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LIFE CYCLE ASSESSMENT OF PRE-CAST CONCRETE VS. CAST-IN-PLACE CONCRETE

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LIFE CYCLE ASSESSMENT OF PRE-CAST CONCRETE VS. CAST-IN-PLACE CONCRETE

CEE 598 Life cycle assessment of Civil Systems

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Table of Contents

Executive Summary

This research study present a life cycle assessment comparing the potential environmental impacts of two concrete construction methods used for building construction projects: Pre-cast and Cast-in-place concrete. The objective of the study was to provide a beneficial assessment of the potential environmental impacts by quantifying global warming potential, acidification and eutrophication associated with the two construction methods. Data for the two construction methods came from numerous industry reports and relatively recent journal article publications on the subject, although a majority of the data came from the Portland Cement Association's Annual U.S. and Canadian Labor Energy Input Survey. Following are some of the findings of the study.

- Global Warming Potential: GWP associated with manufacturing cement is approximately three times greater than the GWP associated with utilizing pre-cast or cast-in-place concrete construction methods. This finding reinforces previous literature that cement production is where the industry should focus to curb CO_2 emissions associated with concrete production.
- Acidification: Acidification potential associated with the manufacture of cement is approximately one magnitude greater than the acidification potential associated with pre-cast or cast-in-place concrete construction. This finding, once again, reinforces previous literature; however, this environmental impact category may not be the best indicator of the potential environmental impacts of concrete construction. This is mainly due to the fact that concrete runoff on the job-site is vigorously controlled and monitored through a storm water pollution prevention plan (SWPPP) which curbs concrete waste runoff, among other runoff streams on the jobsite.
- Eutrophication: Eutrophication potential associated with each concrete construction method could not be calculated due to lack of data and the unavailability of information with respect to this category. Although, eutrophication potential associated with the manufacture of cement was calculated, the value of 0.13 kg PO_4e/m^3 is so small that the environmental impacts for cement production may as well be none.

Chapter 1 Introduction

Manufacturing and construction of the structural elements of a building can take on several different forms. The three most common construction materials are structural steel, wood and concrete. For a majority of commercial construction, the core of a building's frame is structural steel with steel reinforced concrete elements to provide the necessary structural capacity for the walls and roofing systems. Presently, the two primary concrete construction methods are cast-in-place and pre-cast concrete. The shift from the traditional cast-in-place concrete construction methods to precast concrete has steadily increased since the early 1960s. There are many economic and practical reasons for the shift towards increased use of precast methods. Cast-in-place concrete construction (**Error! Reference source not found.**) typically requires construction activities such as mixing, placing and curing. These steps not only increase the duration of the project, but also add to the cost associated with the use of additional material for formwork, on-site labor and a greater amount of waste materials generated from the construction process. Increasingly, pre-cast concrete products such as hollow-core precast concrete panels, precast concrete double walls and pre-stressed concrete slabs are becoming more popular (**Error! Reference source not found.**). This shift to precast is because of faster construction speed, reduced cost per unit and minimization of waste.

While the body of research studying the environmental impacts of cement production is rather large, there has been relatively little research to study the environmental impacts of these two specific concrete construction techniques. Moreover, due to the global scale and effect of building construction activities on the environment, especially from concrete structures, the authors believe that a comparative study of these construction methods is warranted to allow for better understanding for policy making regarding future infrastructure development. This LCA is meant to serve as an **environmental assessment of the two concrete construction methods, which can then serve as the tertiary category for decision-making (the other two categories being cost and schedule considerations).**

Figure 1: Cast-in-Place slab foundation

Figure 2: Pre-Cast hollow-core panels

1.1 Problem Statement

In the U.S. alone, approximately 900 million tons of concrete is used in the building construction industry annually (Environmental Protection Agency, 2012). Concrete is essentially a mix of cement, water, sand and gravel (Figure ***3***). Even though concrete uses approximately 7% to 15% cement by weight depending on performance requirements, the CO_2 emissions from cement production have a critical impact for Global Warming Potential (GWP). In 2006, 2.55 billion tons of cement was produced accounting for an estimated 4.5% of global CO_2 emissions (National Ready Mixed Concrete Association, 2012). It is staggering to think that a single industry can have such a conglomerate effect of potential environmental impacts. Several variables are associated with either method of concrete construction such as prep-work, weather considerations, and concrete strength, set times, and curing times. The consideration of utilizing one construction method over the other depends on the building type, structural design, site constraints and cost factors amongst others.

The utilization of concrete is deeply entrenched in the construction industry and there are no modern sustainable alternatives that can entirely replace its use. Hence, it is believed that a potential solution to the environmental challenges can come from an analysis of how these materials are produced, constructed and/or reused (Johnson 2006).

