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The Portland Cement Association's Environmental Life Cycle Assessment of Concrete

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ABSTRACT

The Portland Cement Association (PCA) is in the process of developing an environmental Life Cycle Assessment (LCA) of portland cement concrete.

The objective of the life cycle assessment the LCA project is to provide an accurate set of data to be used in comparing concrete with competing construction materials. The data will allow individual cement and concrete product manufacturers to conduct Life Cycle Inventories (LCI) of their specific operations. The project is being conducted in a number of discrete phases starting with an LCI of cement and specific concrete products. The next phase, planned for 1998, is the development of LCIs for a range of concrete structures. The project will be advanced to the impact assessment stage when the methodology is more fully developed and more information becomes available.

Cement, a fine gray powder, is the essential bonding agent that, in the presence of water, binds the aggregates in concrete into a rock-hard material. Cement constitutes only 10 to 15 percent of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error that will negatively affect the construction industry.

This paper briefly reviews the manufacturing processes for cement and concrete, selection of system boundaries and data sources. It outlines use of basic input/output models of the manufacturing processes to facilitate updating of the LCIs as new information becomes available. The models can also be used by individual producers to conduct LCIs of their specific operations.

LCI data, normalized per ton of portland cement, were generated and used as input in developing an LCI for a range of selected concrete products. This paper presents preliminary results.

INTRODUCTION

The Portland Cement Association (PCA) is in the process of developing an environmental Life Cycle Assessment (LCA) of portland cement concrete.

Because the methodology for conducting the impact assessment stage of an LCA is not well established, the PCA project started by preparation of a Life Cycle Inventory (LCI) of the cement manufacturing process, followed by LCIs for concrete products including conventional ready mixed concrete, precast and block mixes. This paper documents these first two steps. The third step is the preparation of LCIs for concrete structures, such as walls, roads or bridges.

The database developed by the project should allow, for example, a comparison of:

- Structural components, such as concrete walls, with components of alternative materials.
- Roads made of portland cement concrete and asphalt cement concrete.
- Homes made primarily of concrete (basement, walls, roof) with homes made from competing materials.
- Adjustments in concrete mix design for including recycled materials.

The Portland Cement Concrete LCI project is following the guidelines proposed by SETAC[1]. These guidelines parallel the draft standards proposed by ISO in 14040[2] "Environmental Management - Life Cycle Assessment - Principles and Framework" and other ISO draft documents.

These guidelines require that the product or service being inventoried be described as a system which performs a defined function. The system is separated from its surroundings by a system boundary. The region outside the boundary is referred to as the system environment. Materials and energy flow from the environment into the system; and outputs, products and emissions, flow from the system into the environment.

Goal and Scope of the Concrete Products LCI

Goal

The ultimate goal of the work is to have a complete and accurate information base to be used to compare portland cement concrete with competing construction products. The objective of the LCI stage of the work is to develop accurate and representative sets of data for a specified range of concrete products.

It is anticipated that the data in this report will be incorporated in existing and future LCI models[3,4,5] for comparing alternative materials or improving processes.

Scope

System boundaries

Concrete production is regarded as two linked systems (Figure 1). The boundary includes raw material extraction to concrete ready for shipment at the batch plant gate. The upstream profile of cement manufacturing is "imported" into the concrete manufacturing boundary. Aggregate extraction, transportation of cement, and transportation of aggregates to the concrete batch plant are assumed to be within the concrete boundary, which extends to mixed concrete loaded at the plant gate.

Key Assumptions

1. Cement data are based on the LCI of the weighted average ton of cement produced in the U.S.
2. The functional unit is 1 cubic yard of concrete.
3. English units are used throughout.
4. In concrete production both coarse and fine aggregates are assumed to be crushed stone. This tends to overestimate energy used in aggregate production. The data will be upgraded when further information on the extent of use of sand and gravel becomes available.
5. Energy consumption in concrete production is estimated for a central mix operation.
6. Transportation distances to the batch plant are assumed to be 60 miles round trip for cement and 50 miles round trip for aggregates. All transportation is assumed to be by road.
7. Upstream profiles of energy sources such as coal, diesel fuel and electricity are not included in this LCI.

