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Life Cycle Analysis of Kuert Concrete
Collaboration with Kuert Concrete, INC.
University of Notre Dame – Green Scale Research Project

Environmental Life Cycle Inventory and Analysis of Kuert Standard Batch Concrete and Slag Additive Concrete

Investigative Research into the Pavement Industry: A Case Study on the Consequences of Locally Sourced Construction Materials

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Definitions and Abbreviations

Life cycle assessment (LCA). A systematic method for compiling and examining the inputs and outputs of energy and materials and the environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle.

System boundary. Interface between the product or service system being studied and its environment or other systems. The system boundary defines the segment of the production process being studied.

Functional unit. Standard unit measure of the functional output of the product system; for example, in the following LCI the functional unit is one cubic yard of pavers (169.8 pavers).

Ancillary material. Material input that is used by the system producing the product but is not used directly in product manufacturing; for example, water used for washing the aggregate.

Embodied Energy. The amount of energy that is consumed during the manufacturing processes of a product in order to make it into a form that is usable. This is not to be confused with (chemical) potential energy. Embodied Energy is abbreviated as EE in this report.

Btu. British thermal units, measure of energy.

MJ. Mega Joules, measure of energy.

CO_2. Carbon Dioxide.

CO_2E. Carbon Dioxide Equivalent (CO_2-equivalent). Amount of carbon dioxide plus quantities of other harmful greenhouse gasses multiplied by a factor of how many times as harmful the gas is to the atmosphere.

NO_x. Mono-nitrogen oxides.

GWP. Global Warming Potential, measured in kg CO_2 or kg CO_2-equivalent.

Section 1: Overview

1.1 Purpose

This report represents a study done on three batch mixes of concrete manufactured by Kuert Concrete, Inc., based in South Bend, IN. It presents data on the Life Cycle of the products as their raw materials are gathered from various Midwestern United States, processed accordingly, shipped as necessary, and brought together at either of Kuert's facilities in Leesburg or Rochester, IN. The report consists of a Life Cycle Inventory of each of the mixes under study, including the standard cement concrete, the 20% slag mix concrete, and a hypothetical 40% slag mix concrete. The purpose of this comparison is to determine the degree to which localization of data becomes relevant in the calculated values of embodied energy, embodied water, and greenhouse gas emission over the life spans of the concrete products. In presenting the data, this report follows the guidelines presented by the International Organization for Standardization (ISO) in ISO 14040, "Environmental Management – Life Cycle Assessment – Principles and framework" and ISO 14044, "Environmental Management – Life Cycle Assessment – Requirements and guidelines," as wells as other ISO publications on conducting Life Cycle Assessments.[1][2]

1.2 Relevance of data

This data is specifically relevant to Kuert Concrete, Inc. in its presentation of the difference between the environmental impact of the current situation and a proposed alternative. In a broader sense, this study is an example of the effect the use of local materials in carbon emissions and embodied energy, especially in its comparison to industry standard concrete and other pavement products manufactured and/or distributed by Kuert Concrete, Inc.

As a standard-format Life Cycle Analysis, this report will present the goals toward which the study has worked as well as the boundary definitions of the project. The Life Cycle Inventory will present the embodied energy and carbon emissions directly associated with the manufacturing process of the concrete, and the impact assessment will evaluate the environmental impacts the process generates. In an effort to contextualize the information gathered by the study, an interpretation will follow.

1.3 Information Sources

Data is gathered from a number of online sources, including EIA and EPA databases and documents, as well as the Inventory of Carbon and Energy out of Bath, England. Data regarding the manufacturing of concrete from imported materials in Kuert's facilities was provided by Kuert Concrete, Inc. and companies with which Kuert cooperates.

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[1] ISO 14040 (2006): Environmental management – Life cycle assessment – Principles and framework, International Organization for Standardization (ISO), Geneva

[2] ISO 14044 (2006): Environmental management – Life cycle assessment – Requirements and guidelines, International Organization for Standardization (ISO), Geneva

Section 2: Introduction

2.1 Background

As a measure of the environmental impacts of a product, a Life Cycle Analysis should be comprehensive and detailed so that each environmental impact factor is assessed in its entirety. Thus, this report strives to make a detailed account of the product system under study and thorough in its analysis.

The most-consumed building material globally[3], concrete production has been made efficient, cost effective, and consistent. However, there is still a non-negligible difference in concrete from one manufacturer to another. The major difference is in the embodied energy of the concrete, which largely depends on the sources of the ingredients in the batch mix. The effect of the materials that enter the product system is related to the method of extraction of these materials, how far they are shipped over their life spans, what methods are used to process them and integrate them into the mix, and the energy that powers all these processes.

Kuert Concrete, Inc. has been in business since the 1920s, and the Leesburg and Rochester ready-mix plants have been under Kuert's ownership since 1996.[4] The company has made a number of mergers and acquisitions over the years, and is consistently looking for ways to improve the environmental impact of its concrete products. Kuert performs operations of various scales and applications across northern Indiana and southern Michigan.

One of the ventures Kuert has embarked on is the integration of ground granulated blast furnace slag (GGBFS) into concrete batch mixes. GGBFS acts in lieu of cement, binding the other materials together in a similar manner. The main benefit of adding slag to a concrete batch mix is that as a byproduct of iron or steel[5] smelting, the embodied energy added to the product system only represents the energy of transportation to bring the material to Kuert's facilities. The steel manufacturing product system yields a product separate from the concrete life cycle, so the byproducts for the sake of the concrete product system carry no embodied energy. In terms of carbon dioxide emission, the substitution of one tone of Portland cement for slag prevents approximately one tone of carbon dioxide from entering the atmosphere.[6] A secondary effect of the slag is that it makes the concrete lighter in color, which reflects more light and reduces the urban heat island effect.

These efforts address the issue of cement and concrete being large contributors to global warming especially via carbon dioxide emission. A metric these product systems use to quantify their effects on the environment is Global Warming Potential, or GWP, which takes into account the carbon dioxide and other harmful gases emitted during the product's manufacturing cycle with appropriation according to the harmfulness of the gas.

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[3] Material Flow Analysis of Concrete

[4] http://www.kuert.com

[5] In this case, Kuert uses the runoff from steel manufacturing due to proximity of these operations.

[6] http://www.slagcement.org

Each phase contributes varying levels of embodied energy and embodied carbon to the final value. Hard rock mining and processing, the latter of which is illustrated in Figure 2-1, is considered an energy-intensive process, while river rock gathering is not as energy-intensive. Not surprisingly, indirect oil extraction and refining constitutes a large portion of the large energy consumption of the product system. Stone crushing currently produces 42% of the total material consumed by weight in the US, which is mainly used as highway aggregates.[7] Although this study does not quantify source-specific values for energy consumed during this process, it recognizes that this data point is an insufficiency in representing reality.