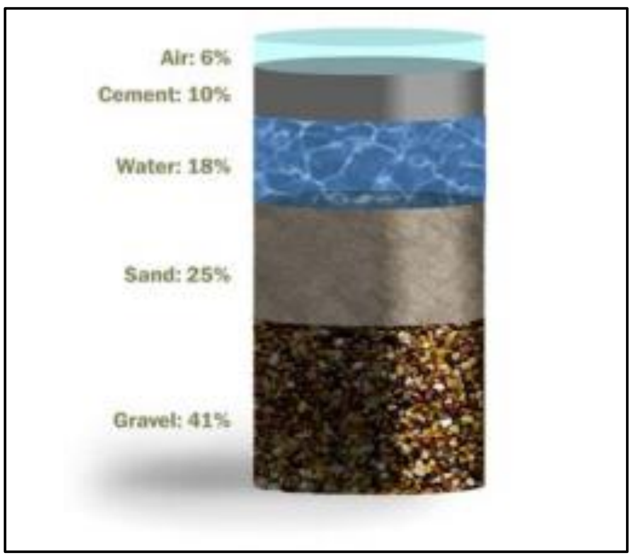

Figure 3: Typical material composition of concrete (NRMCA 2012)

1.2 Goal, Scope and Functional Unit selection

The goal of this study is to answer the following questions:

- What are the environmental impacts from the production and construction of cast-in-place concrete versus precast concrete?
- Which concrete construction process has the most CO_2 emissions?

For the purposes of this study, the authors are including the manufacturing of concrete construction materials, the transportation of these materials to the job site and the two construction processes used, precast and cast-in-place. The use and disposal phases are excluded from this study. A cradle-to-gate Attributional LCA is used for comparing cast-in-place and precast concrete construction methods. The functional unit considered is a 1 cubic meter of concrete available on site. Typically concrete quantities are expressed in volumetric units and for this is the reason we chose such a unit for the analysis. The concrete mix proportions used for this study are shown below in Table 1:

Table 1: Concrete Mix

Raw Material	Amount (kg/m^3)
Cement	223
Water	141
Coarse Aggregates	1,130
Fine Aggregates	830
Total Aggregates	1,360

1.3 Environmental Impacts

The environmental impact categories considered as part of the LCA are as follows:

1. Global Warming Potential from air emissions
2. Water Eutrophication from Nitrogen and Phosphorus runoff
3. Soil Acidification from Nitrogen and Phosphorus runoff

1.4 Assumptions

In order to facilitate ease of analysis in the LCA, several assumptions were needed as follows:

1. The same size of truck was assumed for all transportation operations. These operations included the transportation of sand, gravel and cement to the concrete manufacturing plant, the transportation of the ready mix concrete to the job-site, the transportation of rebar and plywood formwork to the job-site, and the transportation of all necessary materials to the pre-cast plant.
2. Disposal of waste concrete from the manufacturing and construction process + the use of the building were not considered as part of the system boundary.

3. It was assumed that storage of the finished pre-cast product contributed to the environmental impacts.

Chapter 2 System Boundary

Figure 4 presents the system boundary diagram for the LCA. From the diagram, concrete waste procurement, admixture manufacturing, and water source procurement were not included. Additionally, the use and disposal phase of the building's life cycle was not included. Cement manufacturing and sand and gravel processing are included. Transportation of materials to the site is also included in the system boundary. Air Emissions considered in the calculation are CO_2, SO_2, NO_x, CO and CH_4. Water and ground emissions considered in the environmental assessment are nitrogen and phosphorus runoff.

Chapter 3 Inventory Analysis

The group gathered life-cycle inventory data for the elements defined within system boundary. Several construction industry and academic reports were used to collect the inventory information. As previously stated, the group chose and normalized the data gathered to a functional unit of one meter cubed (1 m^3) of concrete with a compressive strength of 25 MPa (Megapascals).

Both pre-cast and cast-in-place concrete use cement, aggregate and water as their constituent materials. Although pre-cast concrete is cast in the manufacturing plant we have included the casting and curing of pre-cast concrete in the on-site section as to ease the comparison of the two concrete construction methods. We have found that cement manufacturing is the main contributor in Global Warming Potential (GWP) of concrete. Typically during cement manufacturing, coal is burned in the kiln to produce the cement clinker, this process results in large amounts of GHG emissions, especially CO_2 emissions.

In order to calculate the mid-point results for the three environmental impact categories the group utilized the following equations:

$$GWP\ (kg\ CO_2e) = 1 * CO_2 + 25 * CH_4 + 298 * NO_x \quad (1)$$

$$Acidifcation\ (kg\ SO_2e) = 1 * SO_2 + 0.7 * NO_x \quad (2)$$

$$Eutrophication\ (kg\ PO_4e) = 0.13 * NO_x + 0.42 * N + 3.07 * P \quad (3)$$

The above equations use multiplication factors to combine constituent elements that affect their respective environmental impact categories. For example methane (CH_4) has 25 times the effect of CO_2 in terms of global warming potential; therefore methane gets multiplied by 25 in order to convert it to equivalent units of CO_2. Similar calculations follow for the other two categories.

