/m^3)	PM_{10} (kg/m^3)	SO_2 (kg/m^3)	VOC (kg/m^3)	Total (kg/m^3)
0% limestone , energy grid mix 1	99.1	0.015	0.982	0.075	0.787	0.013	101.0
0% limestone energy grid mix 2	99.1	0.015	0.988	0.075	0.86	0.013	101.1
0% limestone energy grid mix 3	99.1	0.015	0.988	0.075	0.86	0.013	101.1
0% limestone energy grid mix 4	99.1	0.015	0.988	0.075	0.86	0.013	101.1
5% limestone energy grid mix 1	94.2	0.014	0.933	0.074	0.779	0.086	96.0
5% limestone energy grid mix 2	94.2	0.014	0.941	0.074	0.819	0.086	96.1
5% limestone energy grid mix 3	94.2	0.014	0.941	0.074	0.819	0.086	96.1
5% limestone energy grid mix 4	94.2	0.014	0.941	0.074	0.819	0.086	96.1
10% limestone energy grid mix 1	89.2	0.014	0.884	0.072	0.710	0.162	91.1
10% limestone energy grid mix 2	89.2	0.014	0.892	0.072	0.777	0.163	91.1
10% limestone energy grid mix 3	89.2	0.014	0.892	0.072	0.777	0.163	91.1
10% limestone energy grid mix 4	89.2	0.014	0.892	0.072	0.777	0.163	91.1
12% limestone energy grid mix 1	87.2	0.013	0.849	0.072	0.738	0.192	89.1
12% limestone energy grid mix 2	87.2	0.013	0.873	0.072	0.763	0.192	89.1
12% limestone energy grid mix 3	87.2	0.013	0.873	0.072	0.763	0.192	89.1
12% limestone energy grid mix 4	87.2	0.013	0.873	0.072	0.862	0.192	89.2
15% limestone energy grid mix 1	84.3	0.013	0.837	0.071	0.675	0.237	86.2
15% limestone energy grid mix 2	84.2	0.013	0.843	0.071	0.736	0.237	86.1
15% limestone energy grid mix 3	84.2	0.013	0.843	0.071	0.736	0.237	86.1
15% limestone energy grid mix 4	84.2	0.013	0.843	0.071	0.736	0.237	86.1
20% limestone energy grid mix 1	79.3	0.012	0.788	0.069	0.695	0.380	81.2
20% limestone energy grid mix 2	79.3	0.012	0.797	0.069	0.672	0.380	81.2
20% limestone energy grid mix 3	79.3	0.012	0.797	0.069	0.672	0.380	81.2
20% limestone energy grid mix 4	79.3	0.012	0.797	0.069	0.672	0.380	81.2

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Figure C.1: Data sources for production (Green Concrete web tool)

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Figure C.2: Data sources pre-combustion (Green Concrete web tool)

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Figure C.3: Data sources combustion (Green Concrete web tool)

TRANSPORTATION DATA

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Figure C.5: Data sources for transportation (Green Concrete Web tool)

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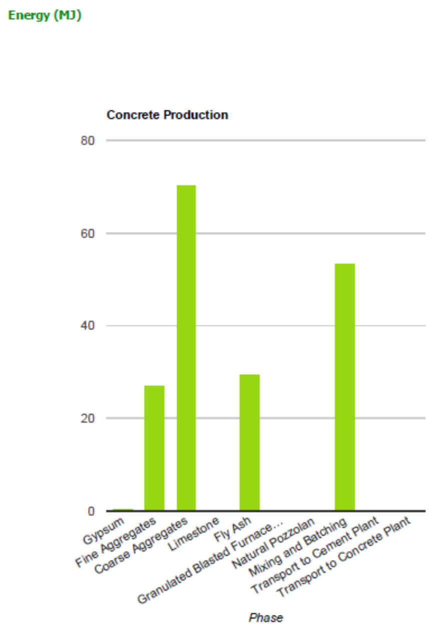
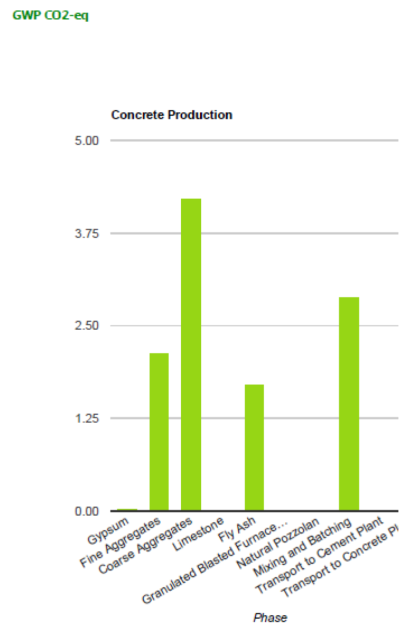
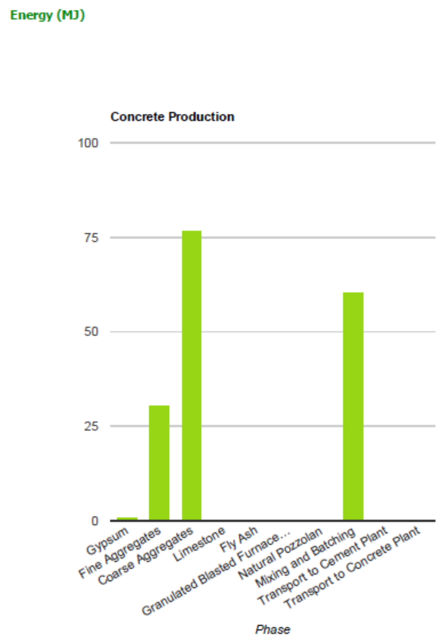
Figure C.6: Data sources for electricity (Green concrete web tool)

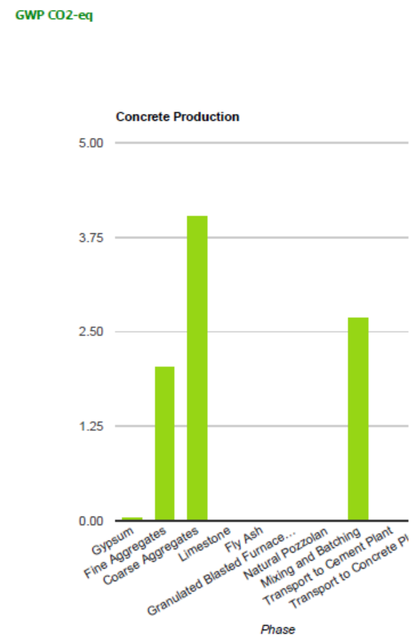




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.011	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.010	0.000	0.004	0.000	0.009	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	99.090	0.015	0.949	0.026	0.722	0.012
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.019	0.000	0.007	0.000	0.016	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.7: Result with 0% limestone ball mill

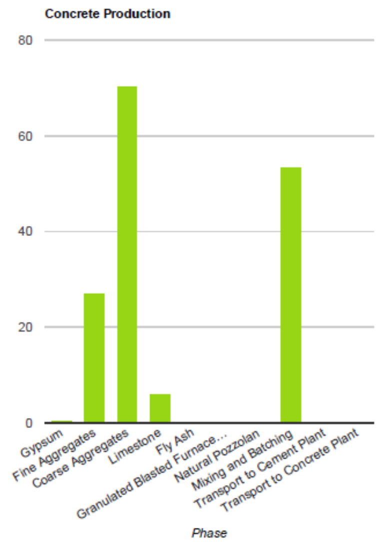




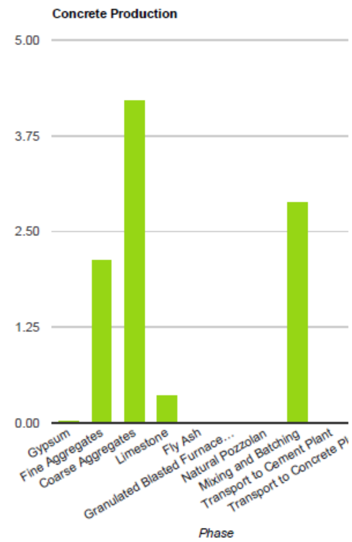
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.001	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash	0.002	0.000	0.002	0.002	0.011	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.8: Result with 0% limestone with fly ash

Energy (MJ)

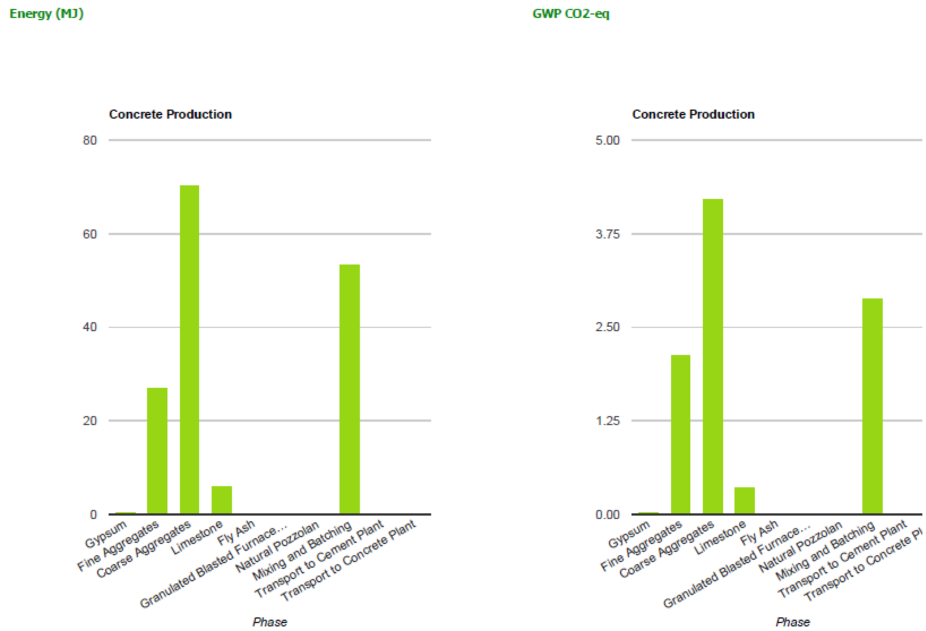


GWP CO2-eq



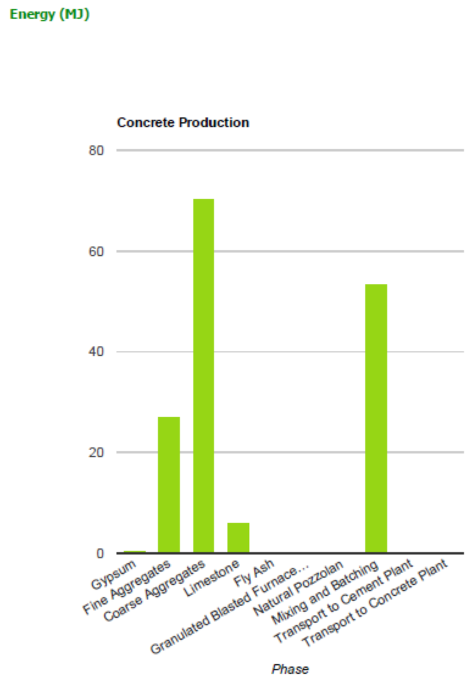
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

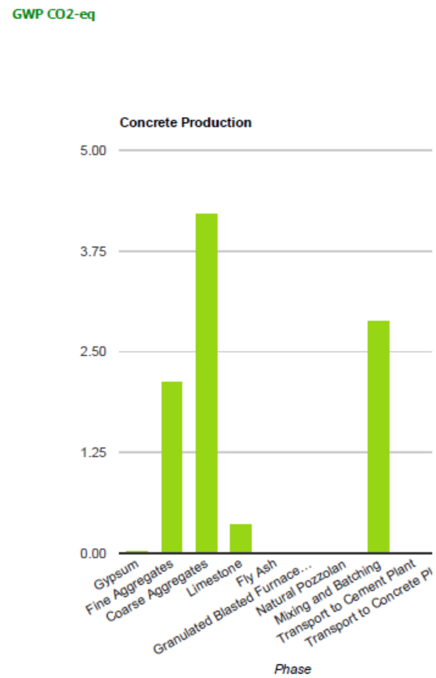
Figure C.9: Result with 0% limestone tube mill



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

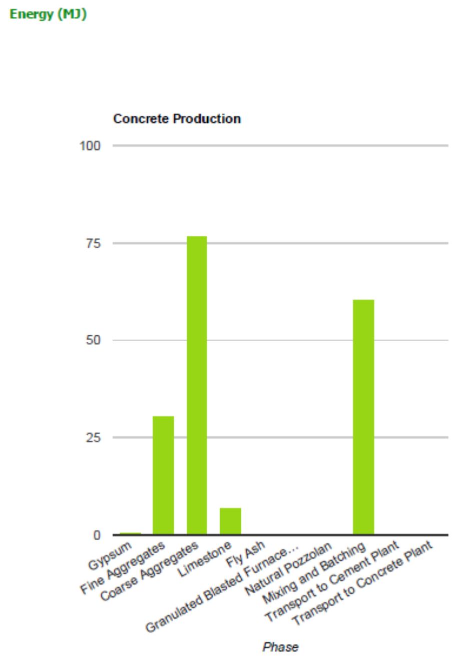
Figure C.10: Result with 0% limestone vertical roller mill

