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Environmental Life Cycle Inventory of Portland Cement Concrete

by Michael Nisbet, Martha G. VanGeem, John Gajda
and Medgar Marceau

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ENVIRONMENTAL LIFE CYCLE INVENTORY OF PORTLAND CEMENT CONCRETE

by Michael A. Nisbet, Martha G. VanGeem,

John Gajda, and Medgar L. Marceau*

EXECUTIVE SUMMARY

Purpose

The Portland Cement Association (PCA) is developing *Life Cycle Inventory* (LCI) and *Life Cycle Assessment* (LCA) data for use in evaluating environmental aspects of concrete products. The work is being conducted according to recognized guidelines with a clear definition of the system boundaries, data sources, process steps and functional units.

This report presents data on the LCIs of eleven portland cement concrete mixes.

Goal

The ultimate goal of the LCA is to have a complete and accurate information base that can 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 input and emission data for a specified range of concrete products. The data will be available for incorporation in existing and future LCA models designed to compare alternative construction materials or improving processes.

System boundaries and functional units

This document contains LCI data for manufacturing concrete from raw material extraction to units of concrete product. The three cases considered are (1) ready mix concrete exiting the plant gate, (2) concrete block exiting the manufacturing plant, and (3) precast concrete ready for placement in forms.

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Concrete production, as shown in Figure ES-1, consists of two linked operations, cement manufacture and concrete manufacture. The upstream profile of cement manufacturing is imported into the concrete manufacturing boundary. Aggregate extraction and preparation, and transportation of cement, fly ash and aggregates to the concrete plant are assumed to be within the concrete boundary.

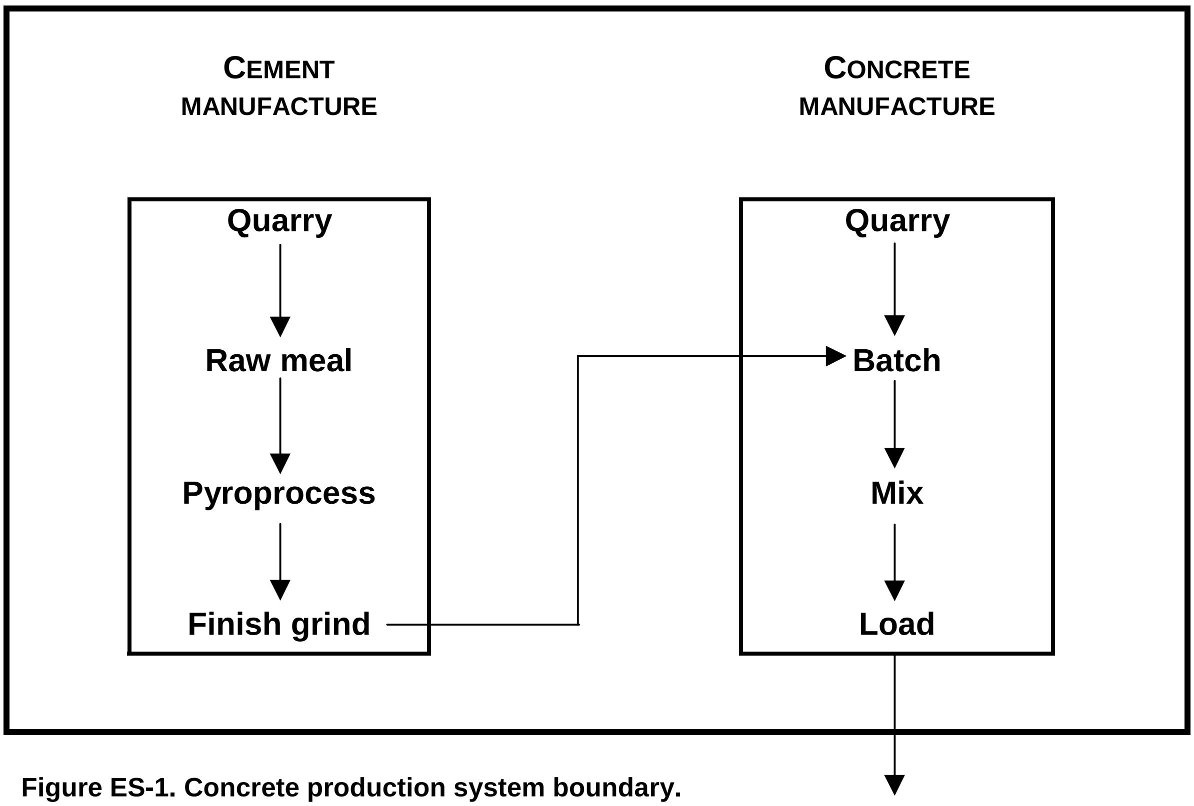

Figure ES-1. Concrete production system boundary.

The functional units are 1 cubic yard of ready mixed concrete, 1 cubic yard of precast concrete and one concrete block also referred to as a concrete masonry unit (CMU). A standard block is assumed to measure 8 x 8 x 16 in. and has 50% solid volume.

Mix designs

The eleven concrete mix designs used for the LCI are presented in Table ES-1. Ready mixed designs 1, 2 and 3 were chosen to represent 28-day compressive strengths of 5,000, 4,000 and 3,000 psi. The different compressive strengths of concrete represent different broad use categories. Structural concrete for beams, columns, floors, slabs, and other uses often specify 4,000 or 5,000 psi. Residential and other general use concrete is often 3,000 psi or less. Mixes 4 and 5 are for 3,000 psi concrete where 15% and 20% of the cement is replaced with fly ash, respectively. The purpose of including the LCI's of these mixes is to demonstrate the reduction of energy and emissions resulting from replacement of cement with other cementitious materials such as fly ash. It should be noted that approximately 90% of the ready mixed concrete market is in the 3,000 psi range, approximately 8% is 4,000 to 5,000 psi and only 1 to 2% is higher strengths.

Table ES-1. Concrete Mix Designs Used for LCI

Mix	28-day Compressive Strength, psi	Fly Ash Content, %	Silica Fume Content, %
Ready Mixed 1	5,000		
Ready Mixed 2	4,000		
Ready Mixed 3	3,000		
Ready Mixed 4	3,000	15	
Ready Mixed 5	3,000	20	
Ready Mixed 6 (Budget)	Not Specified	14	
Block Mix	Not Specified		
Block*	Not Specified		
Precast Mix 1	7,500		
Precast Mix 2	10,000		11
Precast Mix 3**	Not Specified		

Source: Portland Cement Association.
*8 x 8 x 16 in. CMU.
**Architectural precast panels.

Ready mixed design 6 was provided by the National Ready Mixed Concrete Association as a “budget” mix. This mix contains fly ash, slag and silica fume, all of which are assumed to be fly ash in the calculations.

The representative concrete mix used to make concrete block is expressed in terms of lb/cu yd and lb/concrete masonry unit (CMU). One cubic yard of mix makes approximately 104 blocks. Two high strength mixes and one architectural panel mix are included in the precast concrete analysis.

Information sources

Cement data are taken from the cement manufacturing LCI carried out by the Portland Cement Association in 1996 and updated with 1998 energy data. 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).

Calculations for each of the concrete mix designs have been made using an input/output model for concrete production. This allows rapid calculation of energy consumption and emissions for a wide range of mix designs.

Results

Portland cement content of the mix has a major impact on the LCI results for concrete. For example, as shown in Table ES-2 for the 3,000 psi mix, cement content accounts for approximately 71% of embodied energy up to the concrete plant gate. Cement content of the mix is also the main contributor of combustion gases.

Table ES-2. Embodied Energy by Process Step for 3,000 psi Mix

Process step	Embodied energy million Btu/yd^3	Percent of total energy
Cement production	0.87	71
Aggregate production	0.10	8
Transportation	0.09	7
Concrete plant operation	0.18	14
Total	**1.24**	**100**

Conclusions

The concrete products LCI has been carried out according to SETAC guidelines with a clear definition of goal and scope. Information used in the LCI is from published reports, U.S. EPA emission factors and information provided by concrete industry associations. The LCI results are calculated by a transparent input/output model. The results of the LCI can be readily updated to accommodate new input or emission data, or modified assumptions.

The results are an average of inputs and emissions from one cubic yard of concrete or one CMU. The LCI does not provide information about the age and efficiency of plants or the scale of operations, nor about regional factors which may affect transportation distances and concrete plant fuel use. The LCI assumes that aggregate consists of 61% crushed stone and 39% sand and gravel, unless otherwise noted.

The data on concrete plant water consumption and recycling, and solid waste generation and recycling are believed to be realistic estimates. These data will be updated when new information becomes available.

Recommendations

The LCI results are based on readily available information. In order to refine the results, it is recommended that more specific data be obtained in the following areas:

- Water consumption and recycling at central mixer and transit mixer operations.
- Concrete plant solid waste generation and recycling.
- Transportation distances for cement, aggregates, fly ash and silica fume.
- Energy consumption in concrete plants.
- Quarry haul road distances and unpaved road particulate emissions.

Upstream profiles of energy sources are not included in the LCI results. PCA's intention is to provide concrete LCI data for use in LCA models that include upstream profiles. It is recommended that PCA consider a parallel course of action and evaluate sources of upstream data that could be included in the PCA concrete LCI.

Representatives of the cement and concrete industries have reviewed the data used in the report. The LCI report contains some subjective indicators of data quality; however, it does not contain indicators rigorous enough to be in compliance with the requirements of ISO 14041. A set of industry standard data quality indicators complying with ISO 14041 has not yet been developed.