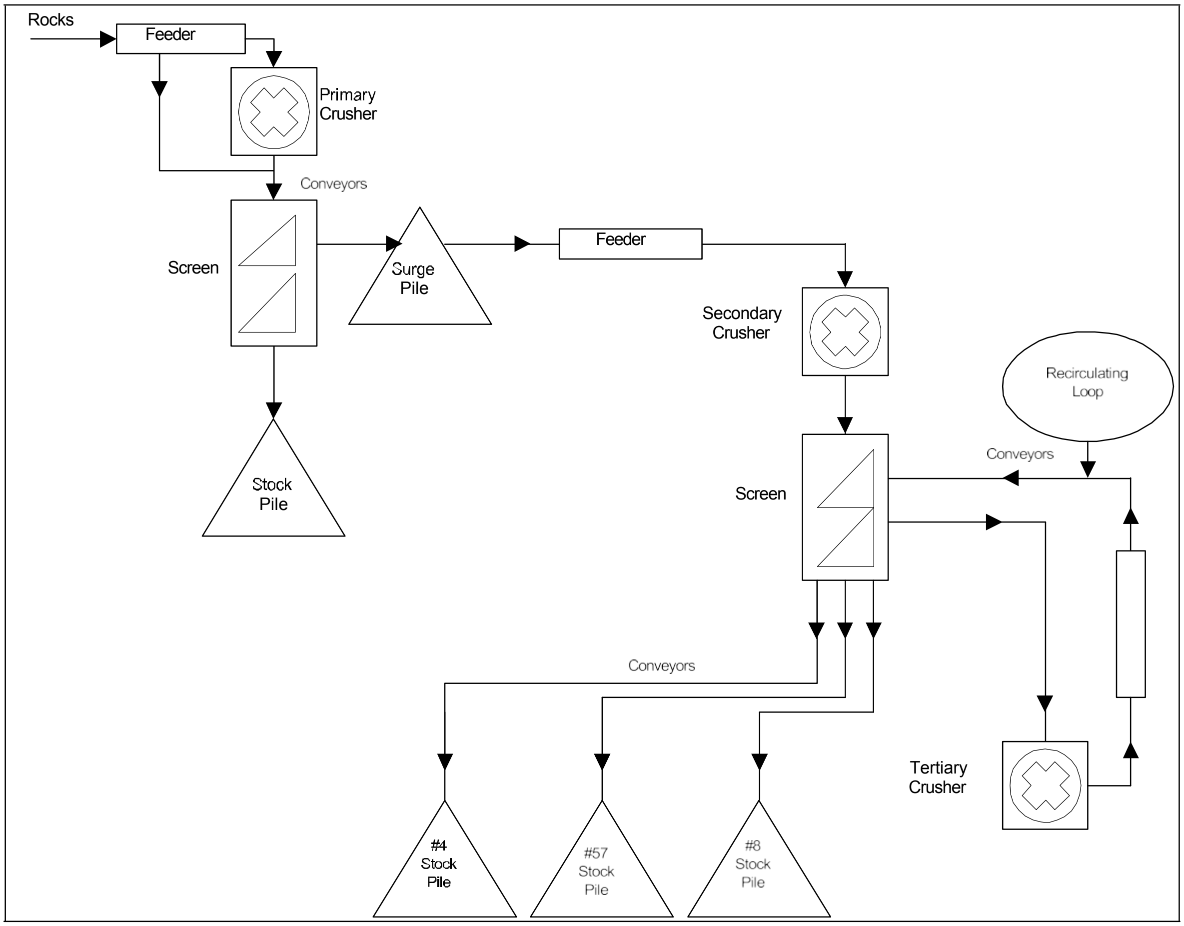

Figure 2-1: Typical Crusher Plant Layout ([8])

The management of building materials in the United States accounts for 42% of the country's greenhouse gas emissions. Of this, ready-mix concrete manufacturing emits 246,842 million metric tons of greenhouse gases[9] from highway, street, bridge, and tunnel construction alone[10]

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[7] Moray, Satyen, et. al. "Energy Efficiency Opportunities in the Stone and Asphalt Industry." Twenty-Eighth Industrial Energy Technology Conference, New Orleans, 2006: http://repository.tamu.edu/bitstream/handle/1969.1/5644/ESL-IE-06-05-27.pdf?sequence=4

[8] Ibid.

[9] C O_2 equivalent: carbon dioxide and other gases weighted to GWP.

[10] http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf

carbon dioxide emissions from Portland cement manufacturing are generated by two mechanisms. As with most high-temperature, energy-intensive industrial processes, combustion of fuels to generate energy releases substantial quantities of carbon dioxide. Large amounts of carbon dioxide are also generated through calcining of limestone or other calcareous material. This calcining process thermally decomposes $CaCO_3$ down to CaO and CO_2. Typically, Portland cement contains the equivalent of about 63.5 percent CaO. Consequently about 1.135 units of CaCO3 are required to produce 1 unit of cement, and the amount of CO2 released in the calcining process is about 1000 pounds per ton of Portland cement produced.[11] If one hundred percent of the materials in the product system were recycled from demolition the construction industry and reused in the concrete production industry, the U.S. emission of CO_2E would be reduced by 150 million metric tons each year. Total waste from the construction industry, including demolition, comes to about 29,744,000 thousand tons of waste material. This includes waste rock and overburden, mill tailings, and other indirectly involved material. If all of this material were to be recycled, an estimated 1,375,000 metric tons of CO_2-equivalent would be eliminated from the atmosphere.[12] Additionally, up to 100 gallons of water are used during the product system, most of which is used to wash off the trucks carrying the materials. Through analysis of the impact of the concrete production system, it is clear that the process has a significant impact on the environment. This study seeks to arrive at a definitive amount of environmental impact given a specific set of boundaries, but due to the nature of the information needed to get there and the necessary approximation and assumptions involved in the research, the magnitude of the impact of the specific system although unresolved, is indicative of the nature of the effects.

2.2 Introduction to LCA

Objectives of Kuert Concrete LCA

As one of the oldest central mixed concrete plants in the United States, Kuert Concrete, Inc. has refined their concrete manufacturing process over the years according to different factors such as efficiency, compressive strength, and cost. Recently, a major concern of the company is to produce concrete products which cause less harm to the natural environment. One of their products leading this charge is their slag mix concrete, which substitutes a portion of the cement used in the formula for concrete with slag runoff from steel manufacturing. Since the slag is a byproduct of a separate manufacturing process, it is more economic and environmentally conservative to use it over cement, which consumes a great deal of energy and resources in its manufacturing process.