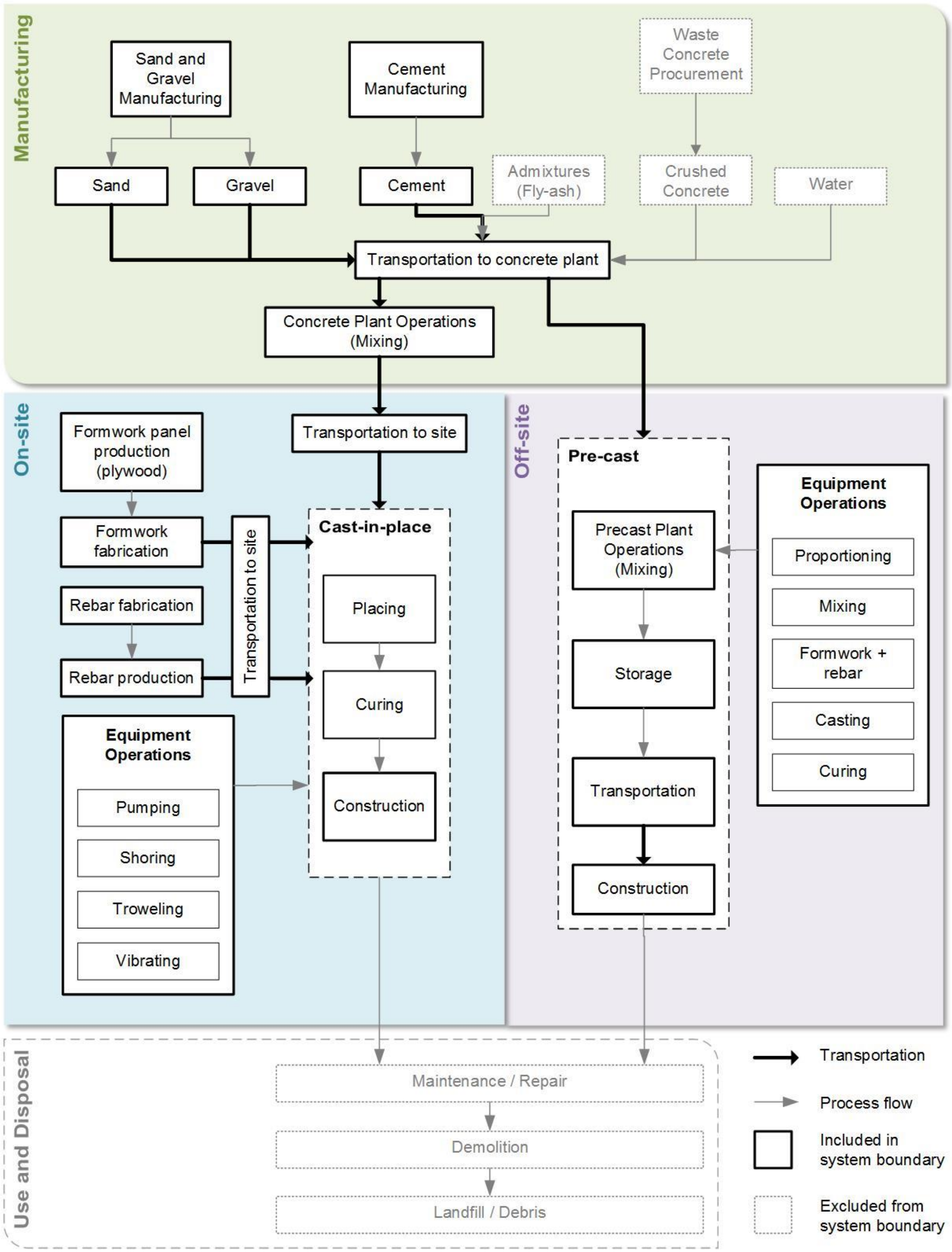

Figure 4: System Boundary diagram

Chapter 4 Interpretation of Results

The results in this section reflect the life cycle assessment comparing two concrete construction methods, pre-cast and cast-in-place concrete. Life Cycle Inventory results as well as mid-point results for the environmental impacts categories of global warming potential (GWP), acidification, and eutrophication are presented in graphical format.

4.1 Life Cycle Inventory Results

Life cycle inventory results are presented in this section. Inventory results for CO_2 are shown separately from the other GHG emissions. This was due to the fact that CO_2 emissions were the most prevalent out of all the other emissions included in the analysis.

Figure 5 shows the CO_2 results of the LCI. From the figure, one may notice that the manufacturing of sand + gravel + cement accounts for a majority of the CO_2 emissions from the entire life cycle process considered in this study, i.e. cradle-to-gate emissions. Moreover, the amount of CO_2 released during the manufacturing of cement is approximately one magnitude greater than the CO_2 released as a result of the methods and processes utilized within pre-cast and cast-in-place concrete shown in the system boundary.