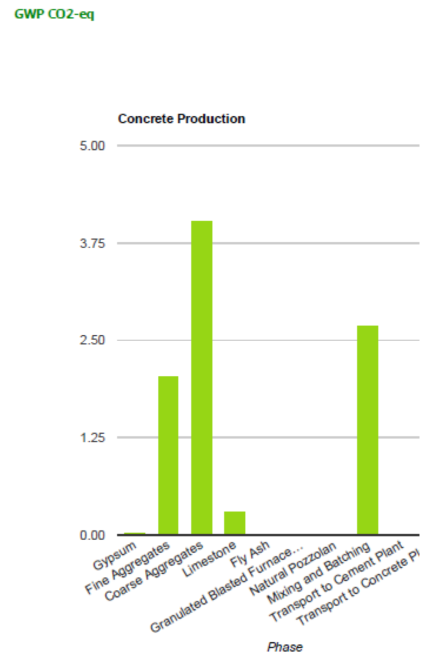




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

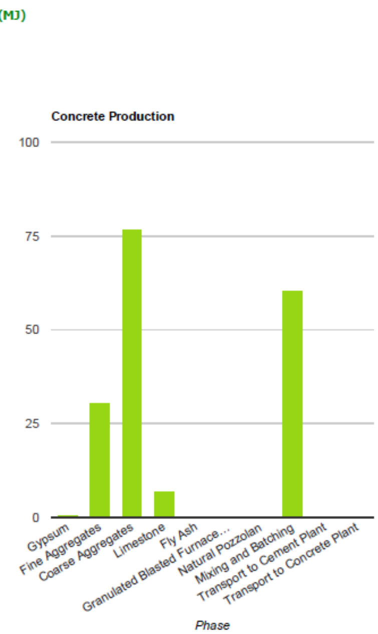
Figure C.11: Result with 0% limestone roller press

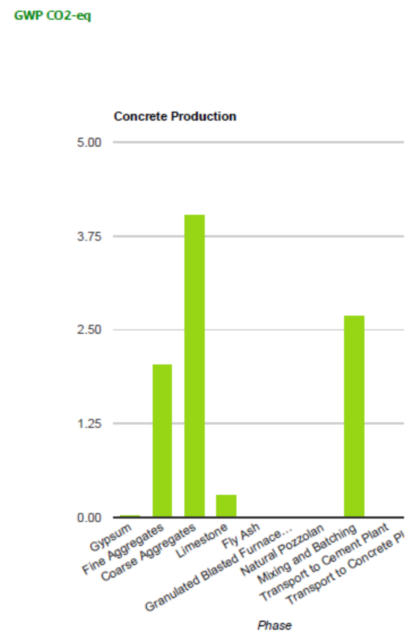




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

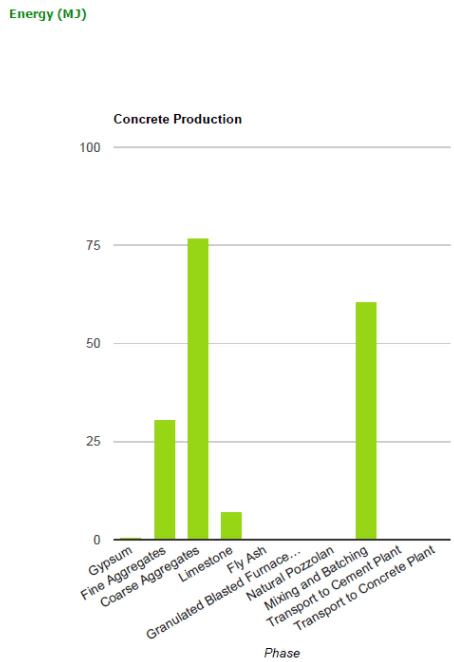
Figure C.12: Result with 0% limestone horizontal roller mill

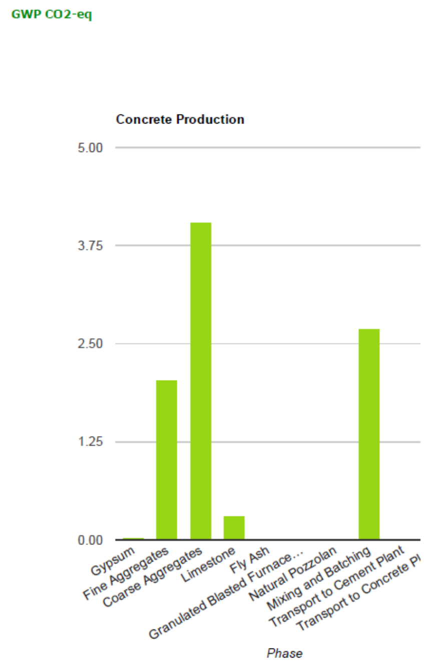




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

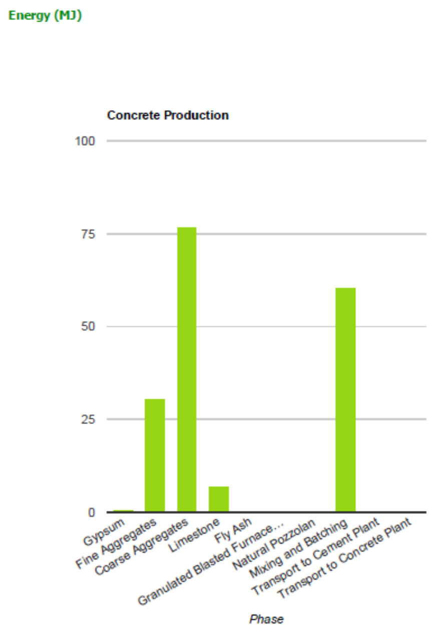
Figure C.13: Result with 0% limestone with electricity grid mix 2

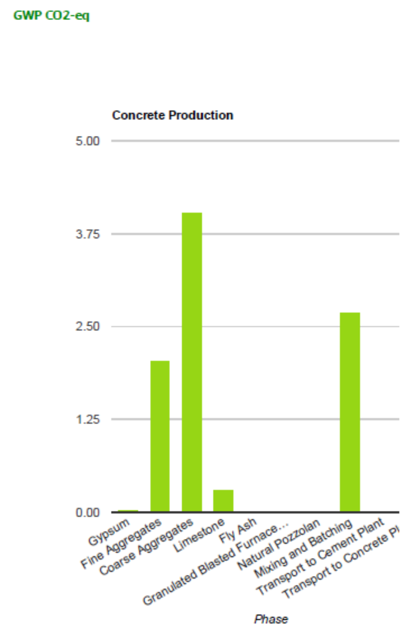




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.005	0.000	0.012	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

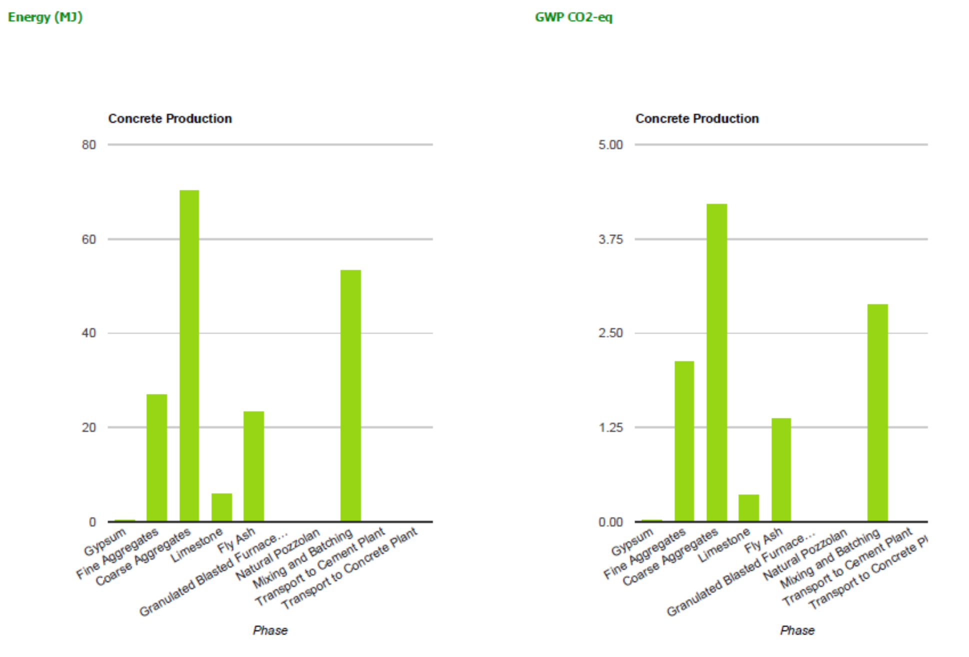
Figure C.14: Result with 0% limestone with electricity grid mix 3





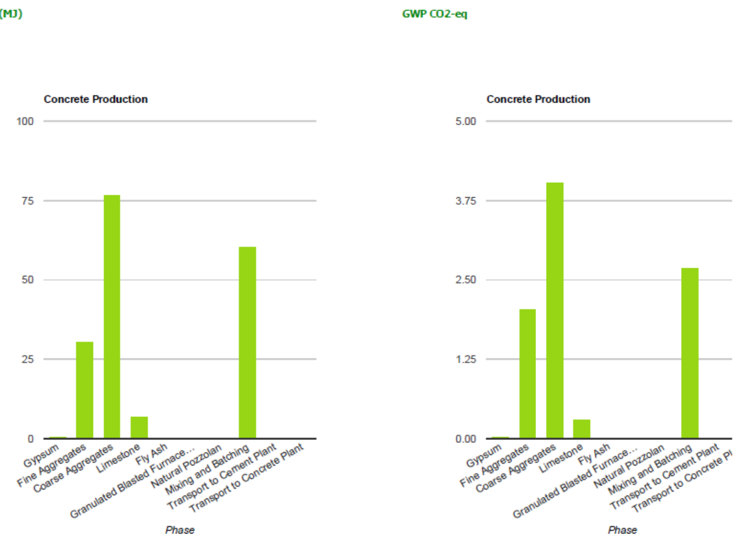
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.007	0.000	0.003	0.000	0.004	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.006	0.000	0.005	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	63.416	0.010	0.602	0.017	0.499	0.007
Cement: Clinker Cooling	0.002	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.008	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.002	0.000	0.001	0.002	0.009	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.15: Result with 0% limestone with electricity grid mix 4



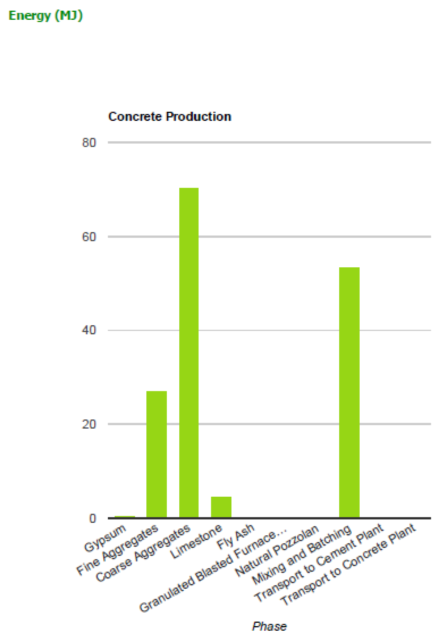
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.759	0.021	0.578	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.005	0.000	0.013	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

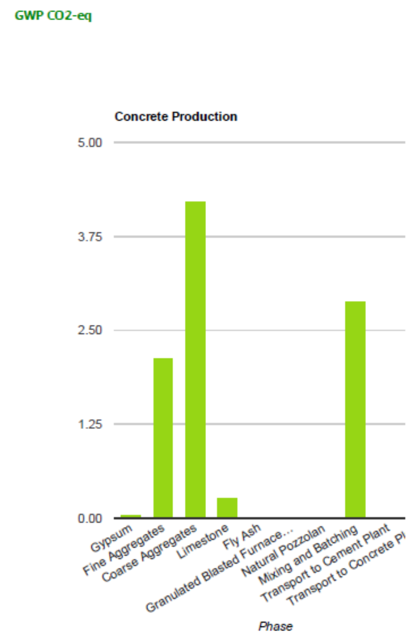
Figure C.16: Result with 5% limestone ball mill



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

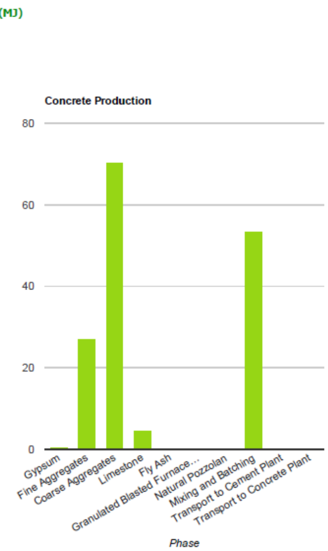
Figure C.17: Result with 5% limestone with fly ash

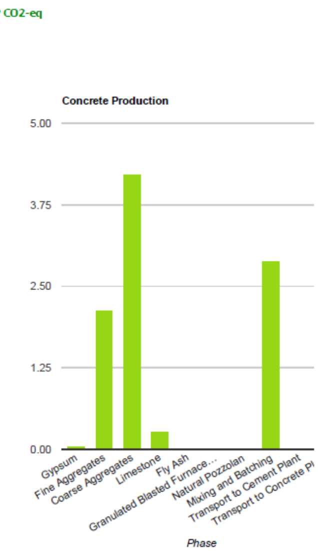




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

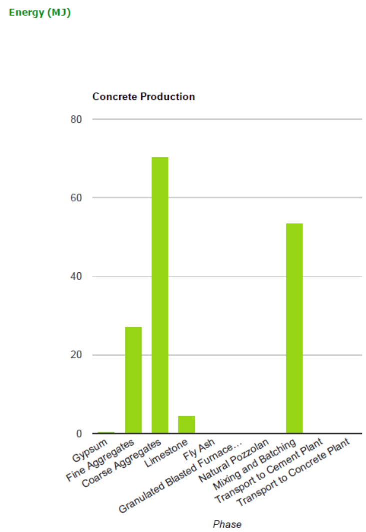
Figure C.18: Result with 5% limestone tube mill

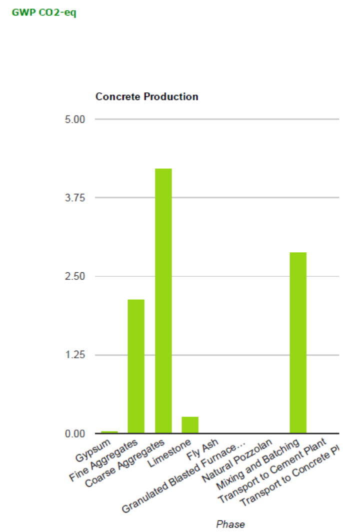




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

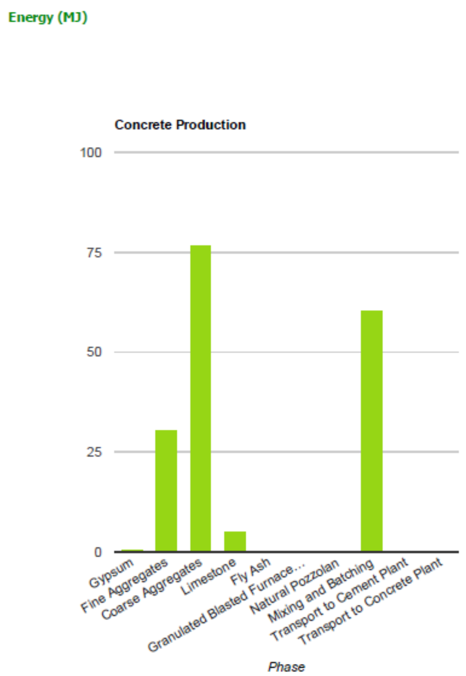
Figure C.19: Result with 5% limestone vertical roller mill