This life cycle analysis seeks to determine and quantify the environmental impact and the energy and resource consumption of the concrete products manufactured by Kuert Concrete, Inc. This will contextualize the company’s products and provide a more realistic understanding of the environmental consequences of their manufacture.

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[11] http://www.epa.gov/ttn/chief/ap42/ch11/bgdocs/b11s06.pdf

[12] http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf

Section 3: Goal, Scope, and General Aspects

3.1 Goals

The primary goal of this study is to use a specific example to quantify the significance of using local materials and products with regard to energy consumption and carbon emission in the construction industry. In order to estimate the impact of a building technique or product with a high level of accuracy, the assumed data used in calculations of important quantities must be reasonably close to representing the actual situation. Thus, this study seeks to illuminate the degree to which localization of data is reflected in these calculations as a collateral goal.

As a scholarly pursuit, the direct benefit of this study will be as a tool in the arsenal of architects and planners to consider the impact of their design decisions when presented with the options of different degrees of locality. The intended application of this particular Life Cycle Analysis is to quantify the improvement in environmental impact of each concrete batch mix, including a hypothetical one.

The results of this study are catered to Kuert Concrete, Inc. from whom information was gathered to conduct the life cycle analysis of the products. Due to the non-disclosure agreement made between this company, its business partners, and the University of Notre Dame, the results of the study will only be released to the discretion of the company. Two larger groups can benefit directly from this study: the academic community who deals with buildings and energy, as well as the firms in the construction industry who manufacture and/or distribute pavement materials. Decision makers in the industry can benefit can this example as a microcosm of the environmental product system of their products.

The functional unit for the basis of comparison in this study is one cubic yard of concrete. This is typical of life cycle analyses largely due to the cubic yard's use as an industry standard amount around which to proportion their batch mix designs. The purpose of the functional unit is to make the data from this study easily comparable to other analyses of concrete products within Kuert Concrete and industry standard data, or other pavement products. The data will also be presented in terms of embodied energy per weight, which is relevant to the architectural and engineering fields, and embodied carbon per weight, which contextualizes the issue of sustainability within a larger scope.

Assumptions

In the scope of this study, a number of assumptions were necessary to make in order to arrive at a quantifiable conclusion while remaining close to reality. In the legs of shipment truck load was assumed to be consistently 23586.8 kg, with the truck being filled to capacity in every leg of shipping. In addition, the study assumes that each truck returns empty each time it delivers its cargo, meaning that the embodied energy for a leg of shipment represents the energy used to get the truck from its origin to its destination and back. It is assumed that during the return trip the truck consumes the same amount of diesel fuel as its original trip, thus contributing the same amount of emissions to the air.

3.2 Scope

The **Product System** is what is referred to as “cradle to gate” which means all inputs and outputs at each stage in the life cycle are considered from raw material extraction until the final product reaches the job site. In addition to the process that entails on-site work, the study excludes from its scope the transportation leg of the mixer from the Kuert manufacturing plant to the site, since the value is variable and not unique to the products under review. The concrete product system includes the sub-systems of all of the ingredients, as illustrated by the green boxes in figure 3-1. They are denoted as such because Kuert imports the materials from independent companies. The grey shaded boxes include all the processes for which there is an energy input and a carbon emission. The blue shaded boxes represent all the transportation processes. Additionally, the amount water accounts only for embodied water, a ration of embodied energy, and the study excludes the admixture from the scope.

The **impact categories** examined in the study primarily include the energy consumption by the product system, or embodied energy; water consumption, or embodied water; and most prevalently, global warming potential, which is quantifiable by means of carbon dioxide emission. Embodied energy is not indicative of the chemical potential energy of substances like diesel or natural gas; rather, it represents the energy that was consumed over the course of its life cycle in order for it to be present in the system in the state in which it is.

Data Quality in this study is slightly different from the previous study. Objectively, since the majority of the information used in this report was provided by members in the supply or manufacturing chain of the concrete under study, the quality of the data can be assured to have a high degree of precision, especially from the companies that keep detailed logs and records of their energy consumption and quantities of production. On the other hand, due to the proprietary nature of much of this information and the hesitance from industry-level suppliers and manufacturers, not all information was available to complete the study with the original intents.

The **methodology** used to analyze the product system is a synthesis of manual calculation of company-specific data as well as industry standard-based computation. The software used in the previous study, GaBi, was not utilized to create product systems, due to the complexity of the process chain. The consequences of this decision include a heavier reliance on the given data to quantify the carbon dioxide and other pollutant emission as well as the elimination of major resource consumption tracking. In future extensions of this study, among the other desirable continuations, the utilization of the GaBi software would benefit the contextualization of this study.

The product system used for this study consists of each of the respective branches of energy consumption and carbon emission according to the material inputs. Given the cooperation and assistance of additional firms, this information might provide a more accurate representation of the reality of the product system. Since not all data was available in the specific target scenario under study to perform a truly comprehensive analysis certain databases were used to fill in these data gaps. The manual calculation of data will be the primary gauge for the different scenarios, since the same data is available for each scenario only under the product system defined by the manual calculations.