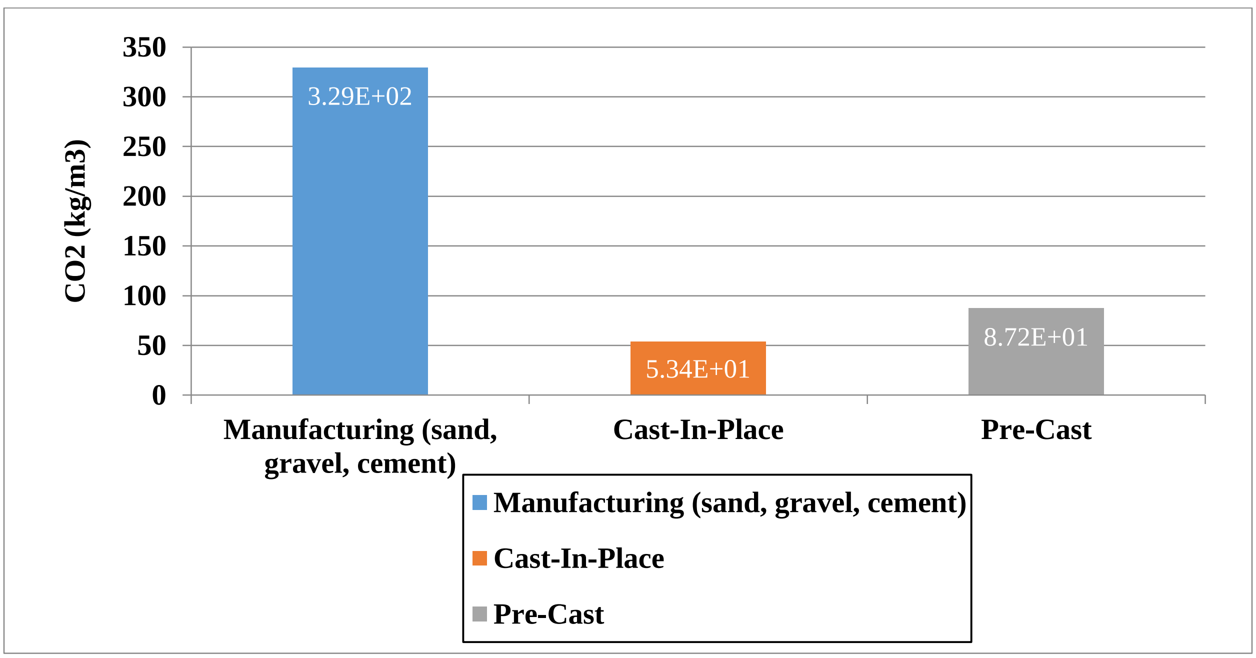

Figure 5: LCI CO2 Results

This result presents two trains of thought: First, in order to curb the amount of CO_2 released as part of the concrete manufacturing process; the industry must evaluate/change the methods used to manufacture cement over all other processes in the life-cycle. This is due to the fact that the relative contribution of emissions from the construction of these materials is much less than the emissions from the manufacture of cement. Second, alternative materials selection could potentially help to curb CO_2 emissions associated with producing cement; however, alternative materials selection should to be taken with a grain of salt, as the method of manufacturing alternative materials may not be as sustainable or environmentally friendly as the processes involved with manufacturing traditional materials. Although the assessment of alternative material selection is outside the scope of this LCA, recommendations are provided in the conclusions.

Figure 6 presents the LCI results for the other GHG emissions and nitrogen and phosphorus emissions. From the figure one may notice that there is only nitrogen and phosphorus emissions associated with the manufacture of concrete, sand and gravel. This was due to the fact that there was a lack of available data for the run-off associated with pre-cast and cast-in-place construction methods. Additionally, the methane emissions associated with pre-cast concrete are much greater than for the other gases. This increase in methane emissions may have been due to the fact that the indirect environmental impact associated with the storage of the pre-cast was contributing more than what would typically be observed.