1. THE PORTLAND CEMENT ASSOCIATION LCA PROJECT

1.1 Report structure

An Environmental Life Cycle Assessment (LCA), as defined in ISO 14040[1], is "*a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.*" Section 1 of the report consists of a brief introduction to the concept of an Environmental Life Cycle Assessment and the steps in developing an LCA. It also presents the objectives of the PCA LCA project. Section 2 deals with the goals, scope and general aspects of the concrete products Life Cycle Inventory (LCI). Sections 3, 4, and 5 cover each of the three types of concrete products for which LCI data have been assembled: ready mixed concrete, concrete block and precast units. Each section contains:

- A brief description of the production process,
- The relevant LCI assumptions,
- Information sources,
- LCI results, and
- A sensitivity analysis.

A set of tables presenting the LCI results is included in Sections 3, 4, and 5.

1.2 Introduction to LCIs and LCAs

An LCA is a measure of the environmental impacts of a product, process or service during the course of its useful life. Developing an LCA consists of three steps as shown in Figure 1-1.

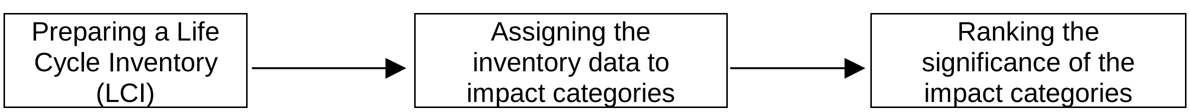

Figure 1-1. Process for developing an LCA.

The LCI consists of estimates of the materials and energy inputs and the emissions to air, land and water associated with manufacture of a product, operation of a process or provision of a service. In the case of ready mixed concrete, for example, materials include cement, aggregate and water whose use is expressed as pounds per cubic yard. Energy input is given in terms of million Btu per cubic yard and units of each energy source. Emissions to air are expressed as pounds per cubic yard.

The methodology for conducting an LCI has been documented by the US EPA[2], the Society of Environmental Toxicology and Chemistry (SETAC)[3] and the International Organization for Standardization (ISO)[1]. The Portland Cement Concrete LCI project follows the guidelines proposed by SETAC. These guidelines parallel the standards proposed by ISO in 14040 "Environmental Management Life Cycle Assessment - Principles and Framework," ISO 14041, "Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis" and other ISO documents.

The LCI results do not include the upstream profiles of cementitious materials other than portland cement or energy sources, for example, the energy and emissions associated with generating electricity or mining coal. PCA plans to make data on concrete available to LCA models that contain the relevant upstream profiles, or as an alternative, obtain upstream data from recognized databases.

In the LCA process, the data collected in LCI are allocated to impact categories. The number and types of impact categories are still under discussion by the groups standardizing LCA methodology. As an example, the National Institute of Standards in its LCA model, Building for Environmental and Economic Sustainability (BEES)[4] proposes five categories as presented in Table 1-1.

Table 1-1. Proposed Impact Categories and Proposed Weightings in BEES

Impact category	BEES proposed weighting
Global warming	28%
Acidification	17%
Nutrification	18%
Natural resource depletion	15%
Indoor air quality	12%
Solid waste generation	10%

If these categories are selected, the LCI data can be allocated to them in a scientific way. However, the next step in the LCA process, weighting the relative importance of the impact categories, can not be done in a fully objective manner. Choice of the weightings involves subjective judgement that reflects the preferences or priorities of the individual or group responsible for developing the weighting system. Using BEES again as an example, the weightings proposed in that model range from 28% for global warming to 10% for solid waste generation. The BEES model allows the user to change the weightings. Changing the weighting alters the outcome. For example if the LCI data for two competing materials are allocated to the same impact categories, their relative environmental impacts will generally depend on the selection of impact category weights.

Other LCA models may use a wider range of impact categories that could include, for example, stratospheric ozone depletion, photo-oxidant formation, habitat alterations and impacts on biodiversity.

1.3 Objectives of the PCA LCA project

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

The database developed by the project, and used in conjunction with available LCA models, 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 of concrete walls with homes made from competing materials.
- Concrete mixes with various amounts of recycled material.

It is anticipated that the data in this report will be incorporated in existing and future LCA models[4,5,6] for comparing alternative materials or improving processes.

2. GOALS, SCOPE AND GENERAL ASPECTS

2.1 Goal

The goal of this phase of the project is to assemble accurate LCI data for a range of concrete products.

2.2 Scope

This document contains LCI data for manufacturing concrete from raw material extraction to units of concrete product. The three cases being considered are (1) ready mix concrete exiting the plant gate, (2) concrete block exiting the manufacturing plant, and (3) precast concrete ready for placement in forms.

The upstream profile of cement manufacturing is imported into the concrete manufacturing boundary. Aggregate extraction and preparation, and transportation of cement, fly ash and aggregates to the concrete plant are assumed to be within the concrete boundary.

LCI data are presented for an average unit of product produced in the United States. The LCI is supported by spreadsheets that can calculate an LCI for a specific plant or group of plants. These spreadsheets are intended for use by PCA to test the sensitivity of LCI results and to update the LCI when new data become available.

Embodied energy and emissions associated with construction of concrete plant equipment and buildings, and the heating and cooling of the buildings is not included in the LCIs. This is generally acceptable if their materials, embodied energy and associated emissions account for less than 1% of those in the process.

2.3 Primary materials

2.3.1 Cement. The materials used in production of cement have their own set of material inputs and these are imported into the concrete LCI. For example, 2,000 lb of cement requires 3,175 lb of raw meal. Approximately 1.6 tons of raw meal are needed per ton of cement as a result of calcination of calcium carbonate which typically comprises 75% to 80% of the raw meal.

2.3.2 Cementitious materials. Fly ash, slag and silica fume are cementitious materials that can be used to replace some of the cement in concrete. In cases where they are used, they are assumed to replace cement in concrete on a one-to-one basis. The upstream profiles of these materials are not included in this LCI.

2.3.3 Aggregates. The aggregates used in concrete products can consist of crushed stone or sand and gravel. There are no readily available data on the relative quantities of crushed stone used in concrete and the data on energy consumption is limited. However, based on a suggestion by the National Aggregates Association(7), the relative amounts of crushed stone and sand and gravel in the average cubic yard of concrete are estimated from the relative amounts of each type of aggregate produced and used for construction purposes in the United States. Crushed stone and sand and gravel production data for 1997 reported by the U.S. Geological Survey (USGS) are presented in Table 2-1.

Table 2-1. Crushed Stone and Sand and Gravel Production Data for 1997

	Crushed stone(8)	Sand and gravel(9)
Production (thousand metric tons)	1,420,000	952,000
Percent used in construction	82.8	79.5
Amount used in construction (thousand metric tons)	1,176,000	757,000
Percent of total aggregate used in construction	61	39

Source: References 8 and 9.

Reference 8 identifies 82.8% of the total crushed stone production as being used in construction. According to Reference 9 on sand and gravel, 42.8% is used for concrete aggregates, 23.3% for road base and coverings and road stabilization, and 13.4% for asphalt concrete. These uses total 79.5% and are assumed to be equivalent to construction uses in the case of crushed stone. The data indicate that in 1997, roughly 1.2 billion tons of crushed stone and 757 million tons of sand and gravel were used in construction. Therefore, of the amount of aggregate used in construction, approximately 61% is crushed stone and 39% is sand and gravel. Based on these percentages, the aggregate used in the average cubic yard of concrete is assumed to consist of 61% crushed stone and 39% sand and gravel.

The concrete mix designs specify quantities of coarse and fine aggregates. There are no readily available data distinguishing between the energy and emissions associated with production of coarse versus fine aggregates. For this reason we have classified the aggregates used in the mix as either crushed stone or sand and gravel.

For example, 3,000 psi concrete has the following mix design:

Cement	376 lb/yd^3
Water	237 lb/yd^3
Coarse aggregates	1900 lb/yd^3
Fine aggregates	1400 lb/yd^3
Total aggregates	2300 lb/yd^3

Crushed stone in mix equals 2300 x 0.61 = 1403 lb/yd^3
Sand and gravel in mix equals 2300 x 0.39 = 897 lb/yd^3

2.4 Ancillary materials; admixtures

The SETAC guidelines[3] 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 processed materials or product, do not contribute significantly to a particular emission, nor have a significant associated energy consumption.

Admixtures are widely used in concrete to control its properties and performance. The dosage rate of admixtures in concrete is typically well below the one percent level, as noted in Table 2-2, and therefore are excluded from the concrete LCI. A communication from Grace Construction Products[10] indicates that admixtures within concrete are not likely to be a source of emissions or effluent contamination because they are to a large extent chemically bonded and retained in the concrete product.

Table 2-2. Typical Admixture Dosage Rates in Concrete

Admixture	Dosage Rate, mL/100 kg cement	Dosage Rate, oz/100 lb cement	Admixture, as percent of mass of 5,000 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, Reference 10.

2.5 Quarry haul road emissions

The original versions of the cement and concrete LCIs used the U.S. Environmental Protection Agency (EPA) SCC AIRS emission factor[11] to estimate fugitive dust caused by truck traffic on unpaved quarry haul roads. This factor was chosen because there was not enough information to permit application of the EPA AP-42[12] unpaved haul road equation.

The SCC AIRS factor for uncontrolled emissions is 52 lb of total suspended particulates per vehicle mile traveled. With an assumed dust control factor of 70% resulting from water sprays, haul road emissions per ton of quarried material were considered to be too high. The National Stone Association commissioned a study[13] whose objective was to review and update the AP-42 unpaved haul road equation. This study conducted tests in three quarries and found that the AP-42 equation overestimated PM_{10} (particles with and a mass median aerodynamic diameter of less than 10 micrometers) emissions by a factor ranging from 2 to 5 times. The test conditions at the tested quarries are presented in Table 2-3.

The measured PM_{10} emissions resulted in an average emission factor for the three quarries of 1.04 lb of PM_{10} per vehicle mile traveled as shown in Table 2-4. Multiplying PM_{10} by 2.1[24] gave an emission factor of 2.18 lb of total suspended particulates per vehicle mile traveled. This factor is used in the concrete products LCI to estimate unpaved haul road emissions from crushed stone operations and sand and gravel operations.