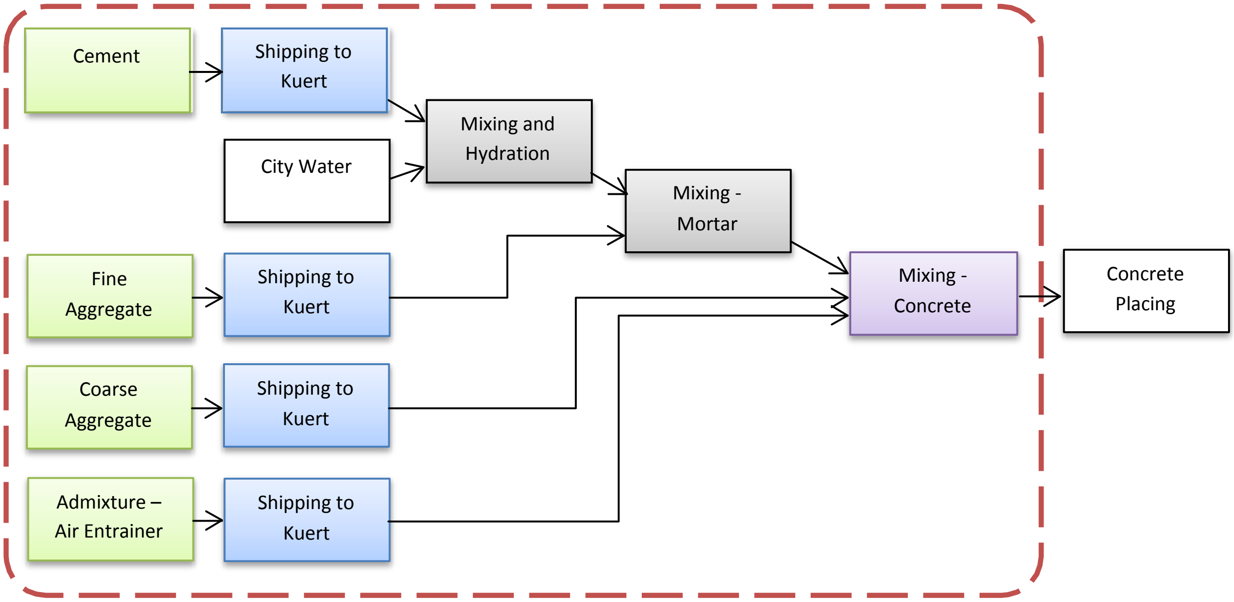

Figure 3-1: Simplified Concrete Product System

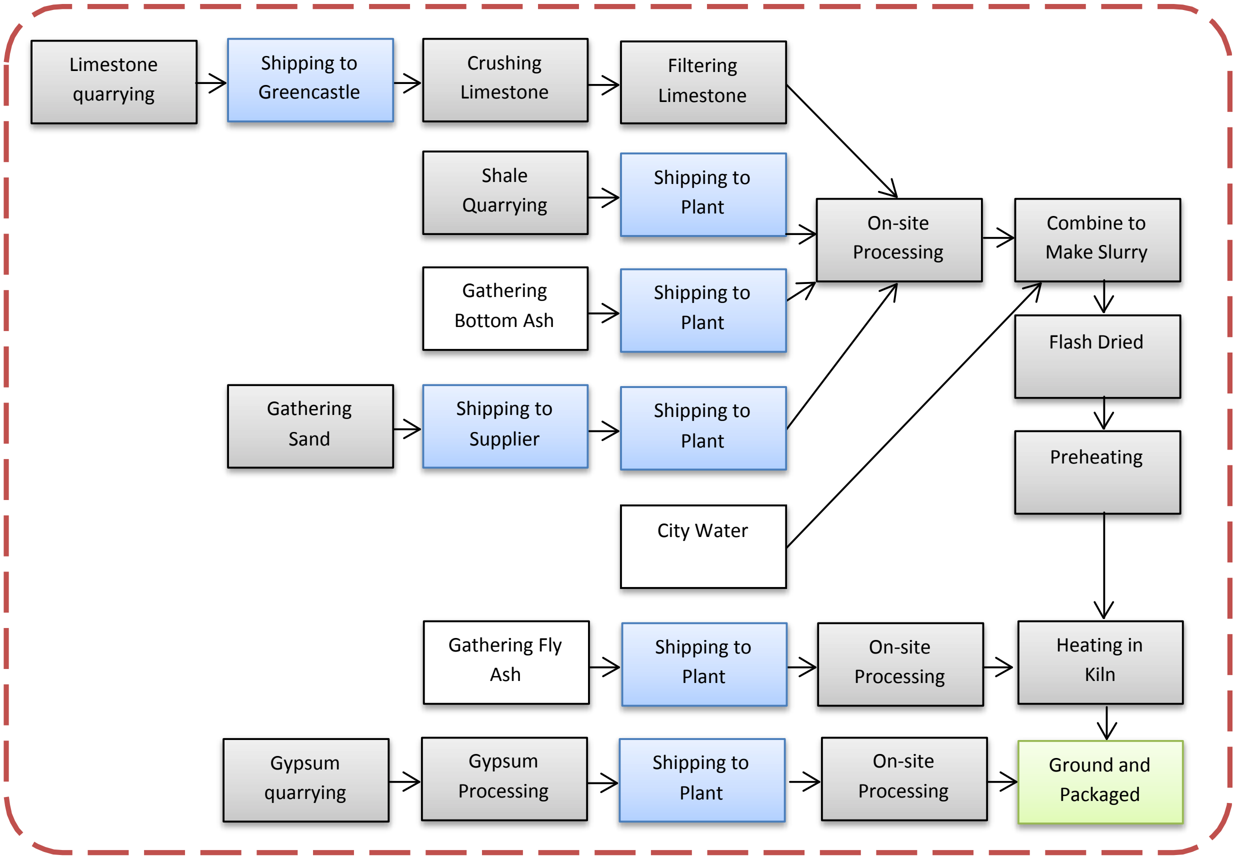

Figure 3-2: Standard Cement Product Subsystem

Section 4: Life Cycle Inventory of Existing Condition

4.1 Product Description

Three products are under study in this report: standard concrete, 20% slag mix concrete, and a hypothetical 40% slag mix concrete, all manufactured by Kuert Concrete, Inc.

The standard concrete mix, identified by Kuert as mix design No. B60L8AB0, is produced at the plants located in Rochester and Leesburg, Indiana. It is used as pavement and for exterior applications, and has a compressive strength of 4000 psi at 28 days. It uses ASTM C33 aggregate and is composed of 5-8% air. A cubic yard of the concrete weighs 3870 lb.

The 20% ground granulated blast furnace slag mix, identified by Kuert as mix design No. P40L8ABS, is produced at the plants located in Rochester and Leesburg, Indiana. It is used as pavement and for exterior applications, and has a 28-day compressive strength of 4000 psi. It uses ASTM C33 aggregate and is composed of 5-8% air. A cubic yard of the concrete weighs 3865 lb. This mix design has decreased amounts of cement and fine aggregate, but a greater amount of coarse aggregate. The amounts of water and air-entraining admixture remain unchanged.

The proposed 40% Slag mix would also be produced at the plants located in Rochester and Leesburg, Indiana. It would also be used as pavement and for exterior applications, and would have an estimated 28-day compressive strength of 4000 psi. It would use the same ASTM C33 aggregate and would be composed of 5-8% air. Amounts of cement, fine aggregate and coarse aggregate were adjusted in this study in the same increments as from the standard to the 20% slag batch mix. A cubic yard of the concrete would weigh 3860 lb.