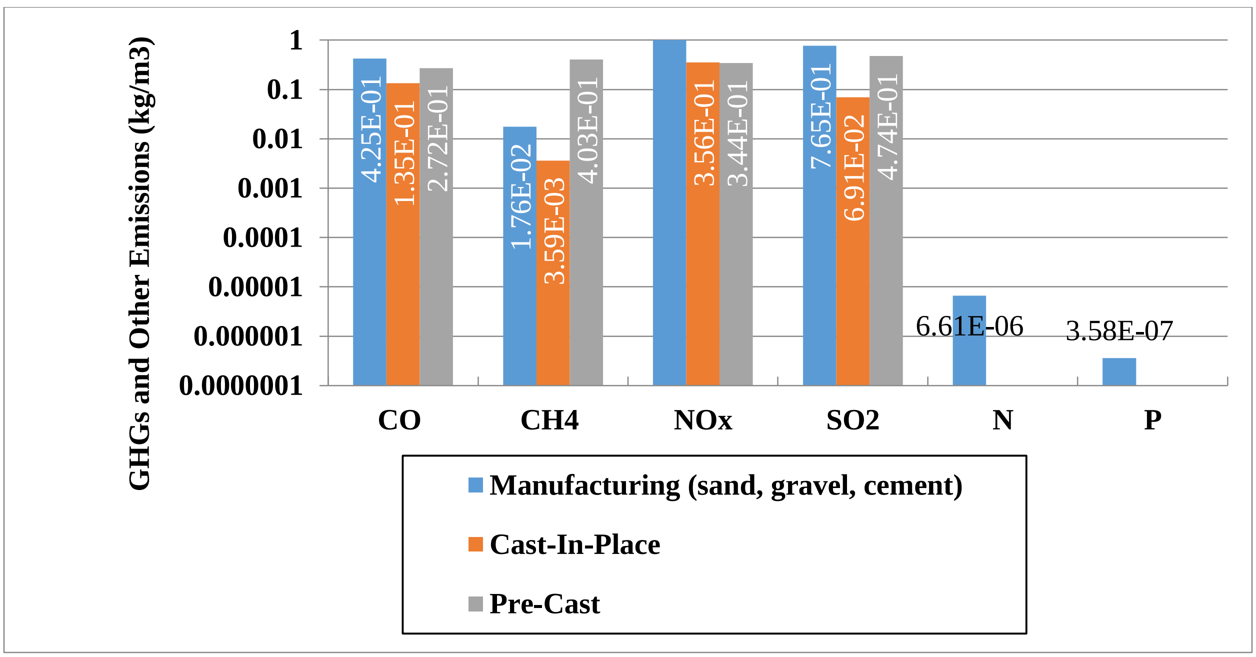

Figure 6: LCI Other Emissions Results

4.2 Environmental Impact Results

Results from the potential environmental impacts are presented in this sub-section. From Figure 7 one may notice that the CO_2e emissions are much greater for the manufacturing process over the CO_2e emitted during the construction of the pre-cast and cast-in-place. These results reinforce previous literature findings that the manufacture of cement plays a major role in the CO_2 emissions associated with concrete production.

Further analysis of the graph indicates that acidification and eutrophication have much less total environmental impact over the GWP. However, acidification and eutrophication are measured in terms of different equivalent elements and therefore direct comparison between each environmental impact category cannot be done.

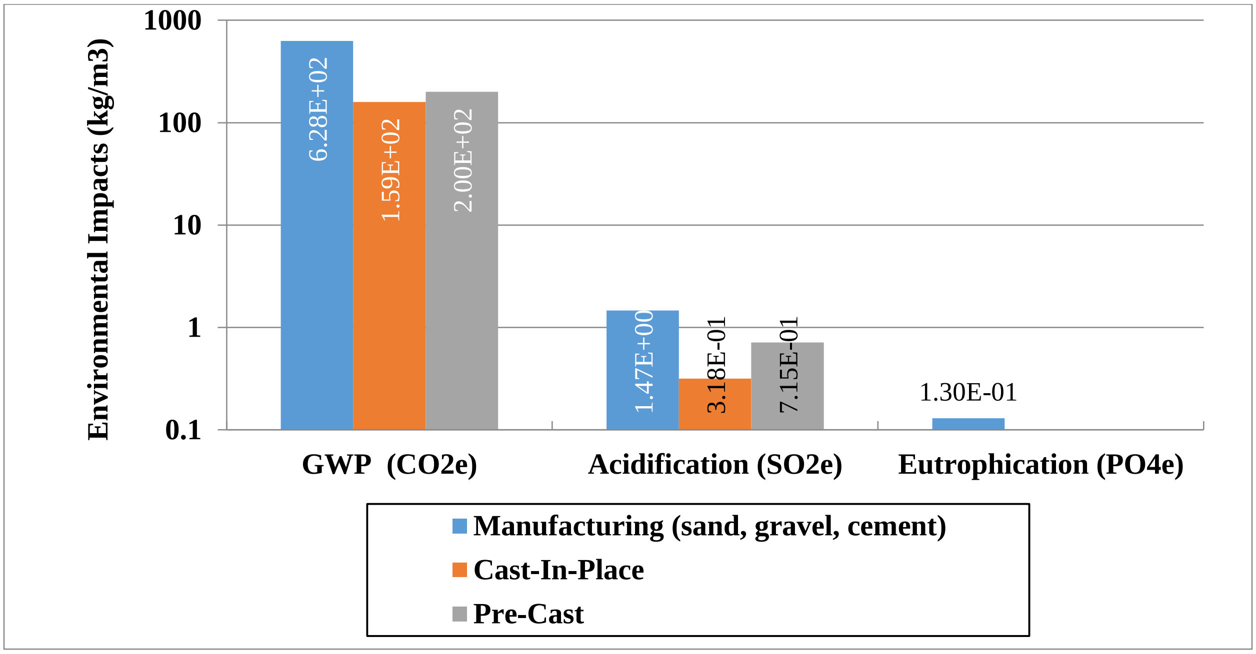

Figure 7: LCIA Results

Furthermore, it would seem that the manufacturing process involved in cement production has the largest potential environmental impact over the construction of pre-cast and cast-in-place concrete.