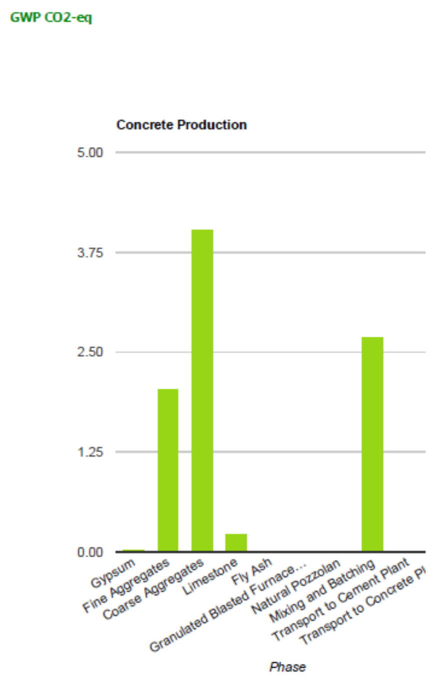




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

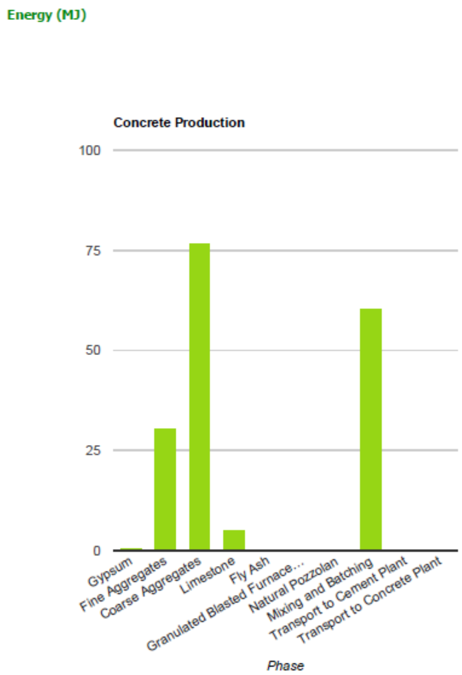
Figure C.20: Result with 5% limestone roller press

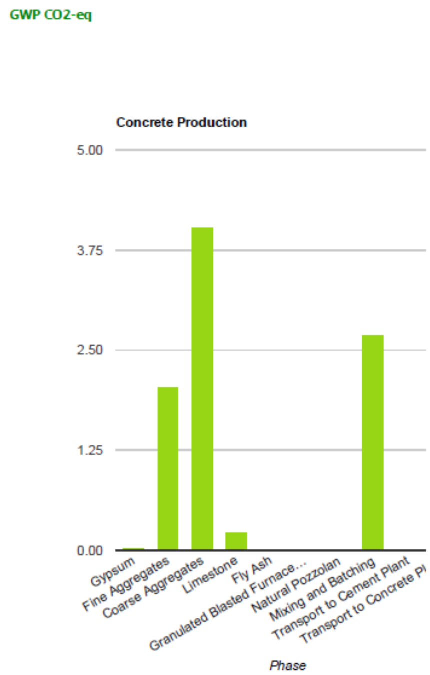




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

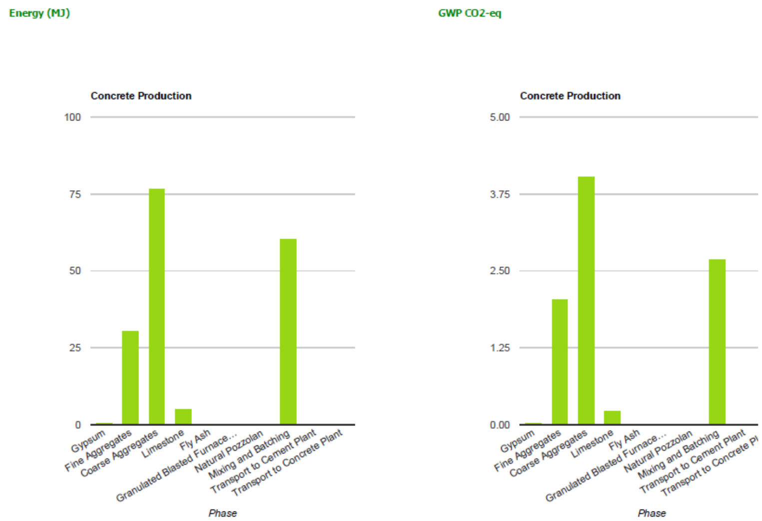
Figure C.21: Result with 5% limestone horizontal roller mill





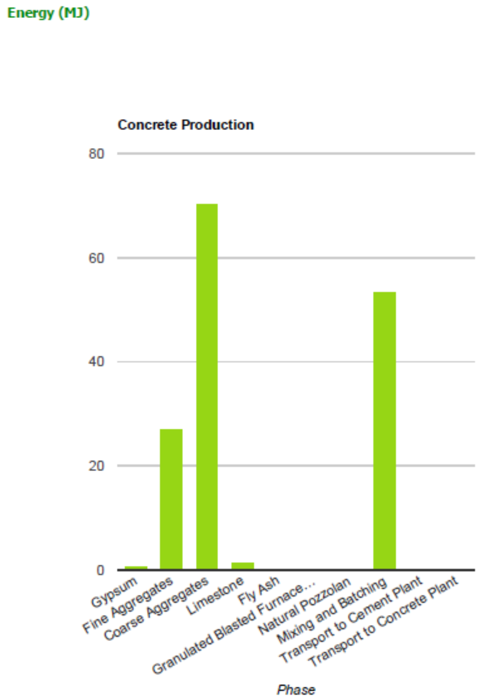
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

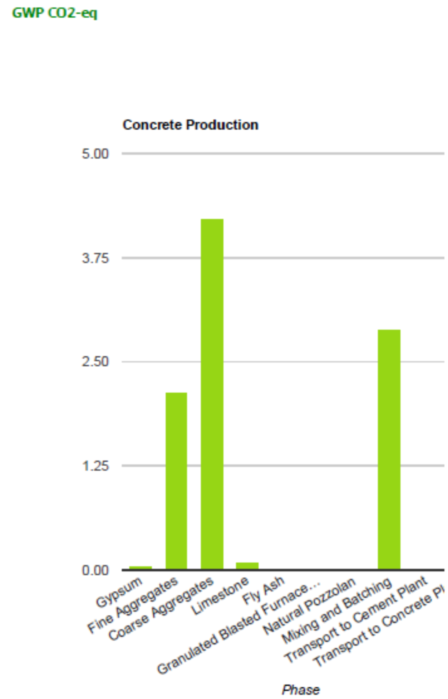
Figure C.22: Result with 5% limestone electricity grid mix 2



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.005	0.000	0.013	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.23: Result with 5% limestone electricity grid mix 3

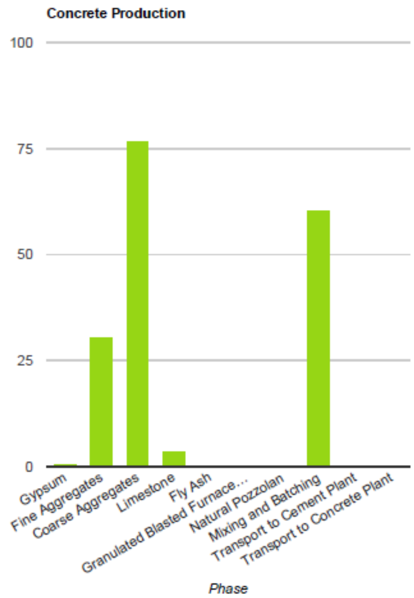




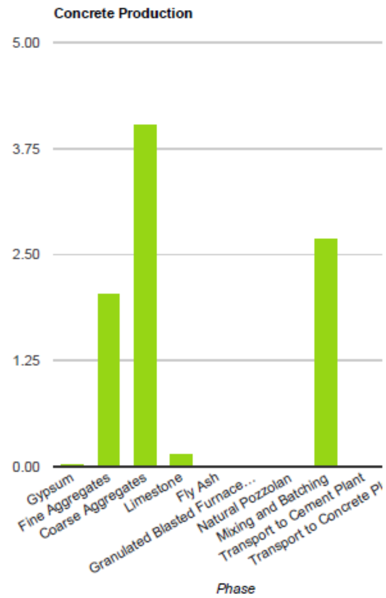
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.005	0.000	0.007	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.007	0.000	0.012	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	94.132	0.014	0.894	0.025	0.740	0.011
Cement: Clinker Cooling	0.003	0.000	0.002	0.000	0.004	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.016	0.000	0.013	0.000	0.021	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.074
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.23: Result with 5% limestone electricity grid mix 4

Energy (MJ)



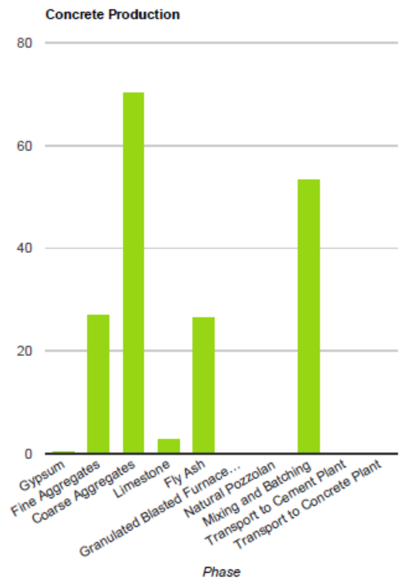
GWP CO2-eq



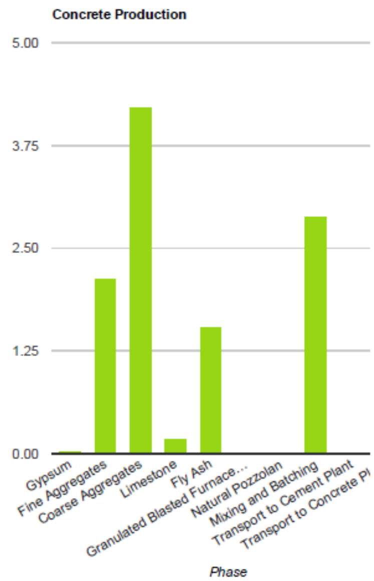
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	89.181	0.014	0.854	0.023	0.650	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.017	0.000	0.006	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.25: Result with 10% limestone ball mill

Energy (MJ)

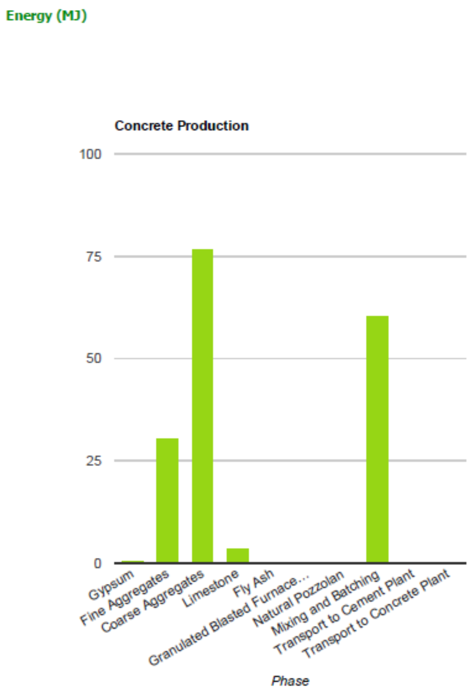


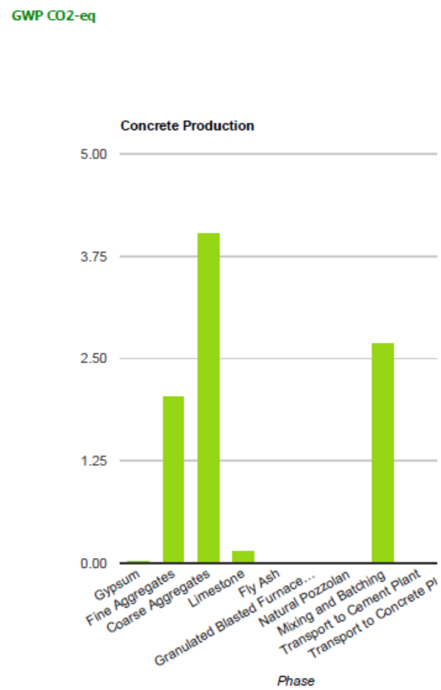
GWP CO2-eq



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.008	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.005	0.000	0.009	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	71.342	0.011	0.678	0.019	0.561	0.008
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.009	0.000	0.016	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.151
Fly Ash	0.002	0.000	0.002	0.002	0.010	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

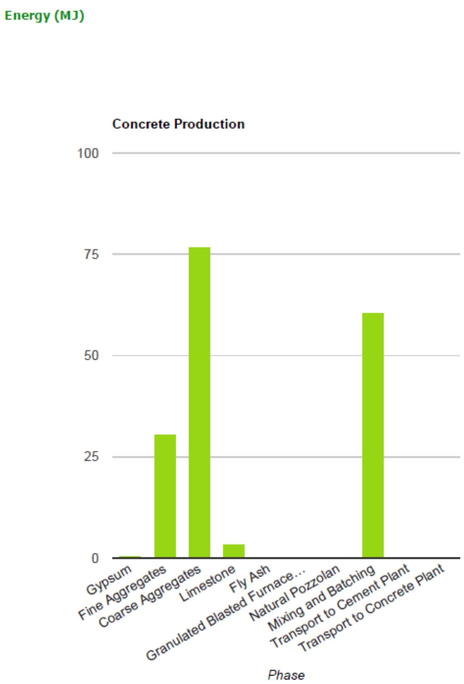
Figure C.26: Result with 10% limestone fly ash