4.2 Material Sources

The final concrete product is a synthesis of cement, gravel, sand, water, and an air-entraining agent admixture. Each of these products entered the product system

The most energy intensive ingredient of the batch mix is the cement. As the key binding ingredient in concrete, cement manufacturing comprises a significant logistic portion of the life cycle of concrete. Cement itself is a product of an energy intensive process that varies by company. The type I Portland cement, regulated by ASTM C-150, which is used by Kuert Concrete for this study, is shipped from Buzzi Unicem’s plant in Greencastle, IN. Before the cement is shipped, many things need to be done to produce the cement. First, the raw materials must be quarried, which means separate operations mining limestone, sand, and shale must be undertaken. Also, fly ash and bottom ash are brought in from coal plants as a runoff byproduct. The process Buzzi Unicem uses is a semi-dry manufacturing process, so the shale, sand, limestone and bottom ash are mixed with water in 2.2 million gallon basins to create a slurry. The slurry is flash dried, then sent through a preheater before the fly ash is added to the mixture and the entire concoction is heated and melted in a kiln. After this is complete, what emerges from the kiln, what is known as clinker, is ground with a small portion of gypsum after it cools. The remaining powder is shipped to Rochester or Leesburg as cement to be used in concrete manufacturing. The cement product chain is complex, and ideally each leg would be quantifiable in terms of energy consumption and emission generation, but the study is limited in its breadth and thus lumps all this data into one value from an independent database.[13]

The water used in the product system is city water provided and delivered by the city network. Due to the absence of unique energy inputs in the water leg of the mix, the water in the batch mix contributes no embodied energy or carbon emission.

Fine aggregate enters the product system from Irving Materials Inc. in Huntington, Indiana to the Rochester plant, and from Leesburg Sand and Gravel in Leesburg, Indiana to the Leesburg plant. A third company, Moose Lake Aggregates in Niles, Michigan supplies the South Bend plant with their fine aggregate. The three companies have the same production method, so Moose Lake Aggregates was used as the paradigm because of the detail to which their records were kept. The sand, in accordance with ASTM C-33, has a relatively limited product system, which consists of excavation and simple processing. First, a dredge and ladder system conveyors sand up through an intake pipe after the sand has been loosened up. It is pumped to shore and after one day passes, it is carried by 7-8 yard CAT front-end loader into a hopper through which the sand is screened. In this process, any sand with a diameter greater than 1/8" is removed. The Sand is then transported into the plant itself, where the sand is sent through a sizing mechanism and washed, and the water is discarded. The plant then burns lignite to power a separator that spins the sand, separating it. The sand is then removed by conveyor and the same front-end loader loads the sand into a delivery truck.[14] The sand subsystem is limited, and the information was readily available, so a quantifiable amount of energy and carbon dioxide emission is available for the fine aggregate in the product system.

Coarse aggregate enters the product system from Hansen Material, who coordinates shipment from Irving Materials, Inc. in Huntington, Indiana. The limestone aggregate, in accordance with ASTM C-33, has a maximum diameter of ¾ of an inch. The limestone is first blasted from the quarry, then sized and run through a series of crushers and screeners. The aggregate is sorted according to size, and then stockpiled until it is ready for shipment. The coarse aggregate subsystem had certain inaccessible data points than prevented the manufacturing process to be completely quantified. As with cement, the embodied energy and embodied carbon values for coarse aggregate rely on an external database.

The GGBFS enters the product system by Lafarge North America in Chicago, Illinois. Since the slag is considered to be a byproduct of an otherwise independent product system, it is assumed to have no embodied energy in this report. Realistically, some processing may occur before it is obtained by Kuert, but that is outside the scope of this study.[15] The slag is scraped from the kilns in which iron and steel manufacturing takes place after the process is complete. From there, it is

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[13] Kuert also imports some of its cement through Essroc Italcementi Group in Logansport, Indiana, but all the cement was assumed to come from Buzzi Unicem for this study due to the limited scope.

[14] Information gained through conversation with Kuert Concrete, Inc.

[15] Some sources indicate that the slag runoff from iron manufacturing is finely ground, indicating some degree of energy usage. Additionally, one source mentioned that the slag cement saves 90% of the energy consumed by making Portland cement implying that the product does in fact consume energy. This study neglects this energy amount.

ground and ready for shipment. The slag subsystem only accounts for the transportation of the GGBFS from Chicago to Kuert.

As mentioned previously, the air-entraining admixture, though present in each product under study, is not within the scope of this project, due to its negligible quantity and lack of variation.

Below are the mix designs for each concrete mix under study:

Material	Cement	Water	Fine Aggregate	Coarse Aggregate	Air-entraining Admixture
Volume (ft^3)	2.87	4.00	8.64	9.74	0
Weight (lbs)	564	250	1402	1654	(1 unit)

Table 4-1: Mix Design No. B60L8AB0 – Kuert Standard Batch Concrete

Material	Cement	Water	Fine Aggregate	Coarse Aggregate	Air-entraining Admixture	Slag Additive
Volume (ft^3)	2.01	4.00	8.25	10.08	0	0.91
Weight (lbs)	395	250	1339	1712	(1 unit)	169

Table 4-2: Mix Design No. P40L8ABS – Kuert Standard Batch Concrete

Material	Cement	Water	Fine Aggregate	Coarse Aggregate	Air-entraining Admixture	Slag Additive
Volume (ft^3)	1.55	4.00	7.86	10.42	0	1.82
Weight (lbs)	226	250	1276	1770	(1 unit)	338

Table 4-3: Proposed Kuert 40% Slag Mix Concrete

The relationship between the slag additive and the cement is near equivalency in terms of binding quality. The mass of cement removed from the standard batch to the 20% slag mix, 169 pounds, equals the mass of slag additive in the mix. To account for the slight difference in adhesion, the mix removes some fine aggregate from the mix design and adds some coarse aggregate. The same increments of cement and fine aggregate were removed and the same amounts of coarse aggregate and slag additive were added to the 40% slag mix from the 20% mix design.

4.3 Energy Inputs

Since the functional unit of one cubic yard of the finished product is the standard upon which the following energy data points rely, the raw data must be weighted appropriately. This weighting process will occur according to the amount of the material in a functional unit of concrete and the portion of the material created during the manufacturing process or transported during the shipment process. This study views the energy inputs in two ways: either as a single-dimension energy consumption process, such as transportation, where the only energy input is the diesel fuel powering the trucks; or as an intermediate process with multiple energy inputs related to its completion.