4.3 Uncertainty Analysis

There are several points of uncertainty associated with the data collected and used in this study. First, all the data collected are secondary data, but the group has taken considerable effort to capture data from the most recent studies and use data from relevant processes in similar geographical locations. The primary resource used was the Portland Cement Association report. This report is intended to represent U.S. and Canadian conditions and is a relatively new publication (2010). The Portland cement association is the leading industrial representative of cement manufacturers and the largest industrial cement and concrete industrial research institution in the world. Other sources of data and their age are listed in Table 2.

Table 2: Citations and Data Sources

Citation	Reference	Data Source
(Johnson 2006)	Johnson, Timothy W. "Comparison of Environmental Impacts of Steel and Concrete as Building Materials Using the Life Cycle Assessment Method." MS Thesis. 2006.	Source 1 = EcoInvent v1.0 Database Source 2 = energy use data from the Portland Cement Association's annual *U.S. and Canadian Labor-Energy Input Survey*
(Marceau et al. 2006)	Marceau, Medgar L., Nisbet, Michael A., and VanGeem, Martha G., "Life Cycle Inventory of Portland Cement Manufacture." 2006.	Energy use data from the Portland Cement Association's annual *U.S. and Canadian Labor-Energy Input Survey*
(Nisbet et al. 2008)	Nisbet, Michael A., Marceau, Medgar L. and VanGeem, Martha G., "Environmental Life cycle inventory of Portland Cement Concrete." 2002.	Data on inputs and emissions from concrete production are from published reports, emission factors and information provided by members of the Environmental Council of Concrete Organizations (ECCO)
(Sjunnesson 2005)	Sjunnesson, Jeannette. "Life Cycle Assessment of Concrete." MS Thesis. 2005.	Source 1 = Hansson PA., Burström A., Noren O. & Bohm M., 1998, Determination of engine emissions from machinery for agriculture and forestry Report 232, Department of Agricultural Engineering, Swedish University of Agricultural Sciences, Uppsala Source 2 = Stripple H., 2001, *Life Cycle Assessment of Road –A Pilot Study for Inventory Analysis*, p.48, 2nd revised Edition, IVL-report B1210E, March 2001, Gothenburg, Sweden URL: http://www.ivl.se/rapporter/pdf/B1210E.pdf
(GHK Bio, 2006)	European Commission "A study to examine the cost and benefits of the environmental end of life vehicles directives"	Source 1 = University of Leiden Source 2 = APME

Although there were some uncertainties associated with the data used in this study; the group felt that due to a majority of the data coming from the Portland Cement Association's Annual U.S. and Canadian Labor Energy Input Survey that the data was pertinent and complete. Further analysis by use of a pedigree matrix could potentially shed light on some of these uncertainties; however, this rigorous task is usually subjective based on further assumptions of the quality of data. Therefore, this analysis method was no explored.

Chapter 5 Conclusions

5.1 Recommendations

We have found that cement manufacturing process especially heating the raw material to produce cement clinker has the largest environmental impacts in concrete production. Several strategies can be employed to reduce impacts from this process as follows: Reduce energy use in the kiln (furnace), increase the quality and durability of cement and concrete to facilitate long-term utilization of infrastructure, alternative material selection for cement manufacturing, use supplementary cementitious materials, use alternative fuels, and utilizing carbon capture and storage technologies..

Figure 8 below shows the use of alternative fuels in kilns as a percentage of total heat content used within the European cement association member countries (Cembureau). These alternative fuels present 15% of fuels used within Cembureau. Not all these fuels are regarded as carbon neutral; they are classified as biomass from sustainable managed systems where the amount of CO2 released by combustion and the amount absorbed by photosynthesis are at equilibrium. Of these alternative fuels only ¼ fall within the bio-fuel categorization the equivalence of 4% of all fuels used.