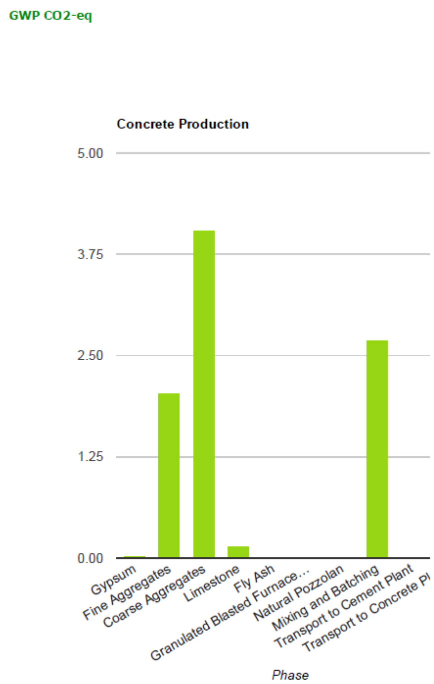




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	89.181	0.014	0.838	0.023	0.692	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.016	0.000	0.006	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

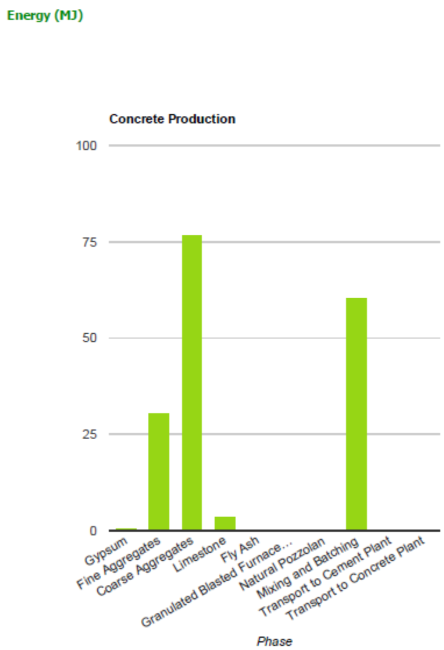
Figure C.27: Result with 10% limestone tube mill

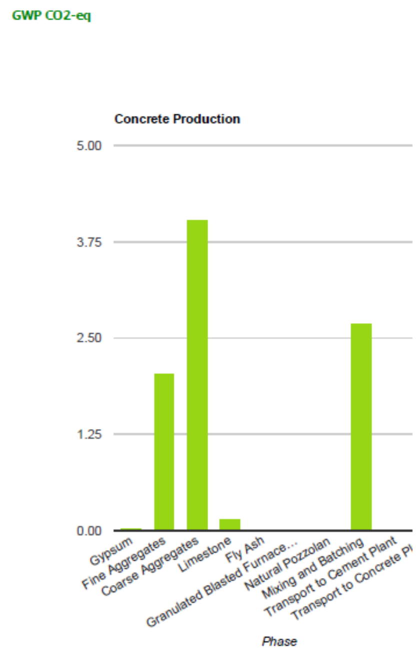




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	89.181	0.014	0.838	0.023	0.692	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

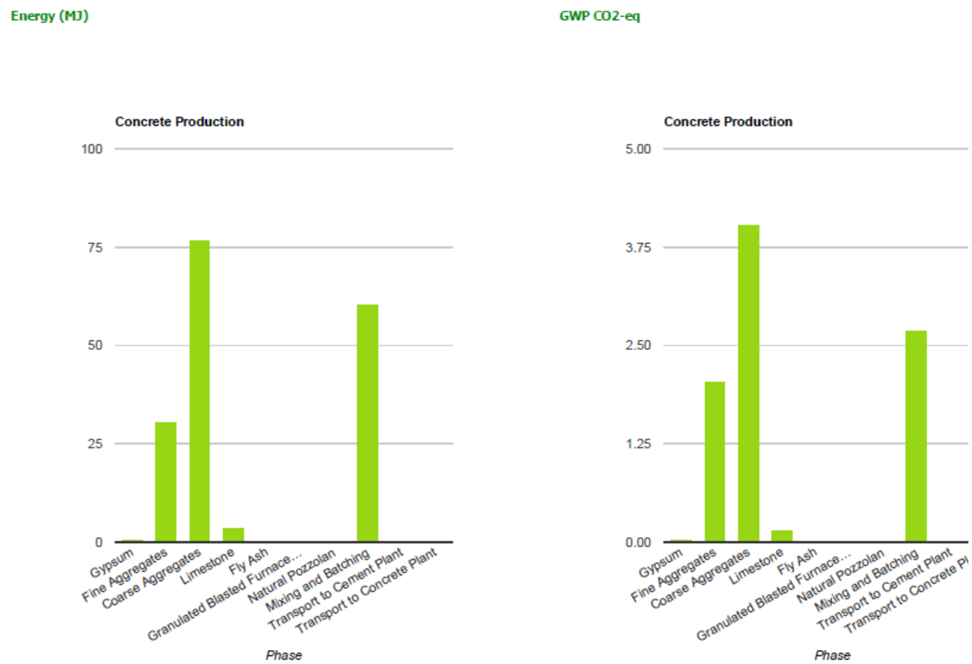
Figure C.28: Result with 10% limestone vertical roller mill





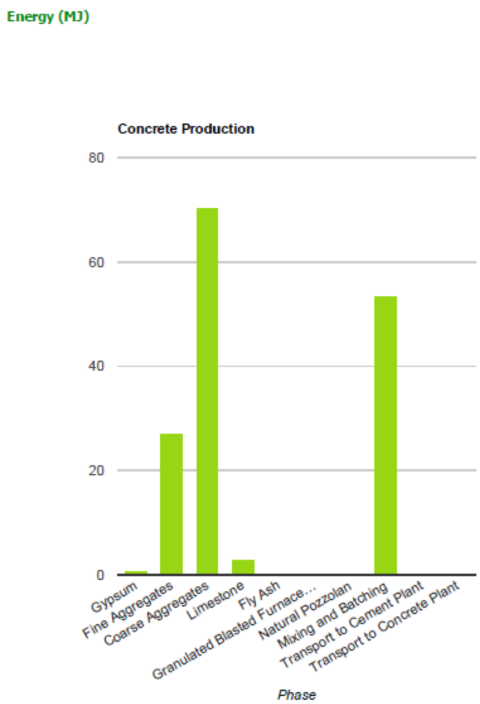
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	89.181	0.014	0.838	0.023	0.692	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

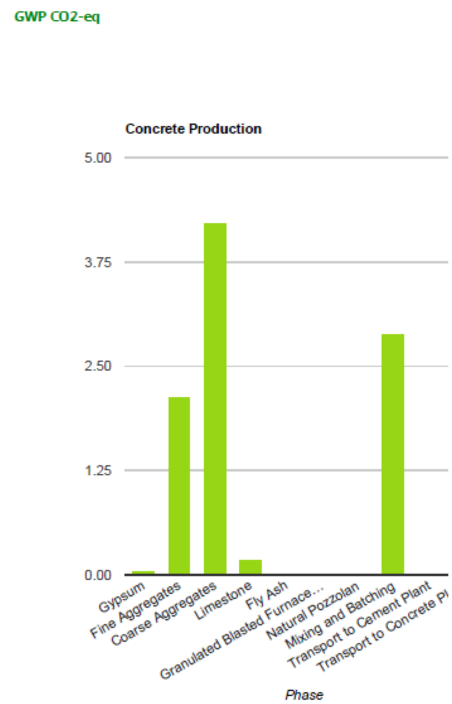
Figure C.29: Result with 10% limestone roller press



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	89.181	0.014	0.838	0.023	0.692	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.000	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

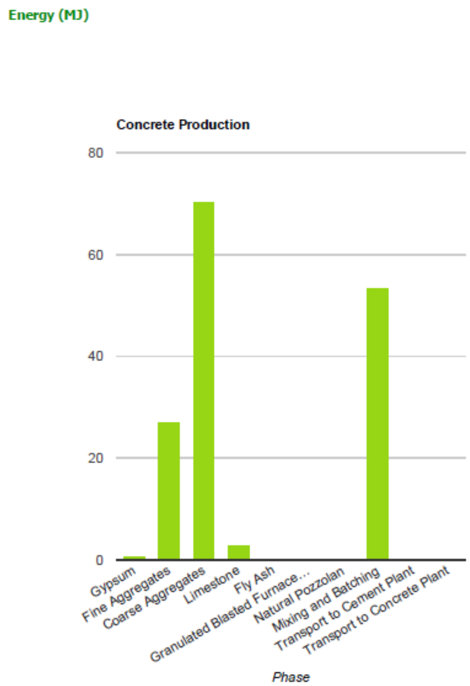
Figure C.30: Result with 10% limestone horizontal roller mill

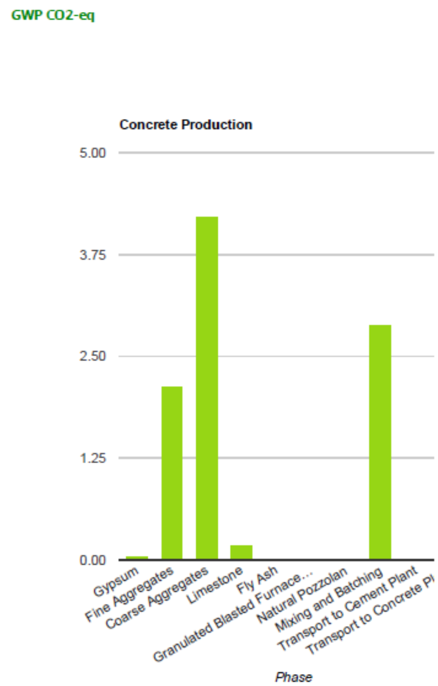




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.007	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	89.178	0.014	0.847	0.023	0.701	0.011
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

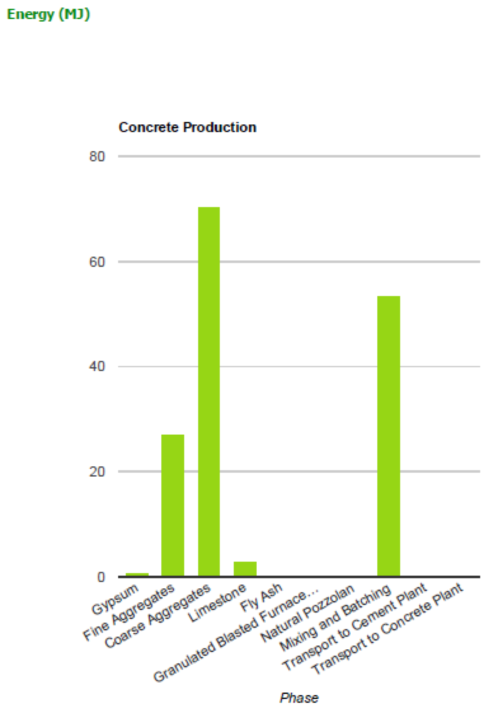
Figure C.31: Result with 10% limestone electricity grid mix 2

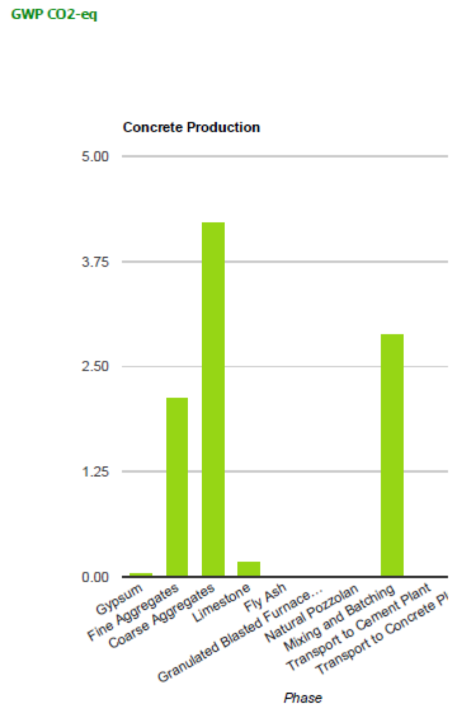




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.007	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	89.178	0.014	0.847	0.023	0.701	0.011
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

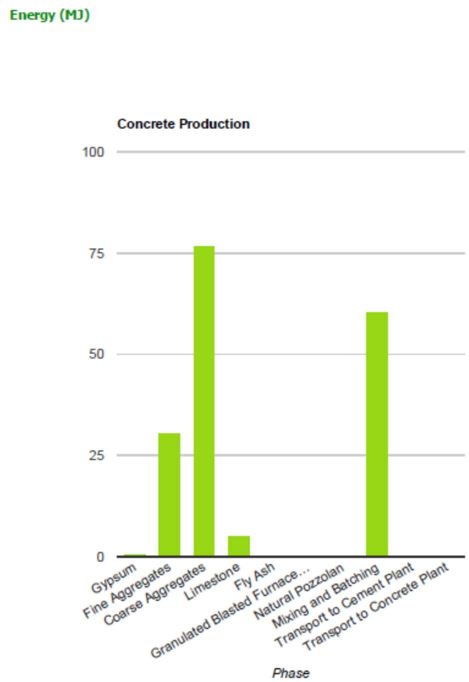
Figure C.32: Result with 10% limestone electricity grid mix 3

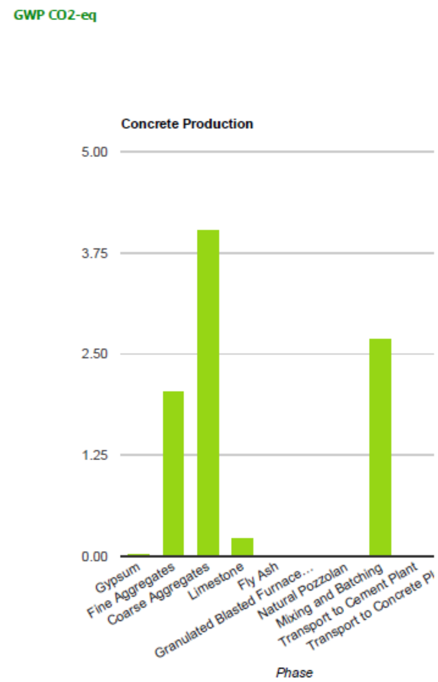




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.007	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	89.178	0.014	0.847	0.023	0.701	0.011
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.151
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