Table 2-3. Test Conditions for Quarry Study of Particulate Emissions

Variable	Quarry No. 1	Quarry No. 2	Quarry No. 3
Average silt content, %	7.39	7.35	7.49
Average moisture content, %	6.42	4.9	5.96
Average truck speed, mph	18.55	16.87	16.94
Average truck weight, tons	52.5	52.5	52.5
Average wind speed, mph	5.74	5.07	1.6
Average watering interval, hours	2.97	3.98	2.29
Water application rates, L/m^2	0.846	0.846	0.846

Source: Reference 13.

Table 2-4. Test Results for Quarry Study of Particulate Emissions

Test location	Emission Factor, lb per vehicle mile traveled (VMT)	
	PM_{10}	Total Suspended Particles (TSP)
Quarry No. 1	0.29	0.61
Quarry No. 2	1.74	3.65
Quarry No. 3	1.08	2.27
Average	**1.04**	**2.18**

Source: Reference 13.

We realize that data based on such a small sample can not be regarded as representative of all quarry operations. LCI results indicate that unpaved quarry roads can account for up to 40% of the emissions associated with aggregate production. Because of this significance, efforts will be made to obtain more complete data on haul road emissions.

2.6 Hazardous air pollutants

The air emission data in the LCI include particulate matter from point and fugitive sources and the combustion gases CO_2, SO_2, NO_x, CO, VOC and methane (CH_4).

Test data are available for emissions from cement kilns of hydrogen chloride, mercury and dioxins and furans[28]. Equivalent data are not readily available for the other steps in the concrete manufacturing process. For this reason we have not, at this time, included emissions of hazardous air pollutants in the LCI of concrete products but plan to do so when we have access to more complete data.

3. READY MIXED CONCRETE LCI

The following process description of the ready mixed concrete production process is taken from AP-42 Section 11.12, *Concrete Batching*[(14)].

> *Concrete is composed essentially of water, cement, sand (fine aggregate), and coarse aggregate. Coarse aggregate may consist of gravel, crushed stone, or iron blast furnace slag. Some specialty aggregate products could be either heavyweight aggregate (barite, magnetite, limonite, ilmenite, iron, or steel) or lightweight aggregate (with sintered clay, shale, slate, diatomaceous shale, perlite, vermiculite, slag, pumice, cinders, or sintered fly ash). Concrete batching plants store, convey, measure and discharge these constituents into trucks for transport to a job site. In some cases, concrete is prepared at a building construction site or for the manufacture of concrete products such as pipes and prefabricated construction parts.*
>
> *The raw materials can be delivered to a plant by rail, truck, or barge. The cement is transferred to elevated storage silos pneumatically or by bucket elevator. The sand and coarse aggregate are transferred to elevated bins by front-end loader, clam shell crane, belt conveyor, or bucket elevator. From these elevated bins, the constituents are fed by gravity or screw conveyor to weigh hoppers, which combine the proper amounts of each material.*
>
> *Truck mixed (transit mixed) concrete involves approximately 75 percent of U.S. concrete batching plants. At these plants, sand, aggregate, cement, and water are all gravity fed from the weigh hopper into the mixer trucks. The concrete is mixed on the way to the site where the concrete is to be poured. Central mix facilities (including shrink mixed) constitute the other one-fourth of the industry. With these, concrete is mixed and then transferred to either an open bed dump truck or an agitator truck for transport to the job site. Shrink mixed concrete is concrete that is partially mixed at the central mix plant and then completely mixed in a truck mixer on the way to the job site. Dry batching, with concrete mixed and hauled to the construction site in dry from, is seldom, if ever, used.*
>
> *Particulate matter, consisting primarily of cement dust but including some aggregate and sand dust emissions, is the only pollutant of concern. All but one of the emission points are fugitive in nature. The only point source is the transfer of cement to the silo, and this is usually vented to a fabric filter or "sock". Fugitive sources include the transfer of sand and aggregate, truck loading, mixer loading, vehicle traffic, and wind erosion from sand and aggregate storage piles. The amount of fugitive emissions generated during the transfer of sand and aggregate depends primarily on the surface moisture content of these materials. The extent of fugitive emission control varies widely from plant to plant.*
>
> *Types of controls used may include water sprays, enclosures, hoods, curtains, shrouds, movable and telescoping chutes, and the like. A major source of potential emissions, the movement of heavy trucks over unpaved or dusty surfaces in and around the plant, can be controlled by good maintenance and wetting of the road surface.*

3.1 System boundary

The ready mixed concrete system boundary, the area inside the frame in Figure 3-1, includes production of cement and aggregates but does not include production of other cementitious materials. The boundary includes energy and emissions associated with transportation of primary materials from their source to the concrete plant. It does not include upstream profiles associated with energy sources or water nor does it include energy and emissions from transportation of energy to the plant.

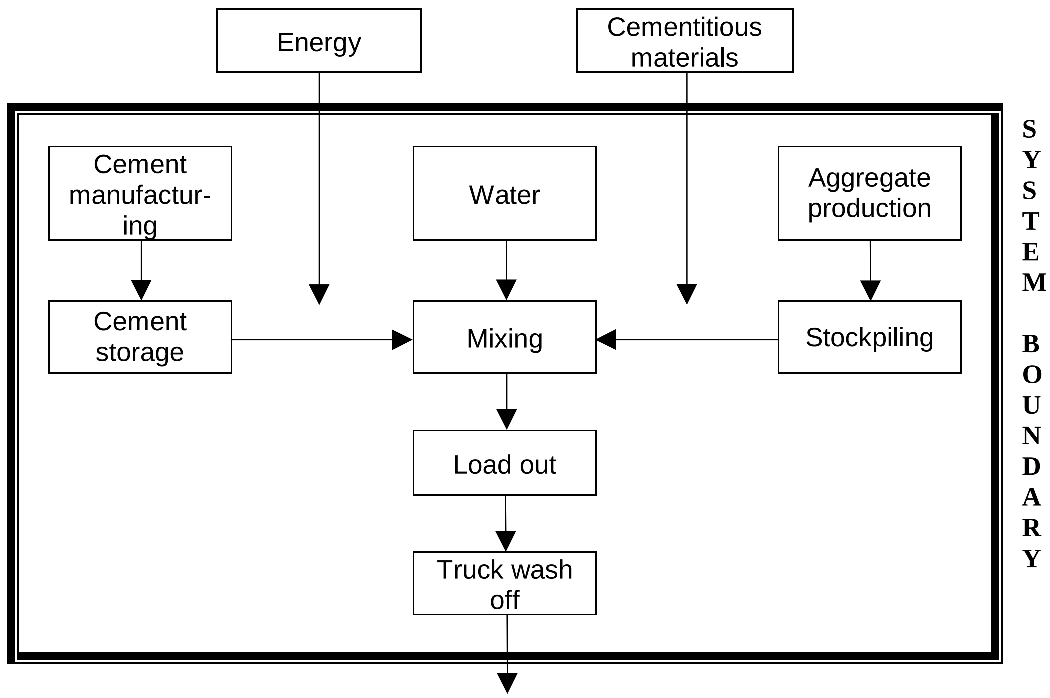

Figure 3-1. Ready mixed concrete system boundary.

3.2 Assumptions

The following assumptions are made for calculating the LCA of the functional unit of concrete.

(a) Functional unit: 1 cubic yard of concrete.
(b) Cement data are based on the LCI of the weighted average ton of cement produced in the U.S.
(c) English units are used throughout.
(d) Aggregates, unless otherwise specified, are assumed to consist of 61% crushed stone and 39% sand and gravel (see Section 2.3.3).
(d) Energy consumption in concrete production is estimated for a central mix operation.
(e) Round trip transportation distances to the concrete plant are:

- Cement: 60 miles.
- Fly ash: 60 miles.
- Aggregates: 30 miles.

(g) All transportation is assumed to be by road. This assumption is conservative because energy consumption and emissions are generally greater for road transportation than for rail or barge.

(h) Upstream profiles of energy sources such as coal, diesel fuel and electricity are not included in this LCI.
(i) Upstream profiles for fly ash and silica fume are not included in this LCI.

3.3 Mix designs

The six concrete mix designs are shown in Table 3-1. Mix designs 1 through 3 were chosen to represent 28-day compressive strengths of 5,000, 4,000 and 3,000 psi. Mixes 4 and 5 are for 3,000 psi concrete but with 15 and 20% of the cement replaced by fly ash. The purpose is to demonstrate the reduction of energy and emissions resulting from replacement of cement with other cementitious materials. Approximately 90% of the ready mixed concrete market is in the 3,000 psi range, approximately 8% is in the 4,000 to 5,000 psi range and only 1 to 2% is for higher strengths[(15)].

Mix 6 was provided by the National Ready Mixed Concrete Association (NRMCA)[(16)] as a "budget" mix. This mix contains fly ash, slag and silica fume, all of which are assumed to be fly ash in the calculations. These account for 14% of total cementitious material. Mixes 1 to 5 assume that aggregates consist of 61% crushed stone and 39% sand and gravel, while the budget Mix 6 as specified by NRMCA consists of 43% crushed stone and 57% sand and gravel.

3.4 Information sources

Cement data is taken from the PCA cement manufacturing LCI report[(17)]. Assumptions, data sources and references relevant to the cement LCI are available in that report.

Data on inputs and emissions for concrete production are from published reports, EPA emission factors, and information provided by the Environmental Council of Concrete Organizations (ECCO) members. Tables 3-2 and 3-3 summarize the references for materials and energy consumption data and emissions data, respectively.

Calculations for each of the concrete mix designs have been made using the PCA spreadsheet for concrete production. This allows rapid calculation of energy consumption and emissions for a wide range of mix designs.