Information sources

The cement manufacturing LCI energy data was developed from the annual energy survey conducted by PCA. The survey covers 76% of U.S. plants representing 81% of capacity.[6] Raw material data was developed from a questionnaire accompanying the 1995 energy survey. Air emission data are from 122 emission test reports conducted between 1989 and 1996,[7] and U.S. EPA emission factors.[8,9] The emission factors, being based in some cases on older data may not represent the operations of modern cement plants

Data on inputs to the concrete production process are from published reports,[10,11] and information provided by concrete industry associations. This data may not fully represent the complete range of concrete plants and will be improved as the project progresses. Air emissions from concrete production are based on EPA emission factors.[12,13]

Input/output models

To facilitate development of the cement LCI and the related concrete LCI, PCA developed input/output models for the cement and concrete manufacturing processes. The model for cement manufacturing is designed to:

1. Calculate materials and energy inputs and emissions per ton of cement, given:
    - Raw data on materials consumption.
    - Raw data on energy consumption.
    - Emission factors or emission test results.

2. Calculate changes in materials and energy inputs and emissions per ton of cement in response to changes in LCI assumptions or new data.

The model's uses are to:

1. Update the cement manufacturing LCI on a routine basis as new data becomes available.

2. Test the sensitivity of the LCI results to changes in energy and materials input or changes in LCI assumptions.

3. Calculate LCIs for individual cement plants.

Similar to the cement model, the concrete input/output model assists in calculating inputs and emissions per cubic yd. of concrete given the mix design, transportation distances, emission factors, and the data from the cement LCI.

The model allows rapid calculation of energy consumption and emissions for a wide range of mix designs. It also provides a means of testing the sensitivity of LCI results to changes in inputs and assumptions.

Manufacturing technologies

Cement

Cement, a fine gray powder, is manufactured from a mixture of naturally occurring raw materials[14]. Limestone typically constitutes about 80% of the raw mix with the remainder being clay or shale as a source of both silica and the necessary small amounts of alumina and iron. The raw materials are quarried, crushed, blended then ground to about 80% passing 200 mesh. The ground material is heated to 2,640 ^{0}F in a rotary kiln to give clinker, an intermediate product. The clinker is cooled and ground with the addition of about 5% gypsum, added to control setting time, to give cement. The process is continuous. It operates 24 hours per day for about 330 days per year. The capacity of the average cement plant in the U.S. is 650,000 tons.[15] Average energy consumption[6] is about 4.8 million Btu (mmBtu) per ton of cement.

Cement is transported from the manufacturing plant by road, rail or water to distribution terminals, and from there to the customer. The primary customer is the ready mixed concrete industry which accounts for about 60% of cement demand.

Concrete

Concrete, the widely used construction material, consists of a mixture of 10 to 15% cement added to a blend of coarse and fine aggregates, and water. The water causes hydration of the cement which sets to give a solid durable mass. Small amounts of chemical admixtures, usually less than 0.5% of the weight of the concrete, may be added to modify the performance of the product. The compressive strength of the concrete is chiefly a function of the cement and water content of the mix. Higher compressive strengths are achieved by increasing the amount of cement and optimizing the water content of the mix.

Concrete production is a batch process. In a central mixer operation, the concrete producer measures the quantities of cement, aggregates, water and admixtures to the customer specifications into a mixer. The mixed product is loaded into trucks with rotating drums for transportation to the job site. An alternative production method is transit mixing where the appropriate blend of cement and aggregates is loaded dry into the concrete trucks. Water is added and mixing takes place in the concrete truck en route to the job site. Central mixer operations are more common in urban centers while transit mixers dominate rural operations where distances from the batch plant to the job site are usually longer. For large projects, temporary batch plants are often set up at the job site.

Preliminary Results

Cement is the essential bonding agent in concrete. Cement constitutes only 10 to 15 percent of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error that will negatively affect the concrete industry.

Materials Input

Primary materials

Concrete mixes were chosen by PCA to represent products in broad use categories. A 28-day compressive strength of 3,000 pounds per square inch (psi) or less is frequently specified for residential and other general uses. These uses include foundations, basements, driveways and sidewalks. Structural applications including concrete for beams, columns and floor slabs often use 4,000 and 5,000 psi mixes, while precast and prestressed applications may require 7,500 or even 10,000 psi compressive strengths.

A range of representative mix designs selected for this project are presented in Table 1, and show that cement content increases from 376 pounds (lbs) per cubic yard in the case of 3,000 psi concrete to 850 lbs in the case of 7,500 psi concrete. Analysis of the LCI data for the various mixes indicates that cement content is the most important contributor to energy consumption and emissions associated with concrete production. The constituents of the concrete for a specific project depend on the required performance of the concrete. More information on mix designs is available in PCA publications.[14]

The total weight of concrete mix is about 4,000 lbs per cubic yard. The water content varies to ensure the workability of the mix but remains relatively constant. The weight of aggregates in the mix designs ranges from 3,300 to 2,700 lbs per cubic yd of concrete, tending to decrease as the cement content rises.