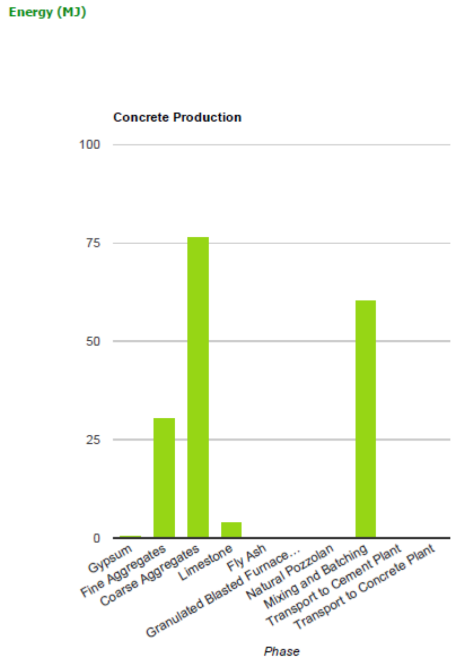
Figure C.32: Result with 10% limestone electricity grid mix 3

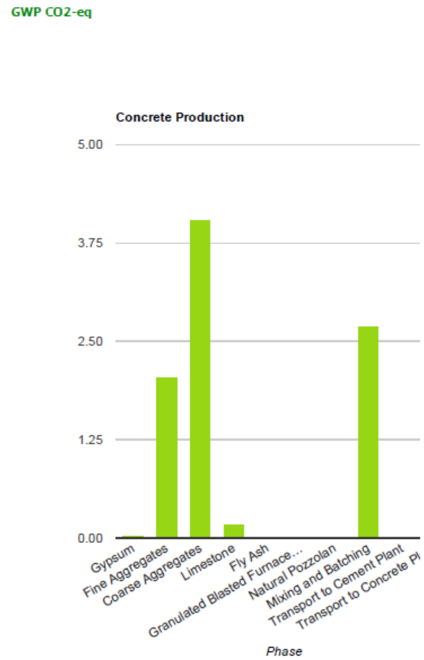




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.807	0.022	0.614	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.016	0.000	0.006	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

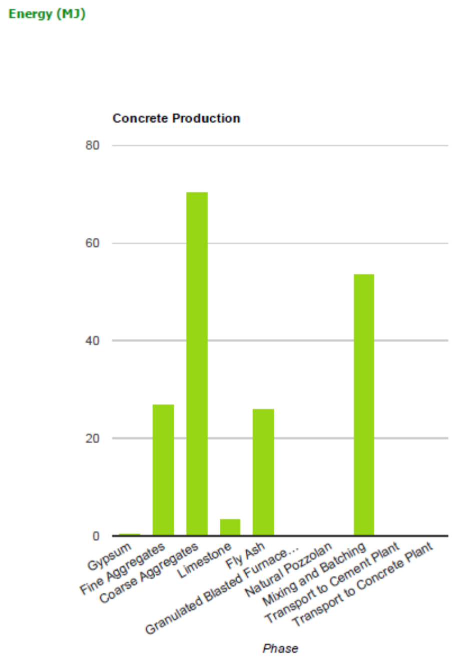
Figure C.33: Result with 10% limestone electricity grid mix 4

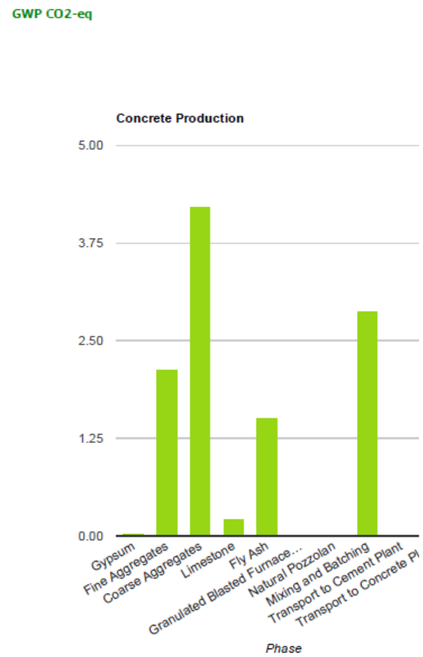




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	87.200	0.013	0.819	0.023	0.677	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.016	0.000	0.006	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

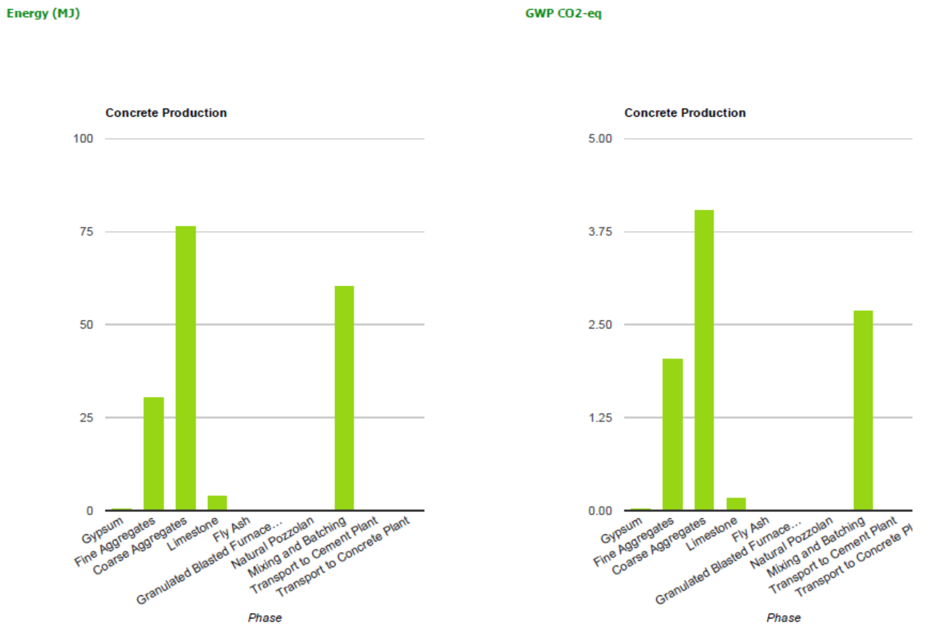
Figure C.34: Result with 12% limestone ball mill





Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.008	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.006	0.000	0.005	0.000	0.009	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	69.757	0.011	0.662	0.018	0.549	0.008
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.009	0.000	0.016	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.002	0.000	0.002	0.002	0.009	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

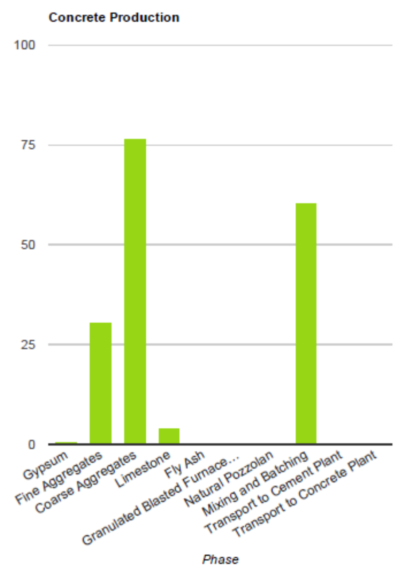
Figure C.35: Result with 12% limestone with fly ash



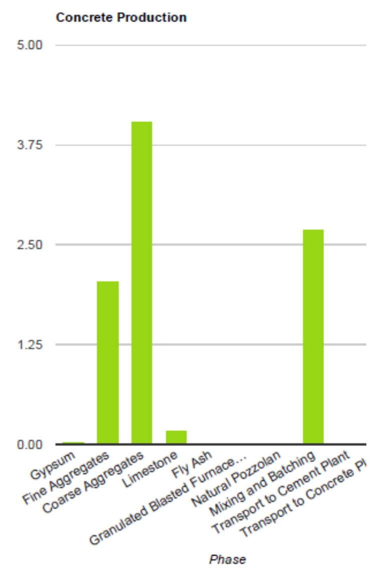
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	87.200	0.013	0.819	0.023	0.677	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.016	0.000	0.006	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.36: Result with 12% limestone tube mill

Energy (MJ)

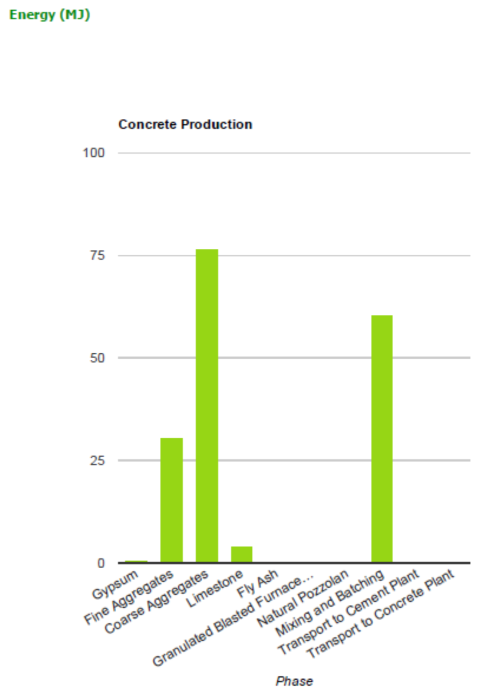


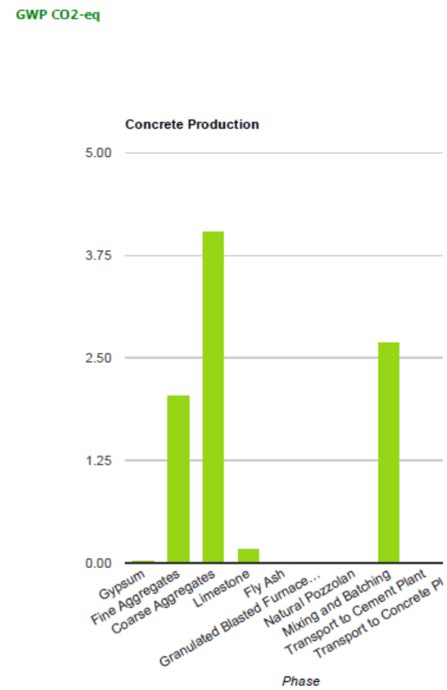
GWP CO2-eq



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	87.200	0.013	0.819	0.023	0.677	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

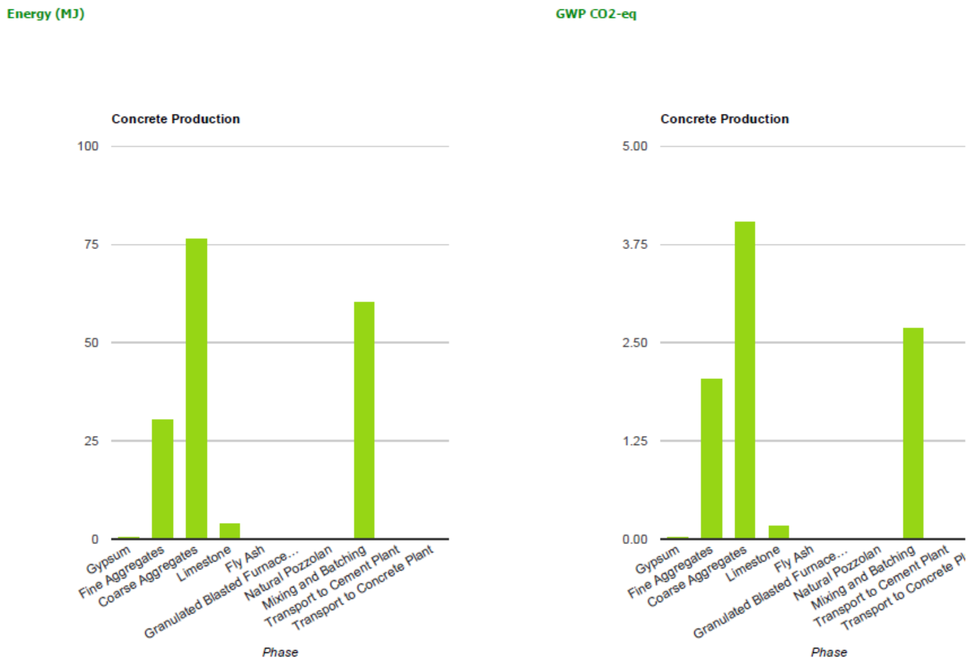
Figure C.37: Result with 12% limestone vertical roller mill





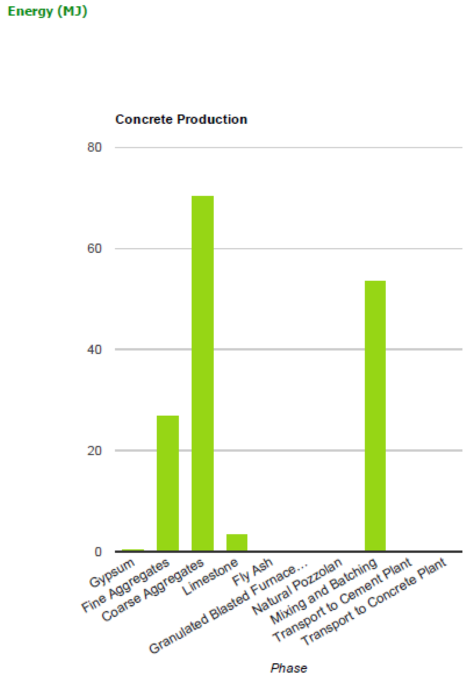
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	87.200	0.013	0.819	0.023	0.677	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