3.5 Energy inputs

Energy used in concrete production includes embodied energy in the cement, energy used to extract and process aggregates, transportation energy, and energy used in the concrete plant.

3.5.1 Embodied energy in the cement. Data is taken from the cement manufacturing LCI[(17)].

Table 3-1. Concrete Mix Designs and Properties*

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget
Fly ash, %	0	0	0	15	20	14
Unit weight, lb/ft^3	148	148	145	145	145	144
Concrete raw material, lb/yd^3 concrete						
Cement	564	470	376	320	301	450
Fly ash	0	0	0	56	75	71
Water	237	237	237	237	237	224
Coarse aggregate	2,000	2,000	1,900	1,900	1,900	1,850
Fine aggregate	1,200	1,300	1,400	1,400	1,400	1,300
Total	**4,001**	**4,007**	**3,913**	**3,913**	**3,913**	**3,895**

*Concretes with different compressive strengths represent different broad use categories. Structural concrete for beams, columns, floors, slabs, and other uses often specify 4,000 or 5,000 psi. Residential and other general use concrete is often 3,000 psi or less.

Source: Portland Cement Association.

Table 3-2. References for Materials Energy and Consumption Data

Materials and Energy Consumption	Reference
Composition of portland cement concrete	LCI assumptions
Primary energy used to manufacture portland cement	17
Primary energy used to produce aggregates	18, 19, 20, 21
Primary energy used in the concrete plant	22
Primary energy used in transportation of materials to the concrete plant	Calculated from Ref. 23
Transportation energy factors	23
Electricity consumption in production of portland cement concrete	Calculated from Refs. 16 to 23

Table 3-3. References for Emissions Data

Emissions	Reference
Emissions from production of portland cement	17
Emissions from crushed stone quarry operations	11, 13
Emissions from crushed stone operations	24
Emissions from sand and gravel operations	25
Concrete plant particulate emissions	14
Transportation emission factors	23
Emissions from transportation of materials to concrete plant	Calculated from Ref. 23
Emissions from fuel used at concrete plant	26, 27

3.5.2 Energy used to extract and process aggregates. Much of the available data on the energy used in aggregate production is from the late 1970s and ranges from 15,000 Btu per ton of sand to 205,000 Btu per ton of washed crushed stone. A representative set of data is shown in Table 3-4. We realize that these data may not fully represent current practices, and are taking steps to obtain more up-to-date information.

The range of 58,000 to 177,000 Btu per ton of dry processed crushed stone reported in the Battelle study was considered too wide to be of practical use. We therefore chose the conservative estimates of 70,000 Btu/ton for crushed stone and 40,000 Btu/ton for sand and gravel for use in the LCI.

Table 3-4. Range of Estimates of Energy Consumed in Aggregate Production

Data source	Type of Aggregate	Embodied Energy, Btu/ton	Ref.
Battelle Columbus Labs.	Dry processed crushed stone	58,000 to 177,000	18
	Crushed washed gravel and washed sand	34,000	18
Texas A&M	Crushed stone	70,000	20
	Crushed gravel	40,000	20
	Uncrushed aggregate	15,000	20
Asphalt Institute	Crushed stone	56,000	21
	Crushed gravel	40,000	21
	Uncrushed gravel	15,000	21
ACPA	Crushed stone	70,000	19
	Sand	15,000	19

It is assumed for the purpose of this LCI that:

- The energy required to produce crushed stone is 70,000 Btu/ton.
- The energy required to produce sand and gravel is 40,000 Btu/ton.
- 50% of the energy used is diesel fuel and 50% is electricity.
- 61% of the aggregate in Mixes 1 to 5 is crushed stone and 39% is sand and gravel.
- 43% of the aggregate in Mix 6 is crushed stone and 57% is sand and gravel.

3.5.3 Transportation energy. Transportation of cement, fly ash and aggregates from their source to the concrete plant is included. All transportation is assumed to be by road using diesel fuel. This assumption is conservative because energy consumption and emissions are greater for road transportation than for rail or barge. The average round trip haul distances are assumed to be 60 miles for both cement and fly ash, and 30 miles for aggregates. ECCO members accepted these distances as reasonable. The energy consumption of 1465 Btu per ton-mile assumes that transportation energy efficiency is 9.4 gallons of diesel fuel per 1000 ton-miles[(23)].

3.5.4 Energy used in the concrete plant. The data presented in Table 3-5 for the concrete plant include electricity and fuel used for equipment and heating, and are from the Forintek report[(22)].

These data, adapted from Canadian concrete plant estimates, are considered to be similar to those of U.S. operations. However, we intend to develop U.S. data to replace that which is currently used in the LCI.

Table 3-5. Energy Used in the Concrete Plant

Energy Source	Metric Units, GJ/tonne	English Units, million Btu/ton	English Units, million Btu/yd^3	Percent of Total
Electricity	0.0060	0.0052	0.0103	5.8
Light petroleum gas (LPG)	0.0175	0.0151	0.0302	16.8
Natural gas	0.0175	0.0151	0.0302	16.8
Middle distillates (Diesel fuel)	0.0630	0.0543	0.1086	60.6
Total	**0.1040**	**0.0896**	**0.1792**	**100.0**

Source: Reference 22.

3.6 Water consumption

Water consumption other than that in the concrete mix is affected by three principal factors:

- **The Type of Plant.** Central mix plants load a wet product into the concrete trucks and tend to require less wash off water than transit mixer operations that load out a dry material.
- **Plant Location.** Rural plants with longer average hauls to job sites are more likely to use transit mixers than urban plants that have shorter hauls.
- **Plant Size.** Larger plants, particularly those in urban areas, are more likely to have water recycling systems.

Reported estimates(22) of the range of water consumption are presented in Table 3-6.

Table 3-6. Estimate of Water Use at a Concrete Plant*

Water Use	Quantity Range, gal/yd^3 of concrete
Truck wash off	3 - 64
Truck wash out	1 - 14
Miscellaneous	3 - 26
Total	**7 - 104**

*Other than that used in the concrete mix.
Source: Reference 22.

The available data on water consumption show wide ranges for each of the applications. Rather than use an average, the NRMCA(15) suggested, in the absence of more complete data on post production water consumption (water that is not used in the concrete mix), that 35 gallons per cubic yard be used as a representative quantity until better data can be obtained.

Total water used at a concrete plant is assumed to be 35 gallons (292 lb) per cubic yard plus the amount used for the concrete mix from Table 3-1.

3.7 Air emissions

The AP-42 emission factors(24) were assumed to apply to production of coarse and fine aggregates from crushed stone. Emissions from sand and gravel operations, because of wet processing, were estimated to be considerably less than crushed stone operations calculated and were also based on AP-42 factors(25).

Aggregate quarries are assumed to be similar to cement plant quarries with an average of 2 miles from the quarry face to a paved road giving a round trip of 4 miles. Stockpiled materials are a significant source of fugitive particulate emissions. The quantity of material in stockpiles at any point in time varies considerably from operation to operation and is difficult to quantify. For the purpose of our analysis we assume stockpiles contain an average of 10% of annual throughput at all times.

Air emissions from diesel trucks are calculated from the energy consumption per ton-mile and emission factors provided by Franklin Associates(23) for combustion gases released per million Btu of fuel consumed. Since these factors do not include methane emissions, we used the methane emission factor provided in Reference 22.

3.8 Solid wastes

Production of the weighted average ton of cement generates approximately 104 lb of cement kiln dust(17). This value is included in the concrete LCI.

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 that requires disposal. The industry average for solid waste is about 2 to 5% of production(15). About 90% of this is recycled. The high level of recycling is due to high landfill costs, typically $25 to $50 per ton.

Recycling options include:

- Windrowing returned material, letting it harden, then crushing it and using it as fill or aggregate.
- Using hydration control agents and reshipping.
- Pouring returned material into forms such as blocks or other shapes.
- Using returned material to pave plant property.
- Reclaiming and reusing the slurry.

Assuming 90% recycling solid waste generated would be about 26 lb per cubic yard of concrete. These data and assumptions will be updated when more recent information is available.

Table 3-7. Estimates of Solid Wastes Generated at a Ready-Mix Concrete Plant

Activity	Wastes, lb/yd^3 of concrete
Returned concrete	212
Truck wash out	46
Mixer wash out	6
Subtotal (assuming no recycling)	264
Recycling (assuming 90%)	238
Total waste (assuming 90% recycling)	**26**

Source: Reference 22.

It is assumed that materials such as lubricating oil and solvents used in maintenance of plant and mobile equipment are used in small quantities compared to the primary materials, and are recycled.

3.9 Waste heat

The cement LCI estimates waste heat from cement production to average 1.19 million Btu per ton(17). This is heat lost primarily in kiln and cooler exhaust gases and also by radiation from the kin shell and other hot surfaces. No data are available on waste heat from other stages of the concrete manufacturing process, therefore, waste heat is not included at this time in the concrete LCI.

3.10 Ready mixed concrete LCI results

3.10.1 Primary materials. The weight of materials including cementitious material, aggregates and water remain relatively constant at about 4,000 lb per cubic yard of concrete regardless of the mix design. As the cementitious content increases in the higher strength mixes it is balanced by a decrease in aggregate content as presented in Tables 3-1. Table 3-8 shows the amount of raw materials required to make a cubic yard of concrete taking into account the fact that an average of 1.6 tons of raw material are needed to produce one ton of cement.

3.10.2 Energy input. Energy consumption data per cubic yard of each mix are presented in Tables 3-9 and 3-10 for cement manufacturing, aggregate production, transportation and operation of the concrete plant. Table 3-9 presents energy consumption in terms of million Btu and Table 3-10 presents the data in terms of energy units, for example pounds of coal, gallons of diesel fuel, or kilowatt hours.