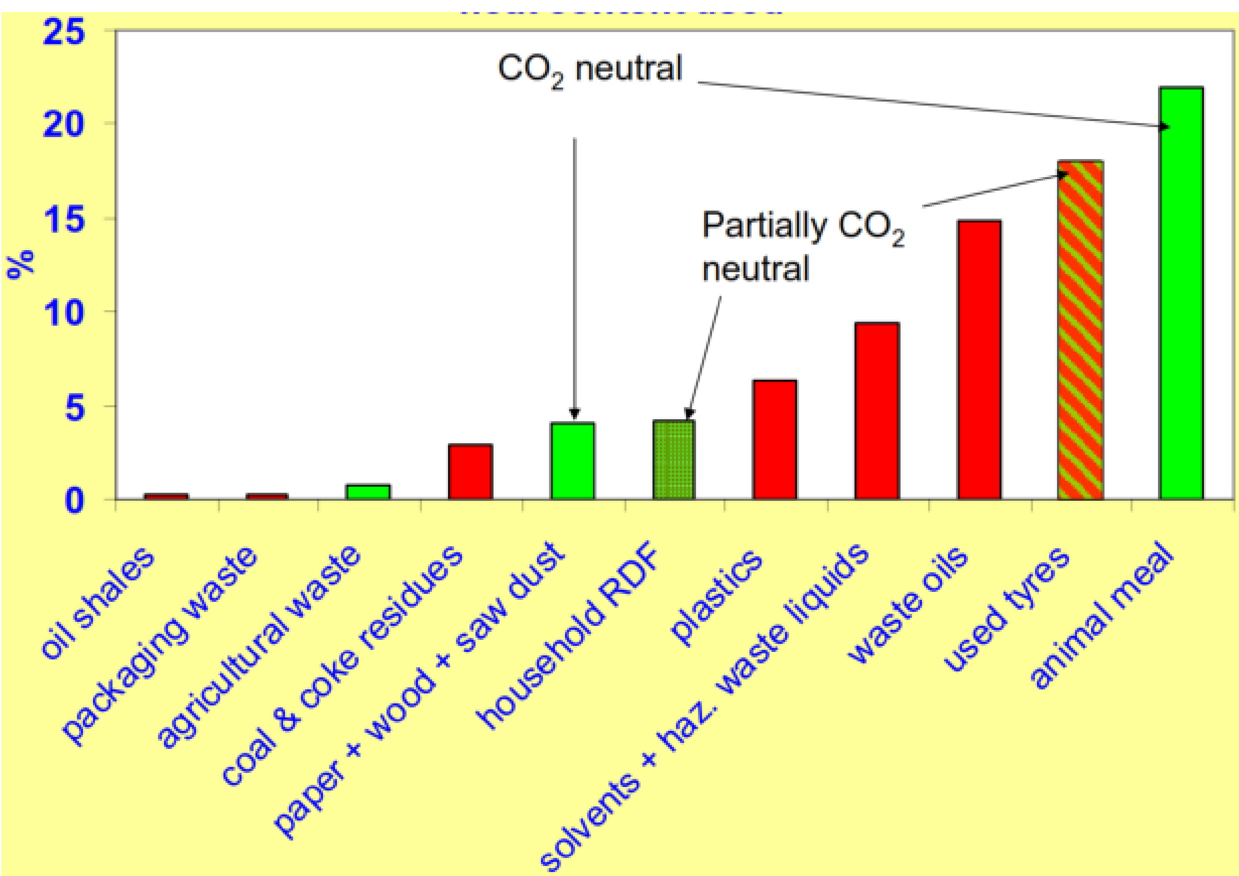

Figure 8: Fuels used in Cement Production Kilns

Apart from improved thermal efficiency in the kiln most significant reductions in CO2 emissions can be achieved by:

- Increased use of bio-fuels
- Use of GBF slag and class C fly ash as raw materials for clinker production where these are locally available
- Increased addition of SCMs through increased strength potential of clinker by mineralization
- Increased use of lime-stone
- Increased used of carbon neutral fuels and conversion to natural gas
- In the long term by CCS, which in addition to the use of bio-fuels, and taking into account concrete carbonation, could even provide a net CO2 sink.

Change the process of manufacturing steel, concrete and wood because we will use the traditional materials forever

$1/kg of steel vs. $100/kg of titanium

Conventional concrete vs. engineered ceramics

5.2 Limitations

- The study does not consider the re-absorption of CO_2 through carbonation of concrete. There are studies that estimate that between 33% and 57% of the CO2 emitted from calcination will be reabsorbed through carbonation of concrete surfaces over a 100-year life cycle (NRMCA 2012).
- The authors observe that pre-cast concrete is more popular construction method for residential construction. Commercial construction would typically utilize a combination of precast and cast-in-place construction methods to construct the necessary structural elements of a building\.

Overall, hopefully this LCA sheds some light of the potential environmental impacts associated with utilizing pre-cast and cast-in-place concrete construction.