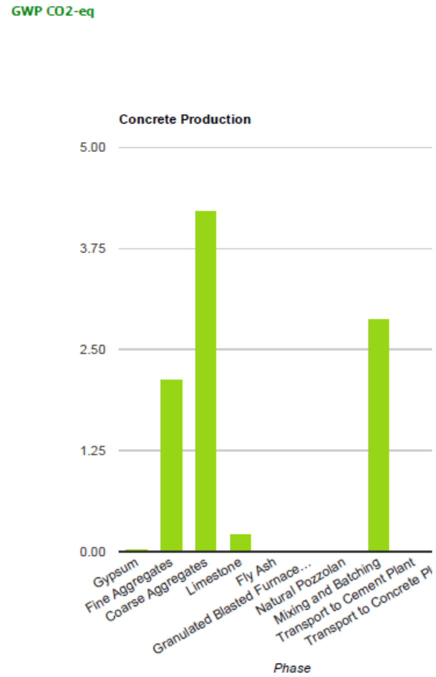
Figure C.38: Result with 12% limestone roller press



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	87.200	0.013	0.819	0.023	0.677	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.004	0.000	0.011	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

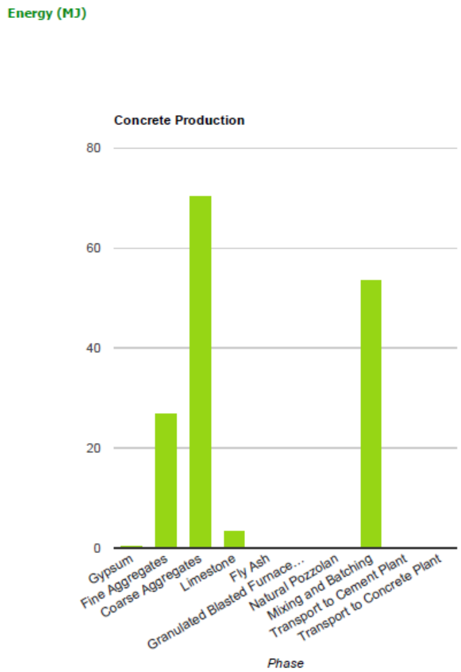
Figure C.39: Result with 12% limestone horizontal roller mill

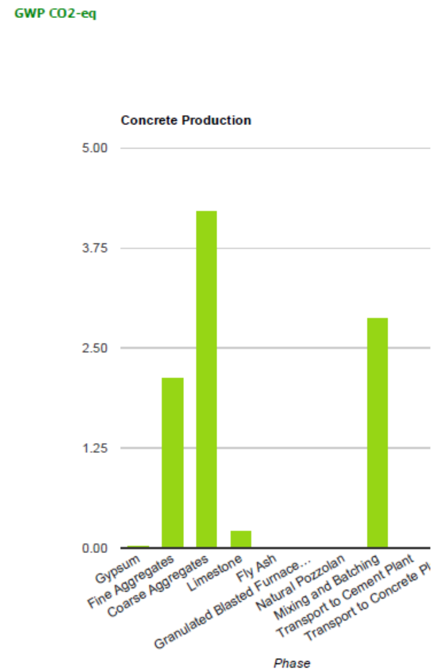




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	87.196	0.013	0.828	0.023	0.686	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.001	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

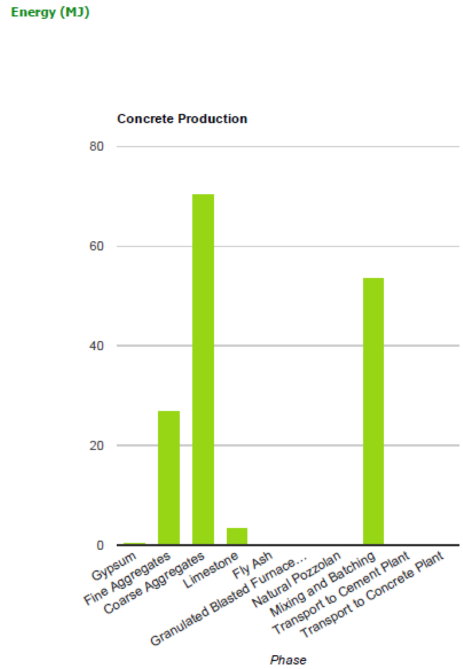
Figure C.40: Result with 12% limestone electricity grid mix 2

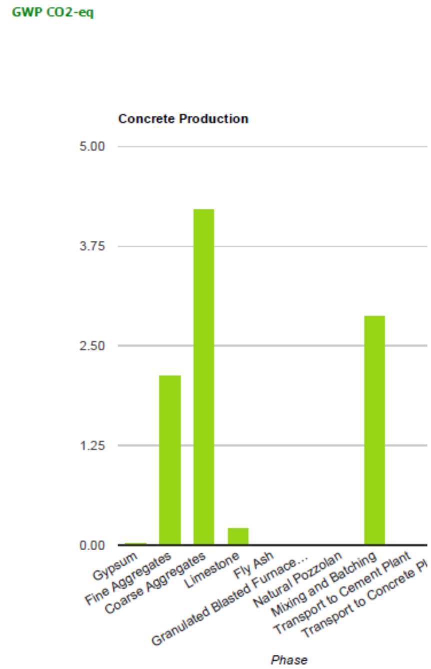




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	87.196	0.013	0.828	0.023	0.686	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.001	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

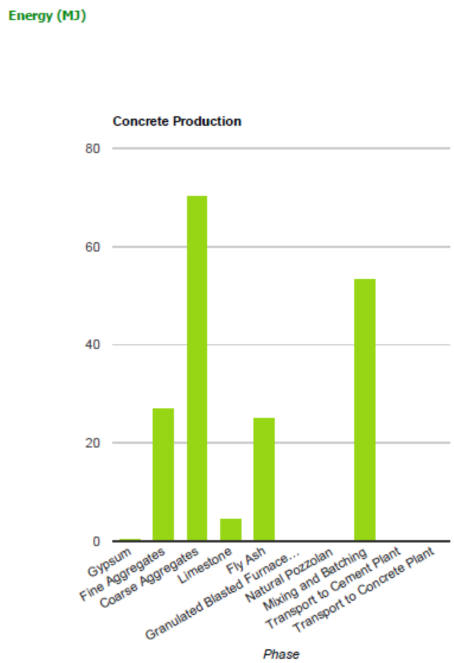
Figure C.41: Result with 12% limestone electricity grid mix 3

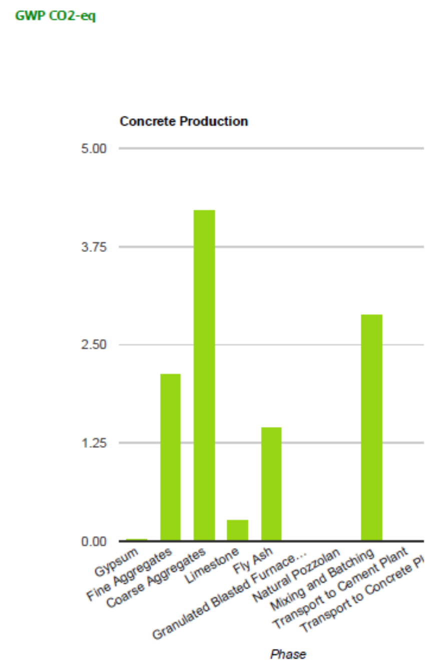




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.010	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.001	0.000
Cement: Pyroprocessing	87.196	0.013	0.828	0.023	0.686	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.012	0.000	0.020	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.001	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.000	0.000	0.000	0.000	0.001	0.181
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

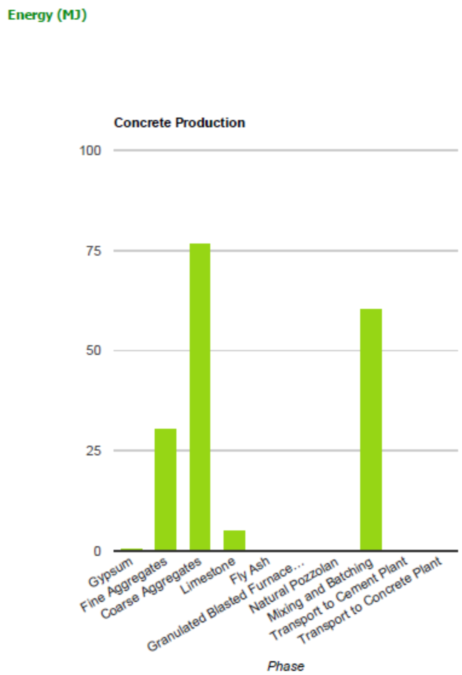
Figure C.42: Result with 12% limestone electricity grid mix 4

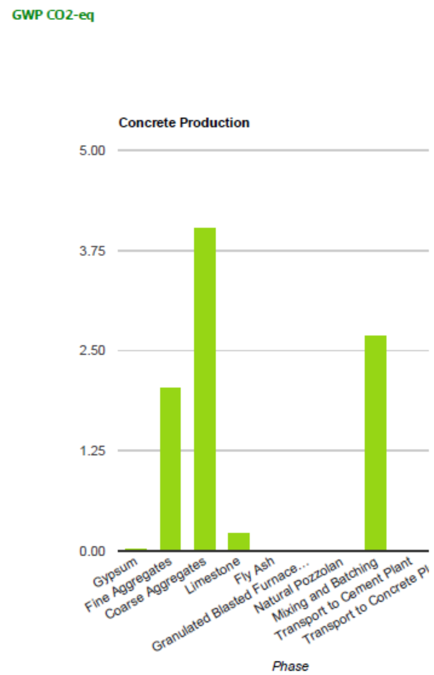




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.007	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.006	0.000	0.005	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	67.379	0.010	0.640	0.018	0.530	0.008
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.009	0.000	0.015	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.002	0.000	0.001	0.002	0.009	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

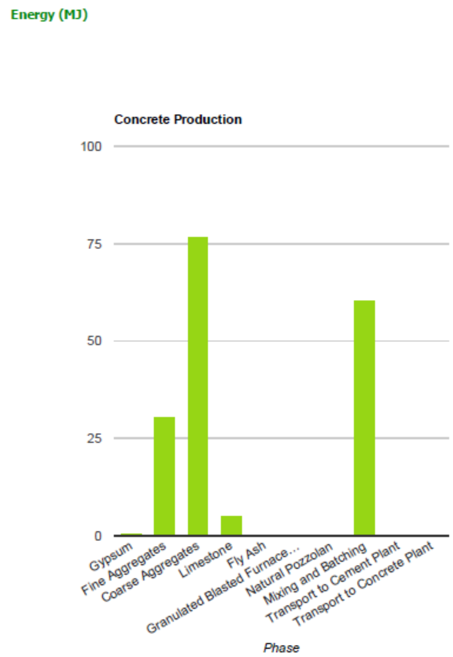
Figure C.43: Result with 15% limestone ball mill

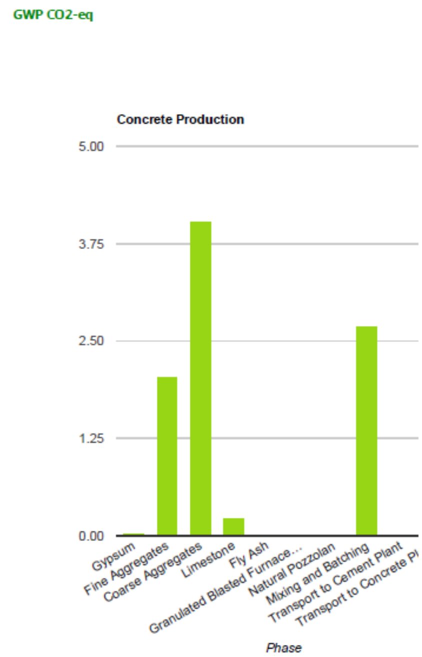




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.005	0.000	0.013	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

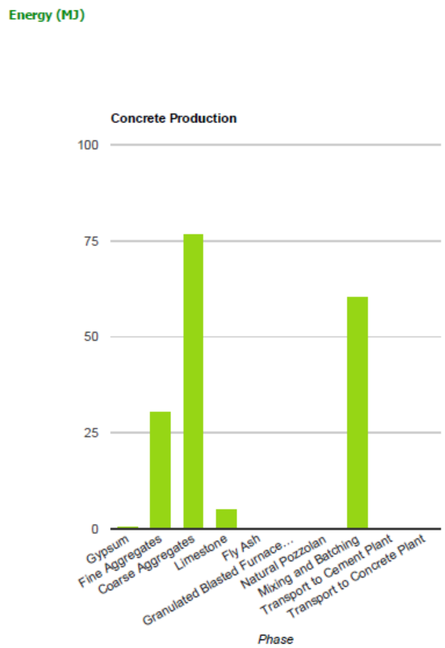
Figure C.44: Result with 15% limestone fly ash

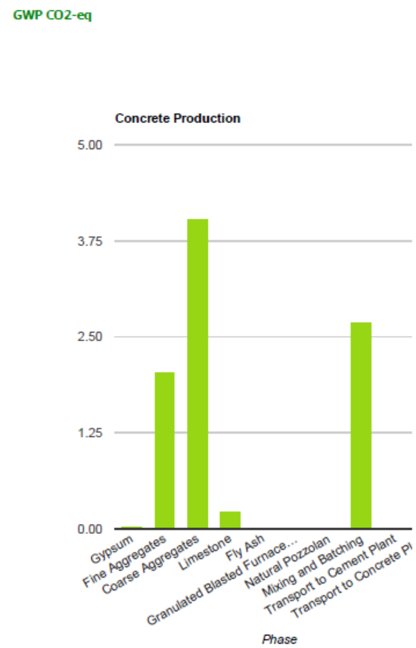




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

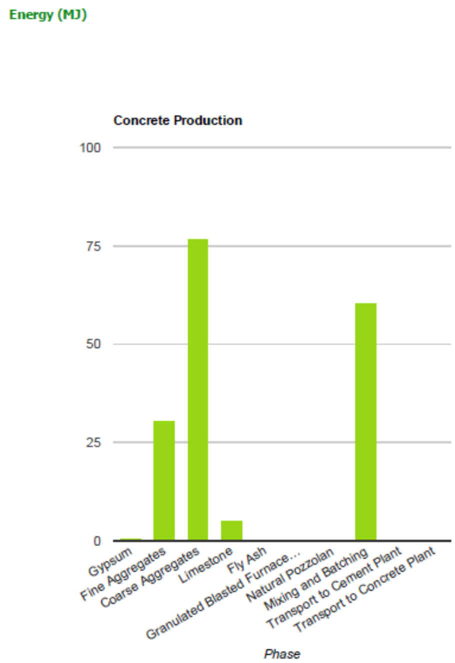
Figure C.45: Result with 15% limestone tube mill