Table 3-8. Material Inputs for Ready Mixed Concrete Production*

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6	Reference
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget	Table 3-1
Cement, lb/yd^3 cocnrete	564	470	376	320	301	450	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement raw material*, lb/yd^3 concrete							
Limestone	651	542	434	369	347	519	17
Cement rock, marl	104	87	69	59	55	83	17
Shale	53	44	35	30	28	42	17
Clay	27	22	18	15	14	22	17
Bottom ash	3	3	2	2	2	2	17
Fly ash	12	10	8	7	6	10	17
Foundry sand	3	2	2	2	2	2	17
Sand	8	6	5	4	4	6	17
Iron, iron ore	2	2	1	1	1	1	17
Gypsum, anhydrite	34	28	23	20	18	28	17
Water	462	385	308	262	247	369	17
Subtotal**	**897**	**746**	**597**	**509**	**477**	**715**	
Other concrete raw material, lb/yd^3 concrete							
Fly ash	0	0	0	56	75	71	Table 3-1
Water	237	237	237	237	237	224	Table 3-1
Coarse aggregate	2,000	2,000	1,900	1,900	1,900	1,850	Table 3-1
Fine aggregate	1,200	1,300	1,400	1,400	1,400	1,300	Table 3-1
Subtotal	**3,437**	**3,537**	**3,537**	**3,593**	**3,612**	**3,445**	

*U.S. and Canadian Labor-Energy Input Survey, Portland Cement Association, Skokie IL, October 1999.

**Approximately 1.6 tons of raw materials are needed to make 1 ton of cement due primarily to calcination of the limestone. Subtotal does not include water.

Table 3-9. Energy Inputs for Ready Mixed Concrete Production in Million Btu

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6	Reference
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacturing, million Btu/yd^3 concrete							
Coal	0.767	0.639	0.511	0.435	0.409	0.612	17
Gasoline	0.000	0.000	0.000	0.000	0.000	0.000	17
LPG	0.000	0.000	0.000	0.000	0.000	0.000	17
Middle distillates	0.011	0.009	0.007	0.006	0.006	0.008	17
Natural gas	0.095	0.079	0.064	0.054	0.051	0.076	17
Petroleum coke	0.190	0.159	0.127	0.108	0.102	0.152	17
Residual oil	0.002	0.001	0.001	0.001	0.001	0.001	17
Wastes	0.106	0.088	0.071	0.060	0.056	0.084	17
Electricity	0.135	0.113	0.090	0.077	0.072	0.108	17
Subtotal	**1.307**	**1.089**	**0.871**	**0.741**	**0.697**	**1.042**	
Aggregate production, million Btu/yd^3 concrete							
Crushed stone							
Diesel fuel	0.034	0.035	0.035	0.035	0.035	0.024	*
Electricity	0.034	0.035	0.035	0.035	0.035	0.024	*
Sand and gravel							
Diesel fuel	0.012	0.013	0.013	0.013	0.013	0.018	*
Electricity	0.012	0.013	0.013	0.013	0.013	0.018	*
Subtotal	**0.093**	**0.096**	**0.096**	**0.096**	**0.096**	**0.083**	
Transporting materials to plant, million Btu/yd^3 concrete							
Diesel fuel							
Cement	0.025	0.021	0.017	0.014	0.013	0.020	**
Coarse aggregate	0.044	0.044	0.042	0.042	0.042	0.041	**
Fine aggregate	0.026	0.029	0.031	0.031	0.031	0.029	**
Fly ash	0.000	0.000	0.000	0.002	0.003	0.003	**
Subtotal	**0.095**	**0.093**	**0.089**	**0.089**	**0.089**	**0.092**	
Concrete plant operations, million Btu/yd^3 concrete							
Diesel fuel	0.139	0.139	0.139	0.139	0.139	0.139	22
Natural gas	0.030	0.030	0.030	0.030	0.030	0.030	22
Electricity	0.010	0.010	0.010	0.010	0.010	0.010	22
Subtotal	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	
Total	**1.674**	**1.457**	**1.235**	**1.106**	**1.062**	**1.397**	

*LCI assumptions and References 18 through 21.

**LCI assumptions and Reference 23.

Table 3-10. Energy Inputs for Ready Mixed Concrete Production by Fuel Type

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6	Reference
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacturing, fuel unit/yd^3 concrete							
Coal, lb	65.5	54.6	43.7	37.2	35.0	52.3	17
Gasoline, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
LPG, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
Middle distillates, gallon	0.1	0.1	0.1	0.0	0.0	0.1	17
Natural gas, ft^3	86.8	72.3	57.8	49.2	46.3	69.2	17
Petroleum coke, lb	13.0	10.8	8.7	7.4	6.9	10.4	17
Residual oil, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
Wastes, lb	10.6	8.8	7.1	6.0	5.6	8.4	17
Electricity, kWh	39.6	33.0	26.4	22.5	21.1	31.6	17
Aggregate production, fuel unit/yd^3 concrete							
Crushed stone							
Diesel fuel, gallon	0.2	0.3	0.3	0.3	0.3	0.2	*
Electricity, kWh	10.0	10.3	10.3	10.3	10.3	6.9	*
Sand and gravel							
Diesel fuel, gallon	0.1	0.1	0.1	0.1	0.1	0.1	*
Electricity, kWh	3.7	3.8	3.8	3.8	3.8	5.3	*
Transporting materials to plant, fuel unit/yd^3 concrete							
Diesel fuel, gallon							
Cement	0.2	0.1	0.1	0.1	0.1	0.1	**
Coarse aggregate	0.3	0.3	0.3	0.3	0.3	0.3	**
Fine aggregate	0.2	0.2	0.2	0.2	0.2	0.2	**
Fly ash	0.0	0.0	0.0	0.0	0.0	0.0	**
Concrete plant operations, fuel unit/yd^3 concrete							
Diesel fuel, gallon	1.0	1.0	1.0	1.0	1.0	1.0	22
Natural gas, ft^3	29.5	29.5	29.5	29.5	29.5	29.5	22
Electricity, kWh	3.0	3.0	3.0	3.0	3.0	3.0	22

*LCI assumptions and References 18 through 21.
**LCI assumptions and Reference 23.

Energy consumption varies primarily with cement content of the mix ranging from 1.235 million Btu/yd^3 for the 3,000 psi mix which contains 376 lb of cement, to 1.674 million Btu/yd^3 for the 5,000 psi mix which contains 564 lb of cement. Energy required to produce aggregate is relatively small ranging from about 0.09 to 0.10 million Btu/yd^3. Transportation energy is relatively constant at about 0.09 million Btu/yd^3 for all the mixes, while energy used in the concrete plant is constant at 0.179 million Btu/yd^3 regardless of the mix design.

The affect on energy consumption of replacing cement with other cementitious materials such as fly ash is shown in Table 3-11 using the 3,000 psi as an example. The data indicates that one percent replacement of cement with fly ash results in approximately 0.7% reduction in energy consumption per cubic yard of concrete.

Table 3-11. Effect on Embodied Energy of Addition of Fly Ash to the Mix

Mix No.	**Ready Mixed 3**	**Ready Mixed 4**	**Ready Mixed 5**
Compressive strength, psi	**3,000**	**3,000**	**3,000**
Cement content, lb/yd^3	376	320	301
Fly ash content, lb/yd^3	0	56	75
Total cementitious material, lb/yd^3	376	376	376
Percent replacement of cement with fly ash	0%	15%	20%
Embodied energy, million Btu/yd^3	1.235	1.106	1.062
Percent reduction in embodied energy	0%	10.5%	14.0%

3.10.3 Air emissions. Table 3-12 presents the air emissions from transportation of finished goods to concrete plant. Table 3-13 presents the air emissions data per cubic yard of each mix for the process stages: cement manufacturing, aggregate production, transportation and operation of the concrete plant. Table 3-14 shows total emissions.

The amounts of CO_2 and other combustion gases associated with concrete production are primarily a function of the cement content in the mix designs. As shown in Table 3-14, CO_2 emissions range from 381 lb/yd^3 for the 3,000 psi mix to 550 lb/yd^3 for the 5,000 psi mix. SO_2 ranges from 1.64 to 2.38 lb/yd^3 for the same mixes, while NO_X ranges from 1.57 to 2.25 lb/yd^3.

Aggregate production and cement manufacturing are similar in their contributions to particulate emissions associated with concrete production. As shown in Table 3-13, particulate emissions from aggregate production range from 0.70 lb/yd^3 for the 3,000 psi mix to 0.68 lb/yd^3 for the 5,000 psi mix. Particulate emissions associated with cement manufacturing are 0.91 and 1.37 lb/yd^3 for the 3,000 psi and 5,000 psi mixes, respectively.

Table 3-12. Air Emissions from Finished Goods Transport to Concrete Plant for Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget
Fly ash, %	0	0	0	15	20	14
Cement and fly ash transportation, lb/yd^3 concrete						
Particulate Matter	0.005	0.004	0.004	0.004	0.004	0.005
CO_2	4.083	3.403	2.722	2.722	2.722	3.772
SO_2	0.006	0.005	0.004	0.004	0.004	0.006
NO_x	0.038	0.031	0.025	0.025	0.025	0.035
VOC*	0.007	0.006	0.005	0.005	0.005	0.006
CO	0.037	0.031	0.025	0.025	0.025	0.035
CH_4	0.001	0.001	0.001	0.001	0.001	0.001
Aggregate transportation, lb/yd^3 concrete						
Particulate Matter	0.015	0.016	0.016	0.016	0.016	0.015
CO_2	11.584	11.946	11.946	11.946	11.946	11.403
SO_2	0.018	0.019	0.019	0.019	0.019	0.018
NO_x	0.107	0.110	0.110	0.110	0.110	0.105
VOC*	0.019	0.020	0.020	0.020	0.020	0.019
CO	0.106	0.110	0.110	0.110	0.110	0.105
CH_4	0.003	0.003	0.003	0.003	0.003	0.003
Total material transportation, lb/yd^3 concrete						
Particulate Matter	0.020	0.020	0.019	0.019	0.019	0.020
CO_2	15.667	15.349	14.668	14.668	14.668	15.175
SO_2	0.025	0.024	0.023	0.023	0.023	0.024
NO_x	0.144	0.141	0.135	0.135	0.135	0.140
VOC*	0.026	0.025	0.024	0.024	0.024	0.025
CO	0.144	0.141	0.134	0.134	0.134	0.139
CH_4	0.004	0.004	0.004	0.004	0.004	0.004

*Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.
Source: Table 3-9, Table 3-10, and Reference 22.