Admixtures

The SETAC guidelines[1] indicate that inputs to a process need not be included in the LCI if they are less than 1% of the total mass of the process materials or product, do not contribute significantly to a particular emission from the process or do not have a significant associated energy consumption.

Admixtures are the main category of ancillary material in concrete. Admixtures are included in the concrete mixture and are used to modify the properties of the fresh and hardened concrete. There are four broad types[16] of admixtures. These include:

- Inorganic chemicals.
- Organic chemicals and byproducts.
- Wood pulp byproducts.
- Meat processing byproducts

Examples of inorganic chemical admixtures include hardening accelerators such as calcium chloride and calcium nitrate. Examples of organic chemical admixtures include sugars and tartaric acid salts used as retarders, and emulsions of paraffins or coal tar used as concrete pumping aids. Wood processing byproducts include lignosulfonates and tall oil derivatives that act as air entraining agents and water reducering agents. Meat processing byproducts derived from tallow, such as stearates, are used for air entrainment or in damp-proofing.

Admixtures have not been included in the concrete LCI because they constitute less than 1% of the mass of the product, and in most cases are considerably less (Table 2). Additionally, the naturally occurring materials, tall oils and lignosulfonates, and fatty acids are byproducts which comprise a relatively small percentage of the mass of the primary products wood pulp and meat processing, respectively. They therefore, carry only a small proportion of the upstream profiles of the primary product. And finally, admixtures are generally retained in the concrete and contribute minimally to air pollution or effluents.

Energy Consumption

Concrete production consists of aggregate extraction, transportation of materials including cement from their source to the concrete plant, mixing and loading. Energy is consumed in each of these steps and energy is embodied in the cement incorporated in the mix. Using the 4,000 psi mix as an example, preliminary estimates indicate that the energy embodied in the cement accounts between 60 and 70% of the energy associated with the concrete. Aggregate extraction, batch plant operations and transportation each account for 10% to 12% of energy consumption per unit of concrete.

A mix containing about 400 lbs of cement, giving a product of approximately 3,000 psi compressive strength, requires a total of 1.5 mmBtu per cubic yd., while a mix with 800 lbs of cement giving a product with approximately 7,500 psi, requires 2.5 mmBtu. As the cement content rises aggregate content declines, and thus the energy used to extract it falls slightly. Energy used in transportation rises marginally as cement content increases because cement is assumed to be hauled a longer distance than aggregate. Energy consumed at the batch plant remains constant per cubic yd. of concrete mix.

Water Consumption

Other than water used in the mix, the amounts of water used in batch plant applications such as washout of mixers and trucks, truck wash off, dust control and general purposes, are not well quantified. Nor is the extent of recycling well characterized. Factors controlling water consumption and recycling include:

1. The type of plant: Central mix plants tend to use less wash off water than transit mixer operations.
2. Location: rural versus urban. Rural plants are more likely to use transit mixing. Urban plants tend to have central mixers.
3. Plant size. Larger plants, particularly those in urban areas, are more likely to have water recycling systems.
4. Availability of water. Water recycling is more prevalent in dry regions where water is scarce.

Detailed estimates of water consumption are not readily available but reported estimates[11] indicate a range of:

Water use	Range, gals/yd^3 of concrete
Truck wash off	3 - 64
Truck wash out	1 - 14
Miscellaneous	3 - 26
Total	7 - 104

Solid Wastes

Waste from aggregate extraction is assumed to consist primarily of over-burden which remains in the quarry and can be used for reclamation. It is not regarded as a waste requiring disposal. Waste generated at the batch plant comes primarily from three sources:

1. **Concrete returned to theconcrete plant**. This material may be:

- Treated with retarder and reused.
- Poured into forms to make a product.
- Used to pave open areas in the plant.
- Landfilled. Washed out into to settling ponds.

Estimates of the quantity of returned concrete range from 1 to 4% of the weight of the concrete. A large percentage quantity is recycled.

2. **Solids from truck wash out**. The frequency of wash out varies from operation to operation and has been estimated to be about 1.5 times per day. Each wash out generates about 130 lb. of waste.[11] This material is washed into settling ponds from which the solids may be recovered, allowed to solidify and used as fill material, or it may be landfilled.