4.3.1 Shipment

The following formula provides the Embodied Energy for a functional unit of concrete for each leg of shipping:

$$EE_{total} = EE/kg_{diesel} * \frac{d}{mpg} * \rho_{diesel} * \frac{m_{mat}}{m_{cap}}$$

EE_{total} : total embodied energy (Btu)
EE/kg_{diesel} : embodied energy per kilogram of diesel (Btu/kg)
d : distance travelled by truck (miles)
mpg : miles per gallon of the truck (miles/gallon)
ρ_{diesel} : density of diesel (kg/gallon)
m_{mat} : mass of the material in a functional unit (kg)
m_{cap} : total capacity of the truck (kg)

Figure 4-4: Embodied Energy equation

Each material in the product system was tracked back to its origins. The major components of the shipment portions of the product system were the legs of shipment from the material supplier to the respective Kuert manufacturing plant, since these were often the greatest distances a material would travel in its life span. Each EE value for a shipping leg is determined by multiplying the embodied energy from the trip by the mass of the material in one functional unit of concrete and divided by the mass the truck carries.

Material Name	Material Source	Distance (miles)	Gallons Per Trip	EE per Trip (Btu)	EE per functional unit (Btu)
Cement	Greencastle, Indiana	125	20.83	3,436,675.41	74,549.37
Coarse Aggregate	Huntington, Indiana	50	8.33	1,374,670.16	87,450.11
Fine Aggregate	Plymouth, Indiana	20	3.33	549,868.07	29,651.56
Total					*191,650.04*

Table 4-5: Transportation Embodied Energy – Standard Concrete, Rochester Plant

Material Name	Material Source	Distance (miles)	Gallons Per Trip	EE per Trip (Btu)	EE per functional unit (Btu)
Cement	Greencastle, Indiana	125	20.83	3,436,675.41	52,210.94
Coarse Aggregate	Huntington, Indiana	50	8.33	1,374,670.16	90,516.68
Fine Aggregate	Plymouth, Indiana	20	3.33	549,868.07	28,318.19
GGBFS	Chicago, Illinois	105	17.50	2,886,807.34	18,764.24
Total					*189,810.10*

Table 4-6: Transportation Embodied Energy – 20% Slag Concrete, Rochester Plant

Material Name	Material Source	Distance (miles)	Gallons Per Trip	EE per Trip (Btu)	EE per functional unit (Btu)
Cement	Greencastle, Indiana	125	20.83	3,436,675.41	29,872.62
Coarse Aggregate	Huntington, Indiana	50	8.33	1,374,670.16	93,583.25
Fine Aggregate	Plymouth, Indiana	20	3.33	549,868.07	26,985.81
GGBFS	Chicago, Illinois	105	17.50	2,886,807.34	37,528.47
Total					*187,970.16*

Table 4-7: Transportation Embodied Energy – 40% Slag Concrete, Rochester Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**EE per Trip (Btu)**	**EE per functional unit (Btu)**
Cement	Greencastle, Indiana	170	28.33	4,673,878.56	101,387.14
Coarse Aggregate	Huntington, Indiana	45	7.50	1,237,203.15	78,705.10
Fine Aggregate	Leesburg, Indiana	1	0.17	27,493.40	1,482.53
Total					*181,574.77*

Table 4-8: Transportation Embodied Energy – Standard Concrete, Leesburg Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**EE per Trip (Btu)**	**EE per functional unit (Btu)**
Cement	Greencastle, Indiana	170	28.33	4,673,878.56	71,006.95
Coarse Aggregate	Huntington, Indiana	45	7.50	1,237,203.15	81,465.01
Fine Aggregate	Leesburg, Indiana	1	0.17	27,493.40	1,415.91
GGBFS	Chicago, Illinois	110	18.33	3,024,274.36	19,657.77
Total					*173,545.65*

Table 4-9: Transportation Embodied Energy – 20% Slag Concrete, Leesburg Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**EE per Trip (Btu)**	**EE per functional unit (Btu)**
Cement	Greencastle, Indiana	170	28.33	4,673,878.56	39,315.54
Coarse Aggregate	Huntington, Indiana	45	7.50	1,237,203.15	84,224.93
Fine Aggregate	Leesburg, Indiana	1	0.17	27,493.40	1,349.29
GGBFS	Chicago, Illinois	110	18.33	3,024,274.36	39,315.54
Total					*165,516.52*

Table 4-10: Transportation Embodied Energy – 40% Slag Concrete, Leesburg Plant

4.3.2 Intermediate Processes

In addition to the embodied energy allocated to the transportation legs of the product system, this study takes into account the energy expended to mine or otherwise gather the raw materials from their natural environments. Each leg of production mainly occurs outside the observation of Kuert Concrete, Inc. so the energy inputs of the operations under study were occasionally limited in their detail and availability.

The cement manufacturing process was outlined by Buzzi Unicem, but key details in the Greencastle plant's production prevented a specific value being assigned to the cement in terms of embodied energy. This necessitated the use of an external database to provide the embodied energy values for standard cement and slag cement. The only data provided by the database on slag cement were for 25% and 50% slag cements. This added an additional level of error to the calculations. The Inventory of Carbon and Energy lists these concretes as having embodied energies of 2.6 MJ/kg, 3.81 MJ/kg, and 3.01 MJ/kg for standard, 25%, and 50% slag cements respectively. These yield embodied energy contributions of 1,112,384 Btu, 647,008.1 Btu, and 292,456.4 Btu respectively.

The fine aggregate product subsystem looks at the energy inputs from extracting the sand from the earth, any local transportation, and processing occurring on the site of the sand supplier. First, the on-site equipment consumes 2200 gallons of diesel fuel per month. The dredge consumes 35000 KWH each month, and the plant consumes 110000 KWH each month. For an operation that produces 62500 tons of sand per month, these energy consumption rates were calculated to contribute totals of 9619.7 Btu, 9187.4 Btu, and 8755.1 Btu for the standard, 20%, and 40% slag cements respectively.

The coarse aggregate product subsystem looks at the energy inputs from extracting the aggregate from the earth, any local transportation, and processing occurring on the site of the stone supplier. Once again the key details in the stone manufacturing chain were missing from the information provided by the suppliers, so values for embodied energy were assigned using the Inventory of Carbon and Energy. Limestone aggregate is noted to have 0.1 MJ per kilogram of aggregate produced. This yielded values of 71,108.77 Btu, 73,602.3 Btu, and 76.095.84 Btu to the total embodied energies of the standard, 20%, and 40% slag cements respectively.