Table 3-13. Air Emissions by Process Step for Ready Mix Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6	Reference
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacture, lb/yd^3 concrete							
Particulate Matter	1.369	1.141	0.913	0.777	0.731	1.092	17
CO_2	502	419	335	285	268	401	17
SO_2	2.201	1.834	1.467	1.249	1.174	1.756	17
NO_x	2.010	1.675	1.340	1.140	1.073	1.603	17
VOC*	0.035	0.029	0.023	0.020	0.019	0.028	17
CO	0.053	0.044	0.035	0.030	0.028	0.042	17
CH_4	0.032	0.026	0.021	0.018	0.017	0.025	17
Aggregate production, lb/yd^3 concrete							
Particulate Matter	0.680	0.701	0.701	0.701	0.701	0.669	11, 13, 24
CO_2	7.683	7.923	7.923	7.923	7.923	6.862	22
SO_2	0.012	0.013	0.013	0.013	0.013	0.011	22
NO_x	0.071	0.073	0.073	0.073	0.073	0.063	22
VOC*	0.013	0.013	0.013	0.013	0.013	0.011	22
CO	0.070	0.073	0.073	0.073	0.073	0.063	22
CH_4	0.002	0.002	0.002	0.002	0.002	0.002	22
Transportation to ready mix plant, lb/yd^3 concrete							
Particulate Matter	0.020	0.020	0.019	0.019	0.019	0.020	Table 3-12
CO_2	15.667	15.349	14.668	14.668	14.668	15.175	Table 3-12
SO_2	0.025	0.024	0.023	0.023	0.023	0.024	Table 3-12
NO_x	0.144	0.141	0.135	0.135	0.135	0.140	Table 3-12
VOC*	0.026	0.025	0.024	0.024	0.024	0.025	Table 3-12
CO	0.144	0.141	0.134	0.134	0.134	0.139	Table 3-12
CH_4	0.004	0.004	0.004	0.004	0.004	0.004	Table 3-12
Concrete plant operations, lb/yd^3 concrete							
Particulate Matter	0.171	0.171	0.171	0.171	0.171	0.171	14
CO_2	23.913	23.913	23.913	23.913	23.913	23.913	26, 27
SO_2	0.141	0.141	0.141	0.141	0.141	0.141	26, 27
NO_x	0.024	0.024	0.024	0.024	0.024	0.024	26, 27
VOC*	0.000	0.000	0.000	0.000	0.000	0.000	26, 27
CO	0.006	0.006	0.006	0.006	0.006	0.006	26, 27
CH_4	no data	no data	no data	no data	no data	no data	26, 27

*Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 3-14. Total Emissions from Ready Mix Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Ready Mixed 4	Ready Mixed 5	Ready Mixed 6	Reference
28 day compressive strength, psi	5,000	4,000	3,000	3,000	3,000	Budget	Table 3.1
Fly ash, %	0	0	0	15	20	14	Table 3.1
Total emissions, lb/yd^3 concrete							
Particulate Matter	2.240	2.033	1.803	1.668	1.621	1.952	Table 3.13
CO_2	550	466	381	332	315	447	Table 3.13
SO_2	2.378	2.012	1.644	1.425	1.351	1.932	Table 3.13
NO_x	2.249	1.913	1.572	1.372	1.305	1.830	Table 3.13
VOC*	0.074	0.068	0.061	0.058	0.056	0.065	Table 3.13
CO	0.273	0.264	0.248	0.243	0.241	0.250	Table 3.13
CH_4	0.038	0.033	0.027	0.024	0.023	0.031	Table 3.13
Waste at cement plant, lb/yd^3 concrete							
Cement kiln dust (CKD)	29	24	20	17	16	23	17

* Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

3.11 Sensitivity analyses

3.11.1 Embodied energy. Embodied energy per cubic yard of concrete is primarily a function of the cement content of the mix. As shown in Fig. 3-2 for the 3,000 psi mix, cement manufacturing accounts for about 70% of total energy. Energy used in operation of the concrete plant contributes close to 14%, while aggregate processing and transportation each contribute about 7.5%. The relative importance of the energy contribution of cement increases as cement content in the mix increases.

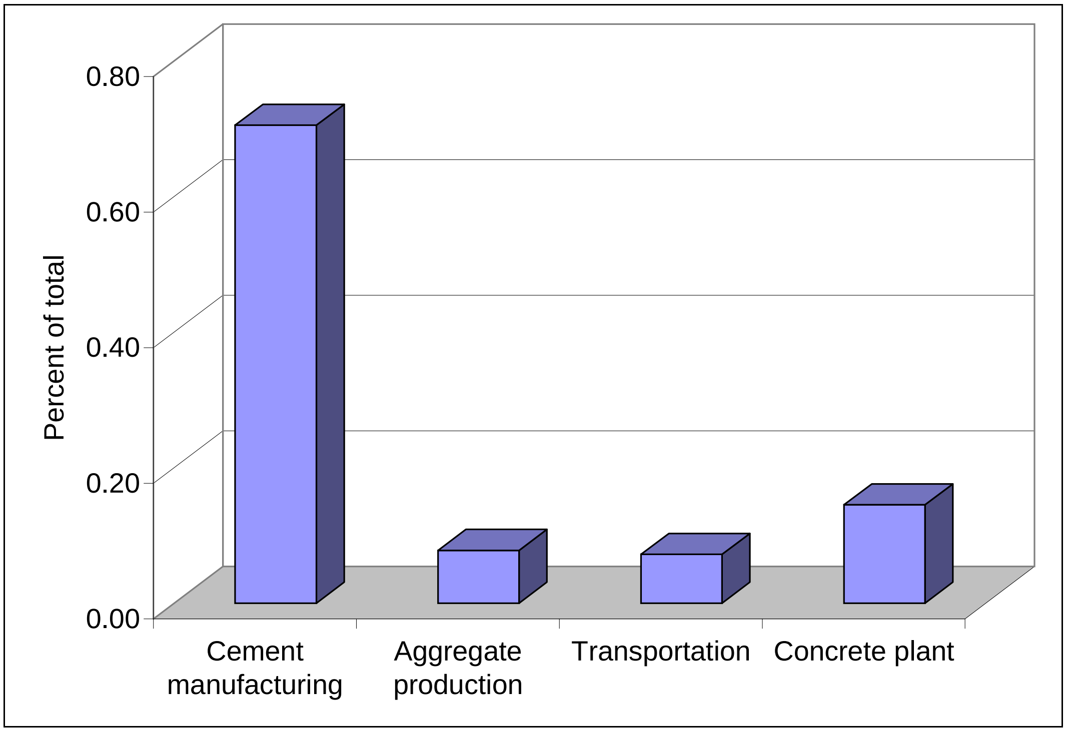

Figure 3-2. Embodied energy by process step for 3,000 psi concrete with no fly ash.

Figure 3-3 shows the embodied energy of a concrete mix increases almost in direct proportion to its cement content. Therefore, the concrete LCI results are sensitive to the mix cement content, and the cement LCI energy data and assumptions.

3.11.2 Combustion gases. Fuel consumption, meaning energy sources other than electricity, used in concrete production follows the same pattern as total energy embodied in concrete. The fuel consumption for the 3,000 psi mix is provided in Table 3-15.

The fact that cement manufacturing accounts for approximately 72% of fuel consumption per cubic yard of concrete indicates that the LCI combustion gas results are sensitive to mix cement content and data on fuel consumption in cement manufacturing.

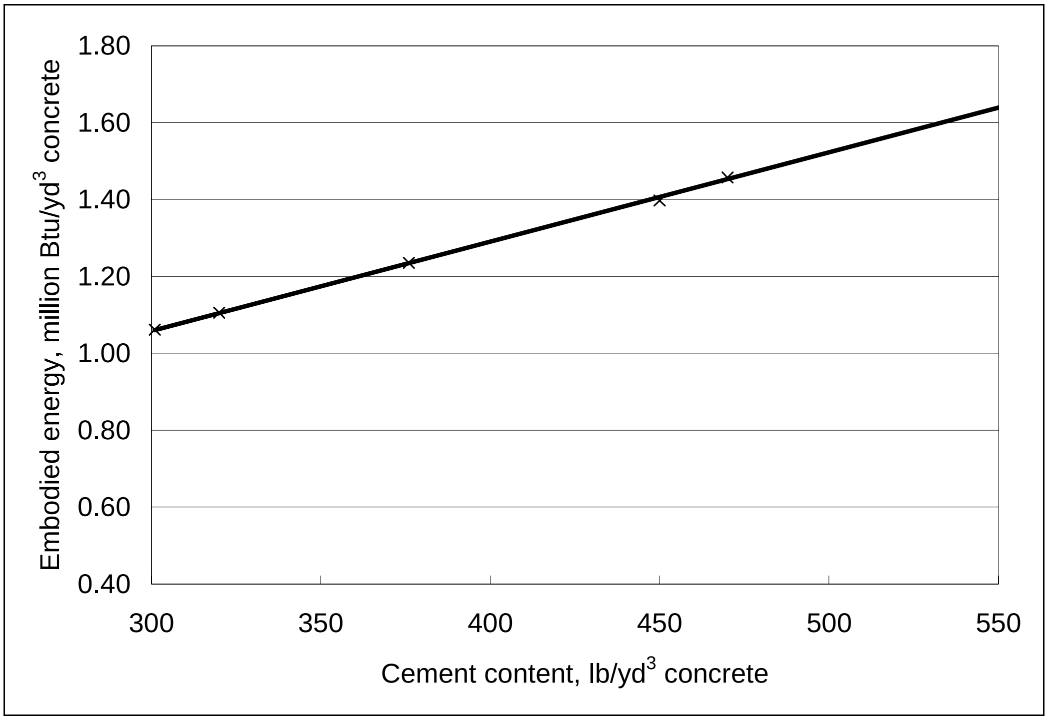

Figure 3-3. Relationship between cement content and embodied energy per cubic yard of concrete.