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APPENDIX A: Data

	Process	Input	Output						
		Combined Energy (MJ)	Air Emissions					Units	Source
			CO_2	CO	CH_4	NO_x	SO_2		
	MANUFACTURING								
	Sand and Gravel Manufacturing								
1	Sand and Gravel + Crushed Stone (Aggregate Production)	0.000129	4.56E+00	4.20E-02	1.00E-03	4.20E-02	7.00E-03	kg/tonne	PCA
	Cement Manufacturing								
2	Cement	0.0178	3.01E+02	2.93E-01	1.20E-02	8.60E-01	6.60E-01	kg/tonne	PCA
3	Transportation of Aggregates + Cement to Concrete Plant (28 ton truck)	0.000131	9.30E+00	8.50E-02	3.00E-03	8.60E-02	1.50E-02	kg/tonne-km	PCA
	Concrete Plant Operations								
4	Concrete Plant Operations (Excludes Mixing)	15	1.42E+01	4.00E-03	0.00E+00	1.40E-02	8.30E-02	kg	PCA
5	Concrete Production (mixing)	32.7	2.56E-01	5.89E-04	1.60E-03	4.91E-04	4.26E-04	kg	PCA
	ON-SITE								
	Cast-in-Place (CIP)								
6	Transporation of Concrete to Construction Site (28 ton truck)	0.000131	9.30E+00	8.50E-02	3.00E-03	8.60E-02	1.50E-02	kg/tonne-km	PCA
7	Formwork Panel Production (Plywood)	7.63	5.20E-01	4.04E-04	6.50E-06	3.10E-03	7.20E-04	kg/form	Paper 2 - MC2A - Johnson 2006
8	Transporatation of Formwork to Pre-Cast Plant (28 ton truck)	0.953	6.62E-02	9.79E-05	1.61E-06	6.46E-04	1.92E-05	kg/tonne-km	Paper 2 - MX - Johnson 2006
9	Formwork Fabrication	52	4.10E+01	4.60E-02	5.80E-04	2.60E-01	4.90E-02	kg/form	Paper 2 - MC2 - Johnson 2006
10	Rebar Production	11.62	8.20E-01	2.80E-03	3.80E-06	3.10E-03	4.10E-03	kg/m3	Paper 2 - MC3B - Johnson 2006
11	Rebar Fabrication	0.546	5.40E-02	2.00E-05	3.20E-07	2.00E-04	1.70E-04	kg/m3	Paper 2 - MC3A - Johnson 2006
12	Transportation of Rebar to Site (28 ton Truck)	0.953	6.60E-02	9.79E-05	1.61E-06	6.46E-04	1.29E-05	kg/m3	Paper 2 - MX - Johnson 2006
13	Construction Site Equipment Operations (Pumping, Shoring, Troweling, Vibrating Machine, Curing)	1	1.60E+00	4.10E-04	0.00E+00	1.90E-03	1.20E-04	kg/m3	Paper 2 - EPA AP42 -Table 3.3.1 - Johnson 2006
	OFF-SITE								
	Pre-Cast								
14	Transportation of Aggregate + Cement to Pre-Cast Plant	0.000131	9.30E+00	8.50E-02	3.00E-03	8.60E-02	1.50E-02	kg/m3	PCA
15	Pre-Cast Plant Operations (Excludes Mixing, includes all necessary concrete production operations)	16	1.74E+01	4.82E-03	0.00E+00	1.78E-02	8.32E-02	kg/m3	PCA
16	Concrete Mixing	32.7	2.56E-01	5.89E-04	1.60E-03	4.91E-04	4.26E-04	kg/m3	PCA
17	Storage Facility Operations (Assumes Standard Warehouse)	14.6	5.09E+01	9.66E-02	3.95E-01	1.54E-01	3.60E-01	kg	Ecoinvent, 2010, CH
18	Transportation of Pre-Cast Concrete to Construction Site	0.000131	9.30E+00	8.50E-02	3.00E-03	8.60E-02	1.50E-02	kg/tonne-km	PCA

APPENDIX B: Equivalency Factors

CO2 Equivalents

Gas	GWP (T = 100 years)
Carbon dioxide (CO_2)	1
Methane (CH_4)	25
Nitrous Oxide (N_2O)	298

PO4 Equivalents

1 kg Nitrogen oxides (NOx, air) 0.13 kg eq PO4

1 kg Total nitrogen (water) 0.42 kg eq PO4

1 kg Total phosphorous (water) 3.07 kg eq PO4

1 kg Chemical O2 demand (COD) 0.022 kg eq PO4

1 kg NH3 0.35 kg eq PO4

1 kg NH4+ 0.33 kg eq PO4

1 kg NO3- 0.095 kg eq PO4

1 kg NO2- 0.13 kg eq PO4

SO2 Equivalents

Acid producer (in air) SO2 equivalence factor

1 kg HCl 0.88 kg eq SO2

1 kg HF 1.60 kg eq SO2

1 kg NO2 0.70 kg eq SO2

1 kg SO2 1.00 kg eq SO2

1 kg H2S 1.88 kg eq SO2

1 kg NH4 0.89 kg eq SO2

1 kg NH3 0.93 kg eq SO2