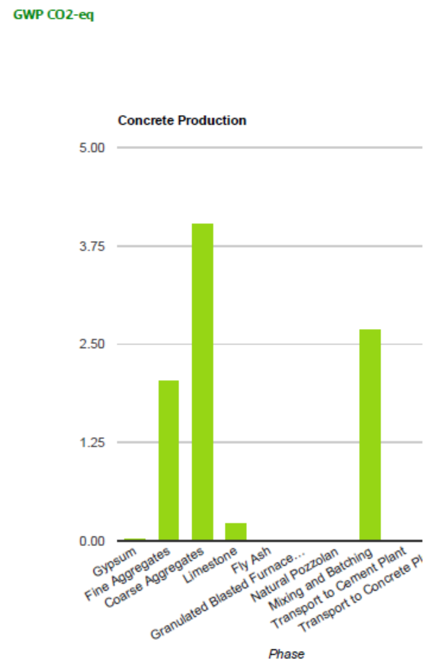




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

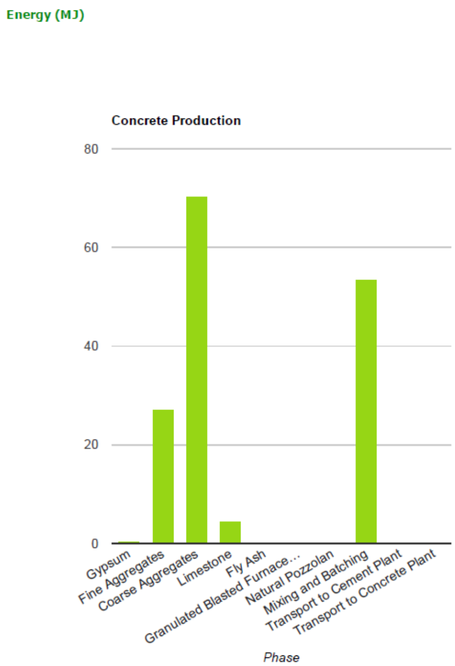
Figure C.46: Result with 15% limestone vertical roller mill

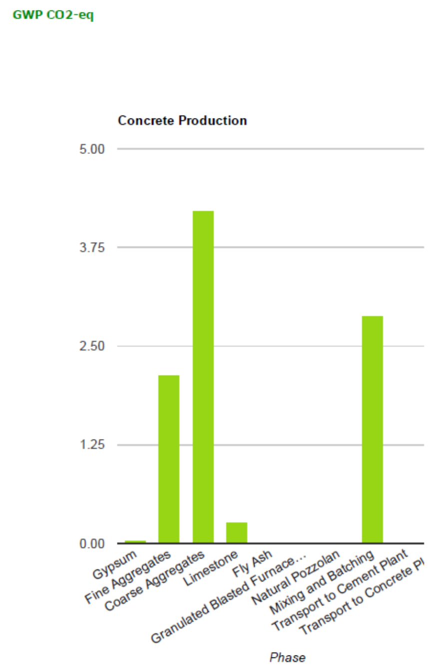




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.010	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.009	0.000	0.003	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.227	0.013	0.791	0.022	0.654	0.010
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.012	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

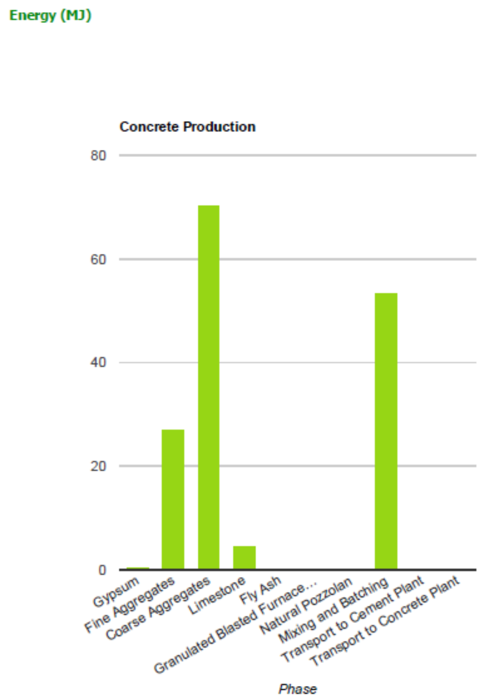
Figure C.47: Result with 15% limestone horizontal roller mill

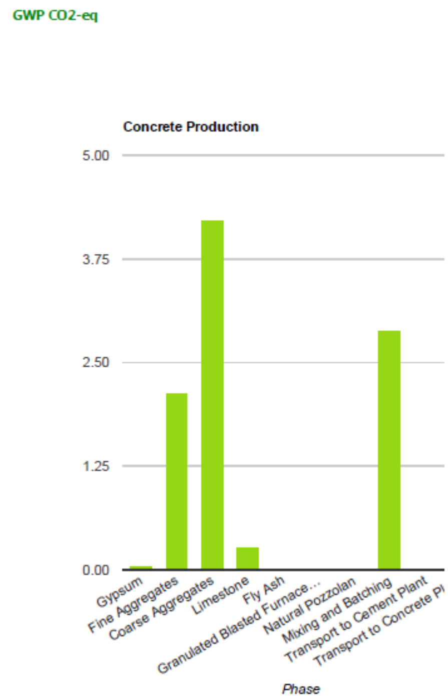




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.48: Result with 15% limestone electricity grid mix 2

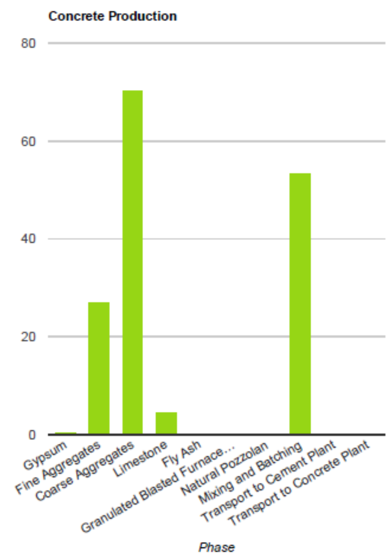




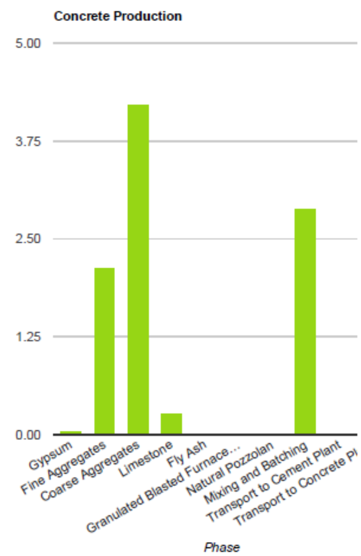
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.49: Result with 15% limestone electricity grid mix 3

Energy (MJ)

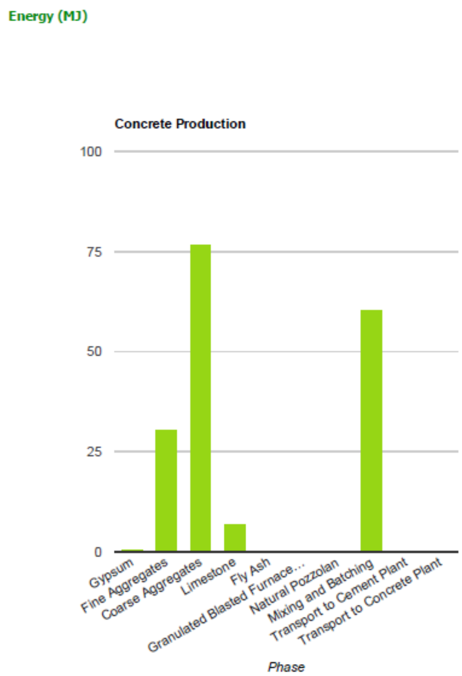


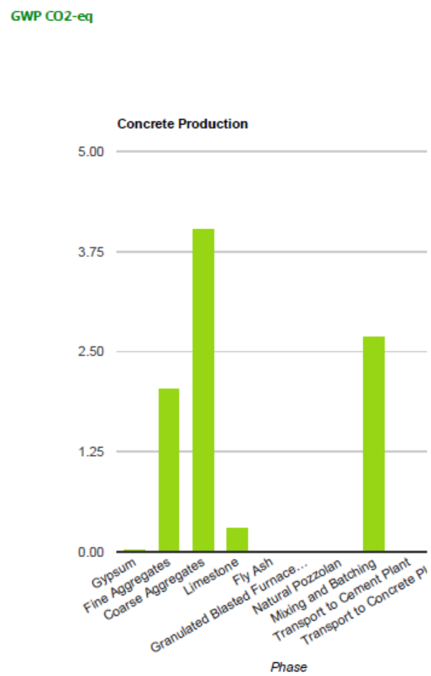
GWP CO2-eq



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.002	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.006	0.000	0.011	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	84.224	0.013	0.800	0.022	0.662	0.010
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.011	0.000	0.019	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.226
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

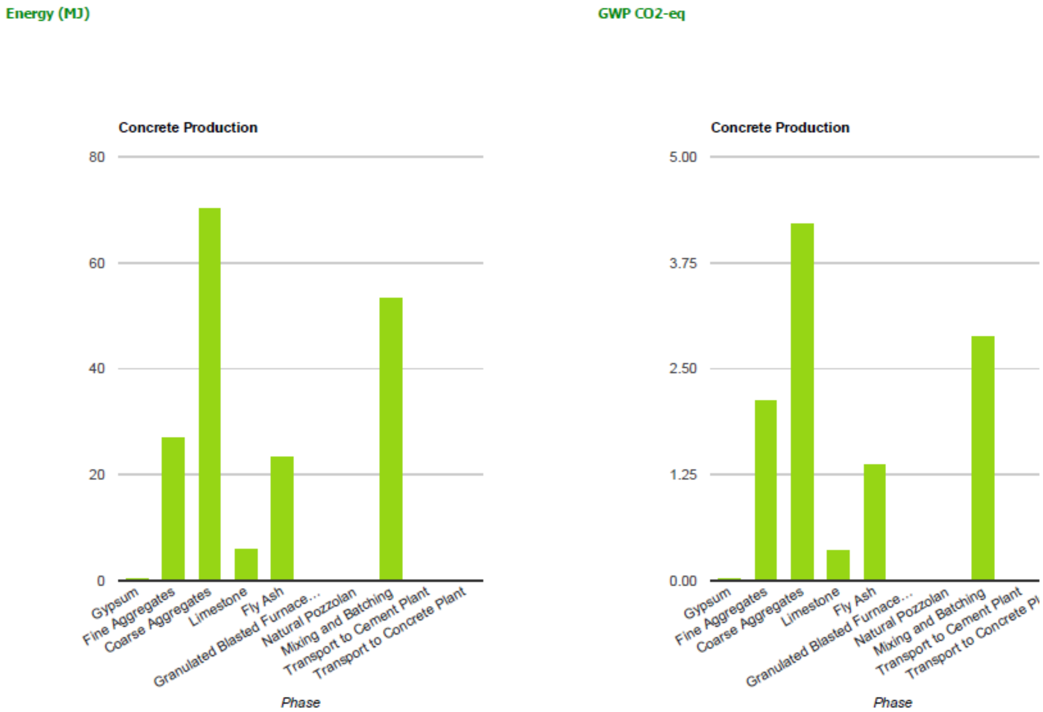
Figure C.50: Result with 15% limestone electricity grid mix 4





Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.759	0.021	0.578	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.015	0.000	0.005	0.000	0.013	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

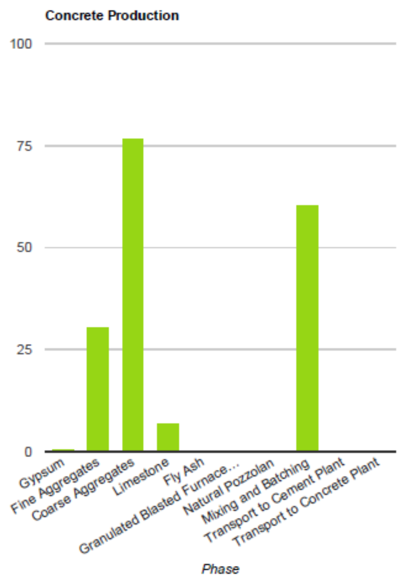
Figure C.51: Result with 20% limestone ball mill



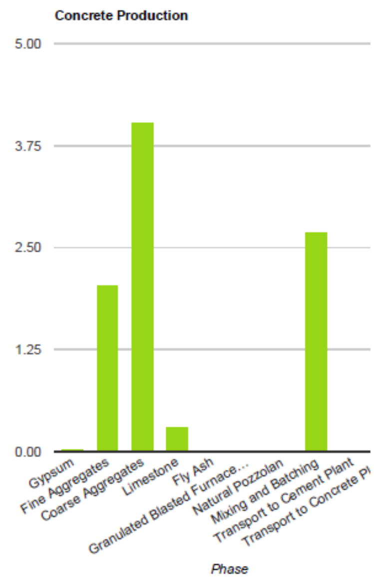
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.007	0.000	0.003	0.000	0.004	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.006	0.000	0.005	0.000	0.008	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	63.416	0.010	0.602	0.017	0.499	0.007
Cement: Clinker Cooling	0.002	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.008	0.000	0.014	0.000
Cement: In-Cement Plant Convey	0.001	0.000	0.000	0.000	0.001	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.002	0.000	0.001	0.002	0.009	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.52: Result with 20% limestone fly ash

Energy (MJ)