Table 3-15. Fuel Consumption by Process Step for Energy Sources other than Electricity

Process step	**million Btu/yd^3**	**Percent of total**
Cement manufacturing	0.781	72
Aggregate production	0.048	4
Transportation	0.089	8
Concrete plant operation	0.169	16
Total	**1.087**	**100.0**

Because of the carbon dioxide emissions from calcination as well as fuel combustion in cement manufacture, the cement content of the concrete mix accounts for 88% of the carbon dioxide emissions associated with concrete production in the case of the 3,000 psi mix. Thus, concrete LCI results are significantly influenced by mix cement content and cement LCI carbon dioxide data.

3.11.3 Particulate emissions. The single largest contributor to particulate emissions both in cement and aggregate production is quarry operations. In cement manufacture, quarry operations account for approximately 61% of total particulate emissions. In aggregate production, quarry operations, which include blasting, haul roads, unloading, and stockpiling, are responsible for about 92% of particulate emissions. Figure 3-4 shows the particulate emissions by process step for the 3,000 psi mix. About 39% of the particulate emissions associated with concrete manufacture are from aggregate production and about 51% are embodied in the cement.

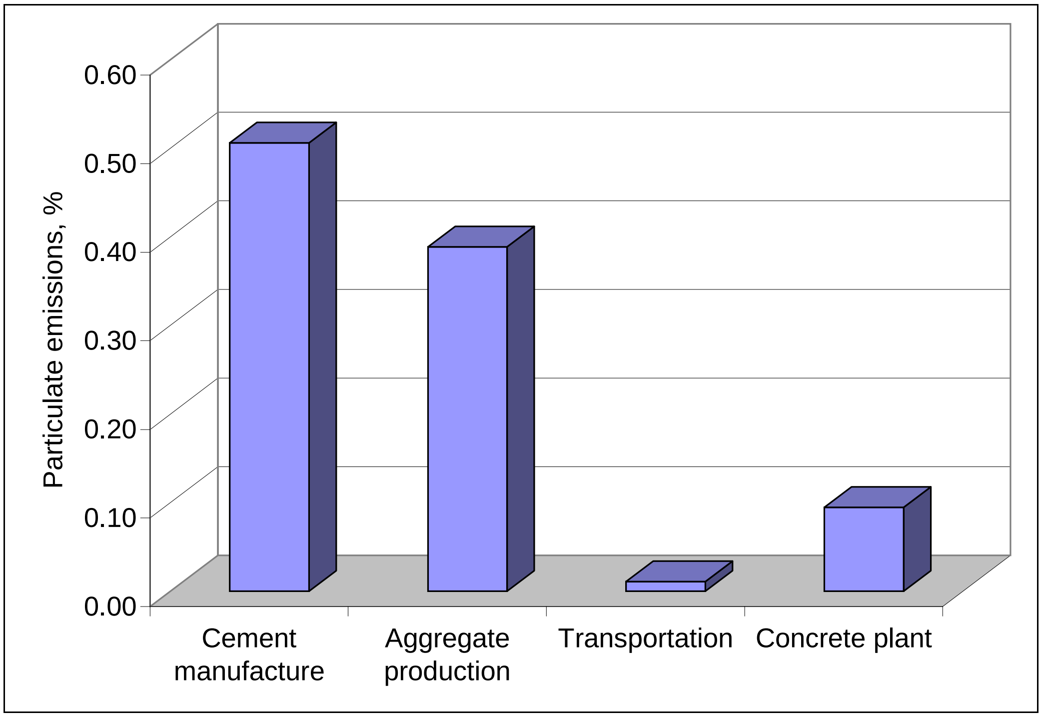

Figure 3-4. Particulate emissions by process step.

3.12 Data quality

The energy data used for cement refer to 1998 and are national in scope. They include the four main cement manufacturing technologies: wet, long dry, preheater and preheater/precalciner kilns. The data are reported from plants representing approximately 70% of the U.S. cement industry and have been collected annually for 25 years. We believe these data have a good level of precision but have not yet developed quantitative indicators of data quality. Air emissions, with the exception of CO_2, are based largely on EPA AP-42 emission factors for which qualitative quality indicators are available. CO_2 is calculated from energy and calcination data.

The data referring to aggregate production and the operations of concrete plants come from published reports and other sources provided by concrete industry associations. These data do not come from industry-wide surveys and in some cases the sources are 20 years old. However, because aggregate and concrete production technologies have not changed significantly since the data were collected, we believe the data are reasonably representative of current technology.

All the data on which the LCI is based and the LCI results have been peer reviewed by the PCA membership and by industry associations that are members of ECCO.

We have not yet developed data quality indicators but are taking steps to develop indicators that comply with ISO 14041. A set of industry standard data quality indicators complying with ISO 14041 has not yet been developed.

4. CONCRETE BLOCK

4.1 System boundary

A concrete masonry plant's operations are similar to those of a central mixer ready mixed plant with the addition of the molding and curing stages prior to shipment of the product.

Concrete masonry plants produce a wide range of units for different specialty applications, however the standard 8 x 8 x 16 in. block, or concrete masonry unit (CMU), is the dominant product. Concrete block is produced by placing very dry, no-slump concrete in molds. After removal from the molds, blocks are subjected to accelerated curing. As a general practice, concrete block is manufactured and cured in a twenty-four hour cycle at a temperature and humidity that results in one-day compressive strength that allows the blocks to be stacked and transported to the storage yard.

The system boundary, illustrated in Figure 4-1, includes energy and emissions associated with production of cement and aggregates and their transportation to the block manufacturing plant. If lightweight aggregate is used, the energy and emissions associated with its production are included. The boundary includes the operation of the block plant up to the point the product is ready for shipment at the plant gate.

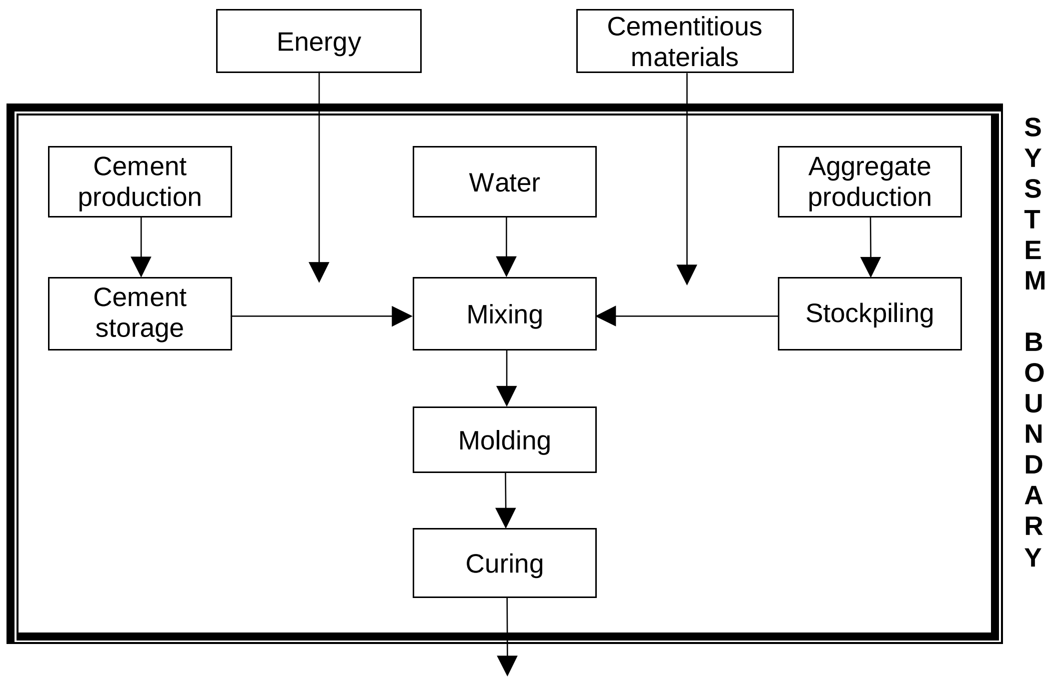

Figure 4-1. Concrete block system boundary.

4.2 Assumptions

The main assumptions are the same as those for ready mixed concrete. Additional assumptions include:

- The functional unit is one concrete masonry unit (CMU) or block. A standard block is assumed to measure 8 x 8 x 16 in. and have 50% solid volume.
- An average CMU contains 0.26 cubic feet of concrete. One cubic yard of mix represents roughly 104 blocks.
- Curing energy estimates assume 3 blocks per pallet in an insulated kiln at 130°F[29] under summer conditions.
- On average, 50% of the fuel used in curing is natural gas and 50% is fuel oil.
- Crushed stone accounts for 30% of the aggregate in the block and CMU mixes[29], and sand and gravel accounts for 70%.

4.3 Mix designs

Table 4-1 presents three mix designs. The first is for the 3,000 psi ready mixed concrete and is presented for comparison purposes. The remaining two are the concrete mix assumed for the CMU. This mix is presented in terms of pounds per cubic yard of concrete and pounds per one CMU.