3. **Solids from washout of the central mixer**. This material is treated in the same way as that from truck wash out.

Emissions

Combustion gases

The main combustion gases are H_2O (steam) and CO_2 (carbon dioxide). Minor combustion gases include SO_2 (sulfur dioxide), NO_x (nitrogen oxides), THC (total hydrocarbons) and CO (carbon monoxide). In general:

- CO_2 - A major portion of carbon dioxide emissions are attributable to the manufacture of cement. This is due to the fact that carbon dioxide emissions associated with cement production come not only from fuel combustion but also from calcination of the limestone in the raw material.
- SO_2 - The majority of SO_2 emissions per cubic yd. of concrete are those embodied in the cement. This SO_2 comes from sulfur in kiln fuels, such coal and petroleum coke.
- NO_x - Most of NO_x is attributable to the cement in the mix as a result of the high temperature in the burning zone of the kiln.
- THC - The majority of THC emissions are associated with aggregate extraction and transportation and result from the use of mobile equipment.
- CO - Emissions are divided almost equally between the cement where they are mainly from kiln operations, and from mobile equipment used in aggregate extraction and transportation.

Particulate Emissions

Particulate emissions, expressed as total particulates per cubic yd. of concrete, are influenced by the assumptions made about quarrying operations. The LCI takes a conservative approach assuming an average haul distance for aggregates of two miles on unpaved roads. The LCI also uses the conservative Source Classification Code (SCC) emission factor[8] of 52 lb. of particulates per vehicle mile traveled and a control factor of 70% as a result of water spray or other dust control treatment.

Based on these assumptions, aggregate extraction accounts for about most of the particulates. Estimates of particulate emissions per unit of product will be refined as more complete descriptions of quarrying operations are obtained.

Sensitivity Analysis

The purpose of a sensitivity analysis is to identify the assumptions and the data sets that have the greatest impact on the results of the LCI. This will permit efficient allocation of effort in validating the relevant assumptions, and refining the quality of the key data.

The sensitivity analysis of the concrete LCI is done using the input/output model which can test the impact on the LCI results of changes in any of the assumptions, input variables or emission factors.

A brief analysis of the preliminary data indicates that the LCI results are sensitive to the following factors:

1. Energy consumption per cubic yd. of concrete is primarily influenced by the cement content of the concrete mix.

2. Materials input is a function of mix design.

3. Water consumption, in uses other than the concrete mix, depends on the assumptions regarding water recycling.

4. Generation of solid wastes depends on the assumptions regarding waste recycling.

5. Emissions of CO_2, SO_2 and NO_x, are primarily dependent on cement content in the mix.

6. Particulate emissions are sensitive to assumptions about quarrying operations.

Conclusions

The data being developed in the PCA life cycle assessment of portland cement concrete will provide a means of comparing concrete with other construction materials and improving existing processes. The work is currently at the LCI stage. The LCI is being conducted according to SETAC guidelines and structured so that the results can be updated as new information becomes available. The preliminary results indicate that the energy input and most emissions associated with concrete production are mainly influenced by the cement content of the concrete mix.

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Table 1

Concrete Mix Designs

Mix No.	1	2	3	4	5	6
28-day Compressive Strength, psi	5000	4000	3000	7500 *	10000 *	Archit. Precast
Cement, lb.	564	470	376	850	750	650
Silica Fume, lb.	0	0	0	0	95	0
Water, lb.	237	237	237	300	230	260
Coarse aggregate, lb.	2000	2000	1900	1770	1875	1800
Fine aggregate, lb.	1200	1300	1400	935	1030	1250
Total weight, lb.	4001	4007	3913	3855	3980	3960
Density lb./ft^3	148	148	145	143	143	143

* Prestressed concrete mix

Table 2

Typical Dosage Rates of Admixtures in Concrete

Admixture	Dosage Rate, ml/100kg cement	Dosage Rate, oz/100 lb cement	Admixture, % of total weight of 5000 psi mix
Air entraining	30 - 520	0.5 - 8	0.004 - 0.071
Water reducers	190 - 590	3 - 9	0.026 - 0.079
Accelerators	390 - 5200	6 - 80	0.053 - 0.705
Superplasticizers	390 - 630	6 - 25	0.053 - 0.220

Source: Grace Construction Products, Cambridge MA, 1997.