4.4 Emissions to Air

Emissions to air from the product system were manually calculated based on typical truck carbon emission rates. Whereas in previous reports, the GaBi model data balance sheets were used to supplement these findings, the nature of the modified product system renders the GaBi process unhelpful. Thus, the calculation below yields the carbon dioxide emission for each of the trips the material takes to arrive in each manufacturing facility.

$$CO_{2,total} = 10.15 \frac{kgCO_2}{gallon_{diesel}} * \frac{d}{mpg} * \frac{m_{mat}}{m_{cap}}$$

$CO_{2,total}$: total carbon dioxide emissions (kg)
10.15 kg CO_2/$gallon_{diesel}$: the constant emission rate of kg carbon dioxide emitted per gallon of diesel burned
d : distance travelled by truck (miles)
mpg : miles per gallon of the truck (miles/gallon)
m_{mat} : mass of the material in a functional unit (kg)
m_{cap} : total capacity of the truck (kg)

Figure 4-11: Embodied Energy equation

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	125	20.83	211.46	4.59
Coarse Aggregate	Huntington, Indiana	50	8.33	84.58	5.38
Fine Aggregate	Plymouth, Indiana	20	3.33	33.83	1.82
Total					*11.79*

Table 4-12: Transportation Carbon Emissions – Standard Concrete, Rochester Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	125	20.83	211.46	3.21
Coarse Aggregate	Huntington, Indiana	50	8.33	84.58	5.57
Fine Aggregate	Plymouth, Indiana	20	3.33	33.83	1.74
GGBFS	Chicago, Illinois	105	17.50	177.63	1.15
Total					*11.67*

Table 4-13: Transportation Carbon Emissions – 20% Slag Concrete, Rochester Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	125	20.83	211.46	1.84
Coarse Aggregate	Huntington, Indiana	50	8.33	84.58	5.76
Fine Aggregate	Plymouth, Indiana	20	3.33	33.83	1.66
GGBFS	Chicago, Illinois	105	17.50	177.63	2.31
Total					*11.5*

Table 4-14: Transportation Carbon Emissions – 40% Slag Concrete, Rochester Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	170	28.33	287.58	6.24
Coarse Aggregate	Huntington, Indiana	45	7.50	76.13	4.84
Fine Aggregate	Leesburg, Indiana	1	0.17	1.69	0.09
Total					*11.17*

Table 4-15: Transportation Carbon Emissions – Standard Concrete, Leesburg Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	170	28.33	287.58	4.37
Coarse Aggregate	Huntington, Indiana	45	7.50	76.13	5.01
Fine Aggregate	Leesburg, Indiana	1	0.17	1.69	.09
GGBFS	Chicago, Illinois	110	18.33	186.08	1.21
Total					*10.67*

Table 4-16: Transportation Carbon Emissions – 20% Slag Concrete, Leesburg Plant

Material Name	**Material Source**	**Distance (miles)**	**Gallons Per Trip**	**CO_2 emissions per trip (kg)**	**CO_2 emissions per functional unit (kg)**
Cement	Greencastle, Indiana	170	28.33	287.58	2.50
Coarse Aggregate	Huntington, Indiana	45	7.50	76.13	5.18
Fine Aggregate	Leesburg, Indiana	1	0.17	1.69	0.08
GGBFS	Chicago, Illinois	110	18.33	186.08	2.42
Total					*10.18*

Table 4-17: Transportation Carbon Emissions – 40% Slag Concrete, Leesburg Plant

In addition to the emissions from transportation, the product system is responsible for the carbon emission from all the processes that go into the preparation of the raw materials, from extraction of the materials to the processing that occurs at the respective plants of the material suppliers from which Kuert receives their raw materials.

The cement manufacturing process was outlined by Buzzi Unicem, but tracking the carbon emission data would be useless without the key pieces of information. The Inventory of Carbon and Energy provided values for embodied carbon, which represented the number of kilograms of CO_2 emitted for every kilogram of cement produced. These values were 0.38, 0.29, and 0.20 for the standard, 25%, and 50% slag cements respectively, which contributed 212.30 kg, 114.65 kg, and 46.112 kilograms of CO_2 emitted from the product systems of the standard, 20%, and 40% slag cements respectively.

The fine aggregate product subsystem looks at the carbon emission from extracting the sand from the earth, any local transportation, and processing occurring on the site of the sand supplier.

In future applications of this study, it would be desirable to have more locally accurate values for carbon emission, but in the context of the other materials drawing their carbon emission data from ICE, so too was the data for sand production. Typically, sand emits 0.005 kg of carbon dioxide for every kg of sand produced, which yields 3.18 kg, 3.04 kg, and 2.89 kg emitted from the product systems of the standard, 20%, and 40% slag cements respectively.

The coarse aggregate product subsystem looks at the carbon emission from extracting the aggregate from the earth, any local transportation, and processing occurring on the site of the stone supplier. Typically, limestone aggregate emits 0.005 kg of carbon dioxide for every kg of sand produced, which yields 3.75 kg, 3.88 kg, and 4.01 kg emitted from the product systems of the standard, 20%, and 40% slag cements respectively.

4.5 Results of Existing Condition

Below are the results of the production of a cubic yard of concrete, according to the values outlined in the sections above:

Rochester Plant	*Shipment*	*Cement*	*Fine Aggregate*	*Coarse Aggregate*	*Total*
Standard	191650.04	1115384.0	9619.67	71108.77	1387762.92
20% Slag Mix	189810.10	647008.1	9187.40	73602.30	917114.37
40% Slag Mix	187970.16	292457.4	8755.13	96095.84	560291.43
Leesburg Plant					
Standard	181574.77	1115384.0	9619.67	71108.77	1377687.65
20% Slag Mix	173545.65	647008.1	9187.40	73602.30	900849.92
40% Slag Mix	165516.52	292457.4	8755.13	96095.84	537837.80

Table 4-18: Embodied Energy in the Product System (Btu)

Rochester Plant	*Shipment*	*Cement*	*Fine Aggregate*	*Coarse Aggregate*	*Total*
Standard	11.79	212.30	3.18	3.75	231.02
20% Slag Mix	11.68	114.65	3.04	3.88	133.24
40% Slag Mix	11.57	45.12	2.89	4.01	57.69
Leesburg Plant					
Standard	11.17	212.30	3.18	3.75	230.40
20% Slag Mix	10.68	114.65	3.04	3.88	132.25
40% Slag Mix	10.18	45.12	2.89	4.01	63.21

Table 4-19: Carbon Dioxide Emitted from the Product System (kg)

Emissions from diesel fuel consumed during transportation include primarily carbon dioxide, with lesser quantities of hydrocarbons like methane, as well as carbon monoxide and mono-nitrogen oxides. Although carbon dioxide is the most significant emission by mass, and therefore has the greatest relative direct global warming potential, the other emissions have indirect consequences that rival the impact of carbon dioxide. For example, mono-nitrogen oxides form photochemical smog which is a significant contributor to air pollution.[16] Its rate of smog formation increases with the amount of light hitting the gas, i.e. in the summer, which also happens to be the time of year when the construction industry is most active and requires the greatest amount of transportation. In order to appropriately determine the relative impacts of the different emissions on global warming, they are assigned Global Warming Potential values, which measure relative impact over one hundred years of the chemical's presence in the atmosphere. The baseline for this value is carbon dioxide, which has a Global Warming Potential of 1.