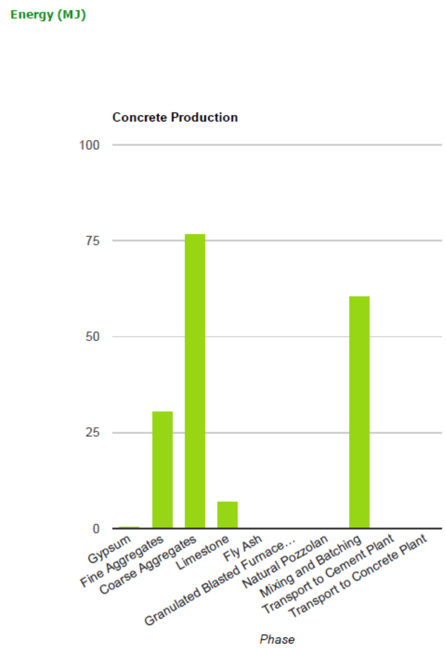


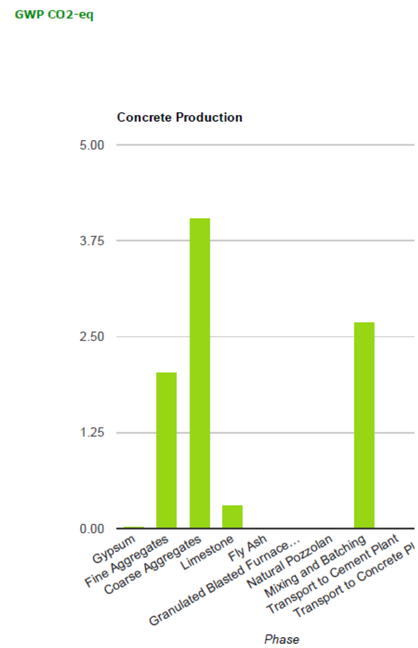
GWP CO2-eq



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.014	0.000	0.005	0.000	0.012	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

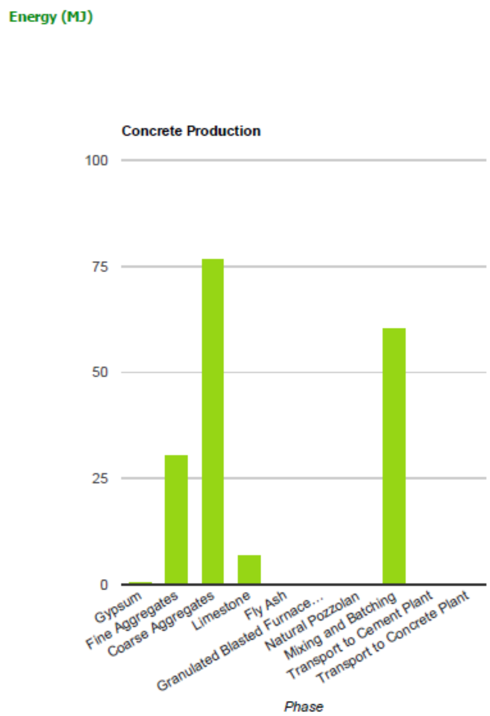
Figure C.53: Result with 20% limestone tube mill

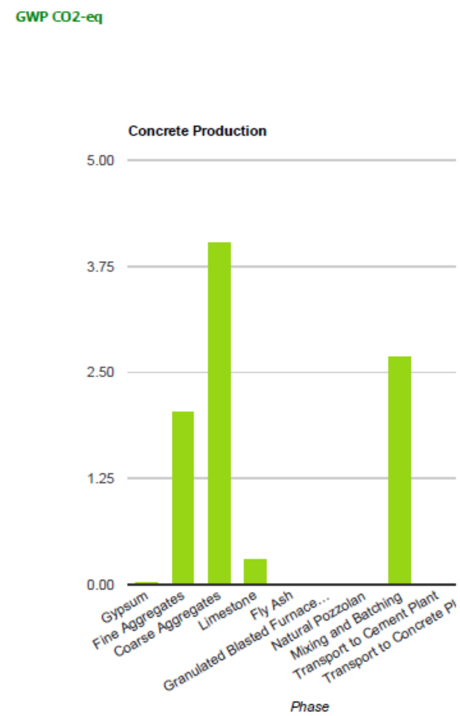




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.54: Result with 20% limestone vertical roller mill

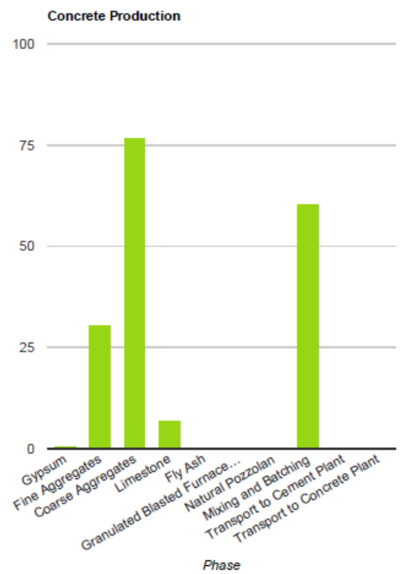




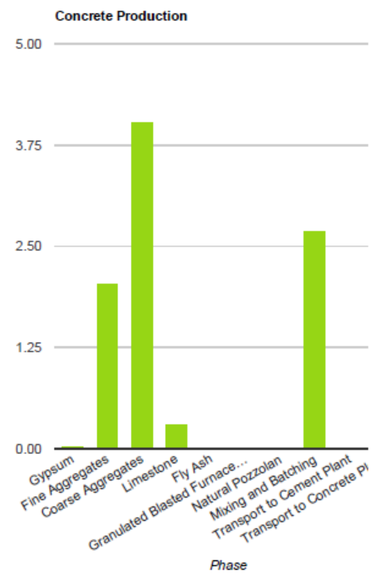
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.55: Result with 20% limestone roller press

Energy (MJ)



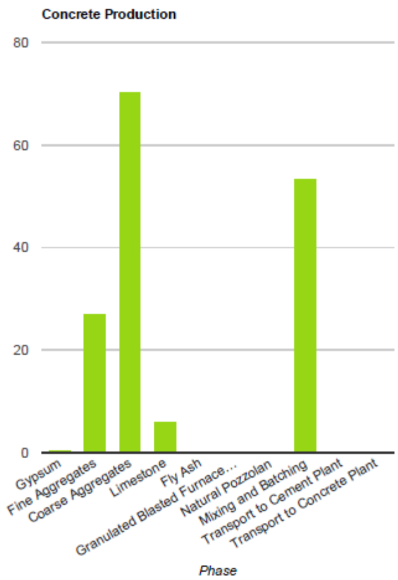
GWP CO2-eq



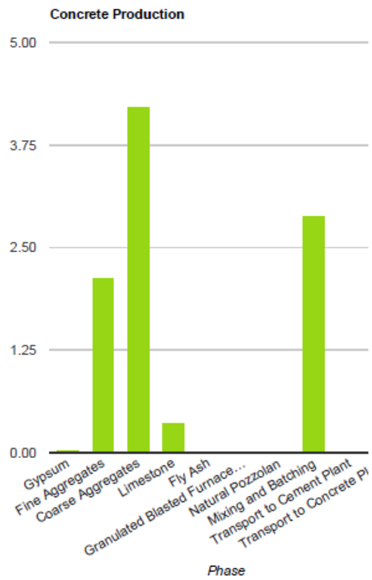
Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.003	0.019	0.005	0.000
Coarse Aggregates	0.018	0.000	0.005	0.028	0.009	0.000
Cement: Quarrying	0.009	0.000	0.003	0.000	0.005	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.008	0.000	0.003	0.000	0.007	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.272	0.012	0.745	0.021	0.615	0.009
Cement: Clinker Cooling	0.003	0.000	0.001	0.000	0.002	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.011	0.000	0.004	0.000	0.010	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.000	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.006	0.000	0.003	0.000	0.005	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.56: Result with 20% limestone horizontal roller mill

Energy (MJ)

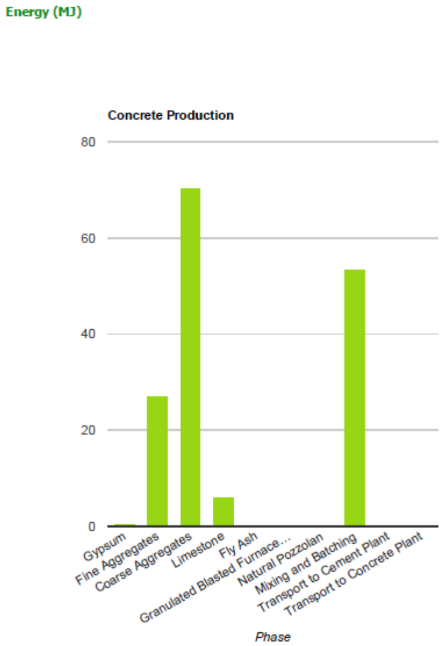


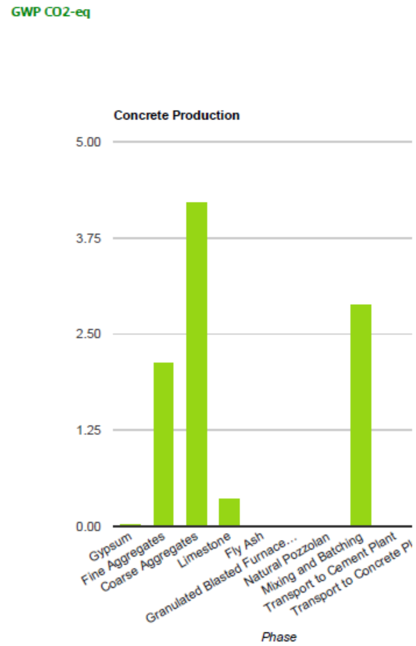
GWP CO2-eq



Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

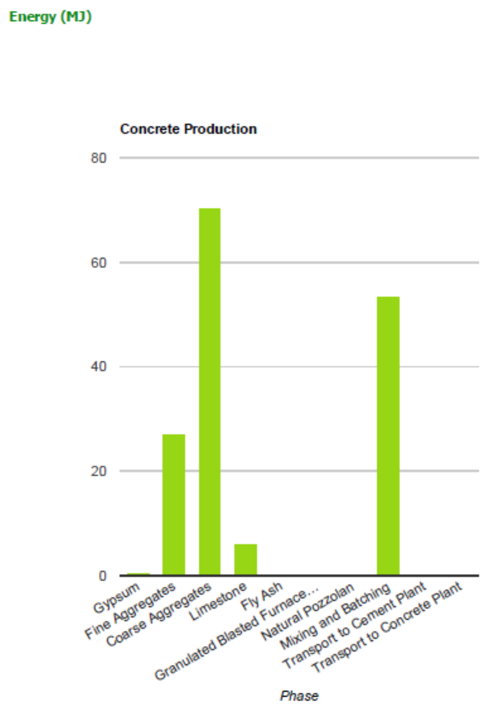
Figure C.57: Result with 20% limestone electricity grid mix 2

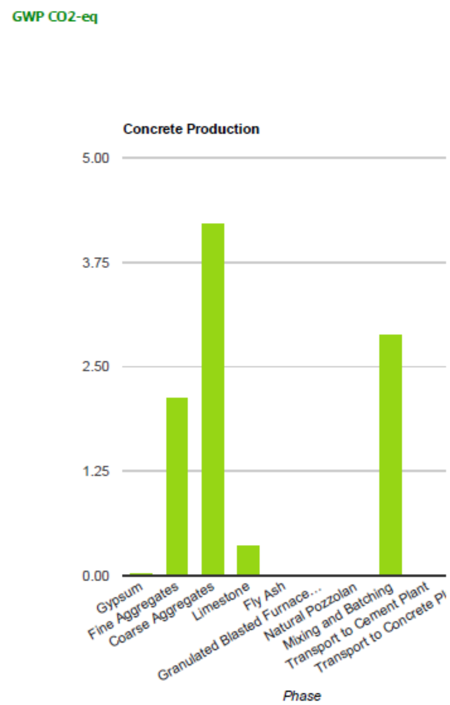




Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.58: Result with 20% limestone electricity grid mix 3





Phase	CO (kg)	Lead (kg)	NOx (kg)	PM10 (kg)	SO2 (kg)	VOC (kg)
Gypsum	0.000	0.000	0.000	0.001	0.000	0.000
Fine Aggregates	0.008	0.000	0.004	0.019	0.006	0.000
Coarse Aggregates	0.017	0.000	0.006	0.028	0.010	0.000
Cement: Quarrying	0.009	0.000	0.004	0.000	0.006	0.000
Cement: Raw Materials Prehomogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Raw Materials Grinding	0.007	0.000	0.006	0.000	0.010	0.000
Cement: Raw Meal Blending/Homogenization	0.000	0.000	0.000	0.000	0.000	0.000
Cement: Pyroprocessing	79.269	0.012	0.753	0.021	0.623	0.009
Cement: Clinker Cooling	0.002	0.000	0.002	0.000	0.003	0.000
Cement: Finish Milling and Grinding and Blending with PC	0.013	0.000	0.011	0.000	0.018	0.000
Cement: In-Cement Plant Convey	0.000	0.000	0.000	0.000	0.000	0.000
Fly Ash in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blast Furnace Slag in Cement	0.000	0.000	0.000	0.000	0.000	0.000
Plasticiser	0.000	0.000	0.000	0.000	0.000	0.000
Superplasticiser	0.002	0.000	0.006	0.000	0.011	0.001
Retarder	0.000	0.000	0.000	0.000	0.000	0.000
Accelerating Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Air Entraining Admixture	0.000	0.000	0.000	0.000	0.000	0.000
Waterproofing	0.000	0.000	0.000	0.000	0.000	0.000
Limestone	0.001	0.000	0.001	0.000	0.001	0.301
Fly Ash	0.000	0.000	0.000	0.000	0.000	0.000
Granulated Blasted Furnace Slag	0.000	0.000	0.000	0.000	0.000	0.000
Natural Pozzolan	0.000	0.000	0.000	0.000	0.000	0.000
Mixing and Batching	0.005	0.000	0.004	0.000	0.007	0.000
Transport to Cement Plant	0.000	0.000	0.000	0.000	0.000	0.000
Transport to Concrete Plant	0.000	0.000	0.000	0.000	0.000	0.000

Figure C.59: Result with 20% limestone electricity grid mix 4