Emission[17]	**CO_2**	**THC**	**NMHC**	**CH_4**	**CO**	**NO_x**
GWP-100[18]	1	12.2	12	24	1.9	298

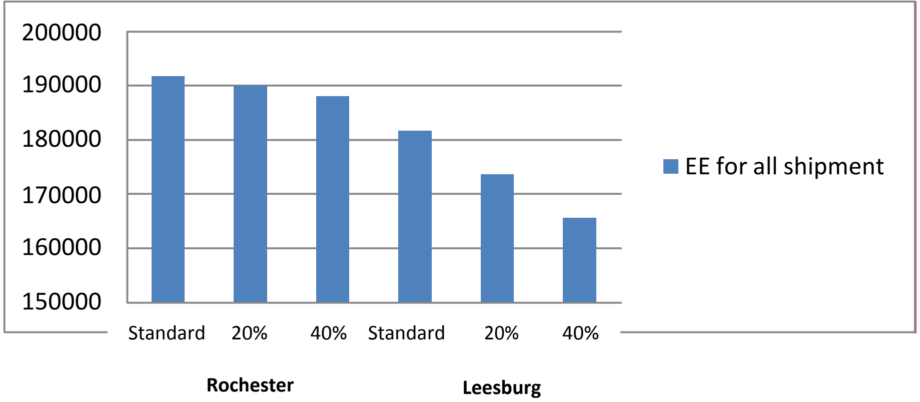
Table 4-20: Global Warming Potential Values for Carbon Dioxide, Total Hydrocarbons, Non-methane Hydrocarbons, Methane, Carbon Monoxide, and Mono-nitrogen Oxides

Mono-nitrogen oxides have a GWP-100 value of 310 according to EPA[19]. This shows how variable the data can be depending on the source of the constants. This study will only present output values for carbon dioxide instead of kilograms of carbon dioxide equivalent, since most sources agree on the carbon dioxide emission rates of the processes included in the product system, while data regarding CO_2-equivalent values make the value vary from 20% to 200% more than the original output value depending on the source of this value.

Section 5: Impact Assessment and Interpretation of Existing Condition

5.1 Impact Assessment

The impact of each of the legs of shipment and production had variable trends with regard to their increase in decrease in how much they affected the total outcome. For example, the embodied energy from shipment dropped more significantly from mix to mix with increasing percentage of slag additive at the Leesburg plant than at the Rochester plant.



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[16] United States Environmental Protection Agency, Air & Radiation: http://www.epa.gov/air/nitrogenoxides

[17] California Environmental Protection Agency Air Resources Board, http://www.arb.ca.gov/ab2588/clearinghouse.htm

[18] Myhre, Gunnar and Drew Shindell, "Anthropogenic and Natural Radiative Forcing." Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

[19] http://nepis.epa.gov/Exe/ZyPDF.cgi/P1001YTV.PDF?Dockey=P1001YTV.PDF

In all, the effects of the segments of the product system that contributed to embodied energy and carbon dioxide emission were expected and understandable.

5.2 Interpretation of Existing Condition

The amount of CO_2 emitted from the product system of the standard concrete, 231.02 kg, is 156.53 cubic yards, enough to fill a spherical balloon with a diameter of 20 feet, or enough to fill about 8820 standard-size party balloons. By replacing the standard concrete with 20% slag mix concrete, the balloon shrinks to a diameter of 17 feet (5108 party balloons), and if the concrete used was the 40% slag mix, the balloon would shrink to a diameter of 12.8 feet (2212 party balloons).

For every kilogram (about the volume of an extruded clay brick) of standard concrete produced, the product system consumes around 834 kJ (.834 MJ) of energy, which is enough to run a 60-Watt light bulb for 4 hours. For the 20% slag mix concrete, 541 kJ (.541 MJ) are consumed, which is enough to run a 60-Watt light bulb for 2.5 hours, and the 40% slag mix consumes 315 kJ (.315 MJ), which would run the light bulb for 1.5 hours.

Section 6: Comparisons

6.1 Comparisons between Specific data and ICE data

In comparing the data gathered to industry standard data, certain aspects of the product system under study come to light. Moreover, the issues that the life cycle analysis ran into show their consequences. Having more data to show the locality of the material would make the conclusions drawn from the data more specific and would more accurately show the impact the product systems were having on the environment.

Rochester Plant	***Total***
Standard	1387762.92
20% Slag Mix	917114.37
40% Slag Mix	560291.43
Leesburg Plant	
Standard	1377687.65
20% Slag Mix	900849.92
40% Slag Mix	537837.80
ICE	
Standard	1580527.35

The Inventory of Carbon and Energy reports a typical embodied energy for general concrete as 0.95 MJ/kg of concrete produced, which for a cubic yard would come to 1,580,527.35 Btu, slightly higher than the calculated embodied energy for the standard concrete under study.[20]

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[20] ICE 1.6, University of Bath, UK

Rochester Plant	***Total***
Standard	231.02
20% Slag Mix	133.24
40% Slag Mix	57.69
Leesburg Plant	
Standard	230.40
20% Slag Mix	132.25
40% Slag Mix	63.21
ICE	
Standard	198.07

The Inventory of Carbon and Energy reports a typical embodied carbon for general concrete as 0.13 kg CO_2/kg of concrete produced, which for a cubic yard would come to 198.07 kg of CO_2, slightly lower than the calculated emitted carbon for the standard concrete under study.[21]

Section 7: Discussion

The product system of Kuert Concrete Inc.'s standard batch concrete includes shipment of materials within a relatively small radius and from trusted suppliers. The alternatives to the standard concrete yield lower embodied energies and lower amounts of carbon dioxide emissions, and the data quality gives confidence that the hypothetical scenario would act as expected given projections of data.

This report is not a complete picture of the current or proposed product system. With that as a given, some data had to be estimated based on industry standards, while others were omitted and recorded as known issues with the product system. Future endeavors will include making this report a more holistic representation of reality.

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[21] ICE 1.6, University of Bath, UK