Table 4-1. Concrete Block Mix Design and Properties

Concrete mix description	Ready Mixed 3	Block Mix	Block**
28 day compressive strength, psi	3,000	Unspecified	Unspecified
Fly ash, %	0	0	0
Unit weight, lb/ft^3	145	149	149
Concrete raw material, lb/production unit*			
Cement	376	350	3.37
Fly ash	0	0	0.00
Water	237	240	2.31
Coarse aggregate	1,900	0	0.00
Fine aggregate	1,400	3,427	32.95
Total	**3,913**	**4,017**	**38.63**

*Production unit is 1 yd^3 for ready mix and block concrete, and 1 CMU for concrete block.
**The concrete mixes for Block Mix and Block are identical, but expressed in different units.
Source: Portland Cement Association.

4.4 Information sources

The information sources are the same as for ready mixed concrete with additional data provided by the National Concrete Masonry Association (NCMA)[29].

4.5 Energy inputs

Energy use is similar to that for ready mixed concrete with the addition of energy consumption used in the curing stage. The curing temperatures from plant to plant vary from ambient to about 190°F. Strength gain at ambient temperature is low and generally means that the block must be yard stored for about seven days before shipping. Curing energy depends on:

- Kiln design and insulation.
- Curing process: continuous or batch.
- Climate: summer or winter.
- Curing temperature.

The variables describing the block curing operation include curing temperature, whether the system is batch or continuous, the degree of insulation, the number of blocks to a pallet and the ambient temperature. Rather than try to develop average conditions, we selected one set of conditions given in the study provided by the National Concrete Masonry Association[29]. For the purposes of the LCI, the conditions presented in Table 4-2 were chosen:

Table 4-2. Curing Conditions and Estimated Energy Used in Curing Concrete Block

Curing	Continuous
Blocks per pallet	3
Temperature	130°F
Conditions	Summer, insulated
Energy consumption, Btu/block	468
Mix design, lb per block:	sand: 22.92 stone: 10.03 cement: 3.37 water: 2.31

Source: Reference 29.

4.6 Water consumption

Block operations do not have the truck wash out and wash off requirements associated with ready mixed concrete production. For the purposes of the LCI it is assumed that block plants consume 25% of the water (not including that in the concrete mix) used in ready mix plants or 8.8 gal/yd^3 (731 lb/yd^3), which is 0.084 gal/CMU. Total water used at a concrete block plant is assumed to be 0.084 gallons (0.70 lb) per CMU plus 0.277 gallons (2.31 lb) per CMU used for the block mix from Table 4-1.

4.7 Air emissions

Sources of air emissions associated with block production are the same as those for ready mixed concrete.

4.8 Solid wastes

It is assumed that 2.5% of the mass of concrete being processed is wasted but since the waste from block production consists primarily of damaged units that are generally crushed and recycled as aggregate or fill, 95% is beneficially recycled. Based on this assumption, solid waste is approximately 5 lb/yd^3, which is 0.05 lb/CMU.

4.9 Waste heat

The available data on waste heat apply only to cement manufacture, and average 1.19 million Btu per ton[17]. There is no readily available information regarding waste heat in the other steps in the block manufacturing process.

4.10 Concrete block LCI results

The LCI results are presented as inputs and emissions per block and as inputs and emissions per cubic yard of the mix used to make the block. The inputs and emissions for a standard 3,000 psi concrete mix are provided as a benchmark.

4.10.1 Primary materials. Table 4-1 containing the assumed mix designs shows that the block mix contains 350 lb of cement per yd^3 compared to 376 lb of cement per yd^3 for 3,000 psi concrete. Table 4-3 shows the total materials required to make a cubic yard of concrete. An average of 1.6 tons of raw material are needed to produce one ton of cement.

4.10.2 Energy input. The energy data is expressed as *units per cubic yard* and *units per block.* Table 4-4 presents energy consumption data of each mix for cement manufacturing, aggregate production, transportation, concrete mixing and block curing. The embodied energy in the block mix, including curing energy is 1.21 million Btu/yd^3 compared to 1.24 million Btu/yd^3 for the 3,000 psi mix. Embodied energy per CMU is 0.012 million Btu or 11,700 Btu. Table 4-5 presents consumption of energy units, for example, gallons of diesel fuel or kilowatt-hours.

As indicated in Section 3, energy consumption of the mixes varies primarily with cement content. Energy to produce cement for the block mix, 0.811 million Btu/ yd^3, dominates energy from other steps of the block production process. Energy required to produce aggregate is relatively small, about 0.10 million Btu/yd^3. Transportation energy is relatively constant at about 0.09 million Btu/yd^3 for both mixes while energy used in the batch plant is constant at 0.179 million Btu/yd^3 regardless of the mix design.

Estimated curing energy is 468 Btu per block assuming a continuous curing system with three blocks per pallet in an insulated kiln at 130°F[29]. The curing energy assumes that the block is manufactured under summer conditions and that, on average, 50% of the fuel used is natural gas and 50% is fuel oil. However, these assumptions can be modified to accommodate site specific information.

4.10.3 Air emissions. Table 4-6 presents the air emissions from transportation of finished goods to the concrete block plant. Table 4-7 presents the air emissions data per cubic yard of each mix for the process stages: cement manufacturing, aggregate production, transportation, operation of the concrete block plant and curing. Table 4-8 shows total emissions. The amounts of CO_2 and other combustion gases associated with block production are primarily a function of the cement content in the mix design.

Table 4-3. Material Inputs for Concrete Block Production

Concrete mix description	Ready Mixed 3	Block Mix	Block	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 3-1
Cement, lb/production unit*	376	350	3.37	Table 3-1
Fly ash, %	0	0	0	Table 3-1
Cement raw material, lb/production unit**				
Limestone	434	404	3.89	17
Cement rock, marl	69	65	0.62	17
Shale	35	33	0.32	17
Clay	18	17	0.16	17
Bottom ash	2	2	0.02	17
Fly ash	8	7	0.07	17
Foundry sand	2	2	0.02	17
Sand	5	5	0.05	17
Iron, iron ore	1	1	0.01	17
Gypsum, anhydrite	23	21	0.20	17
Water	308	286	3.00	17
Subtotal†	**597**	**557**	**5.36**	
Other concrete raw material, lb/production unit				
Fly ash	0	0	0.00	Table 3-1
Water	237	240	2.31	Table 3-1
Coarse aggregate	1,900	0	0.00	Table 3-1
Fine aggregate	1,400	3,427	32.95	Table 3-1
Subtotal	**3,537**	**3,667**	**35.26**	

*Production unit is 1 yd^3 for ready mix and block mix concrete, and 1 CMU for concrete block.
**Approximately 1.6 tons of raw materials (excluding water) are needed to make 1 ton of cement due primarily to calcination of the limestone.
†Subtotal does not include water.

Aggregate production and cement manufacture are similar in their contributions to particulate emissions associated with concrete block production. As shown in Table 4-7 particulate emissions from aggregate production are 0.701 lb/yd^3 for the 3,000 psi mix and 0.644 lb/yd^3 for the block mix. Particulate emissions associated with cement manufacture are 0.913 and 0.850 lb/yd^3 for the same mixes.

Table 4-4. Energy Inputs for Concrete Block Production in Million Btu*

Concrete mix description	Ready Mixed 3	Block Mix	Block	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Cement manufacturing, million Btu/yd^3 concrete				
Coal	0.511	0.476	4,584	17
Gasoline	0.000	0.000	3	17
LPG	0.000	0.000	1	17
Middle distillates	0.007	0.007	63	17
Natural gas	0.064	0.059	569	17
Petroleum coke	0.127	0.118	1,137	17
Residual oil	0.001	0.001	11	17
Wastes	0.071	0.066	632	17
Electricity	0.090	0.084	807	17
Subtotal	**0.871**	**0.811**	**7,807**	
Aggregate production, million Btu/yd^3 concrete				
Crushed stone				
Diesel fuel	0.035	0.018	176	**
Electricity	0.035	0.018	176	**
Sand and gravel				
Diesel fuel	0.013	0.024	229	**
Electricity	0.013	0.024	229	**
Subtotal	**0.096**	**0.084**	**810**	
Transporting materials to plant, million Btu/yd^3 concrete				
Diesel fuel				
Cement	0.017	0.015	148	†
Coarse aggregate	0.042	0.000	0	†
Fine aggregate	0.031	0.075	724	†
Subtotal	**0.089**	**0.091**	**872**	†
Concrete plant operations, million Btu/yd^3 concrete				
Diesel fuel	0.139	0.139	1,369	22
Natural gas	0.030	0.030	298	22
Electricity	0.010	0.010	102	22
Subtotal	**0.179**	**0.179**	**1,769**	
Concrete block curing, million Btu/yd^3 concrete				
Middle distillates	not applicable	0.024	234	29
Natural gas	"	0.024	234	29
Electricity	"	0.000	0	29
Subtotal	"	**0.049**	**468**	
Total	**1.235**	**1.214**	**11,726**	

*Energy use for concrete block is expressed in Btu/CMU.
**LCI assumptions and References 18 through 21.
†LCI assumptions and Reference 22.

Table 4-5. Energy Inputs for Concrete Block Production by Fuel Type

Concrete mix description	Ready Mixed 3	Block Mix	Block	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	
Cement manufacturing, fuel unit/production unit*				
Coal, lb	43.7	40.7	0.391	17
Gasoline, gallon	0.0	0.0	0.000	17
LPG, gallon	0.0	0.0	0.000	17
Middle distillates, gallon	0.1	0.0	0.000	17
Natural gas, ft^3	57.8	53.8	0.518	17
Petroleum coke, lb	8.7	8.1	0.078	17
Residual oil, gallon	0.0	0.0	0.000	17
Wastes, lb	7.1	6.6	0.063	17
Electricity, kWh	26.4	24.6	0.237	17
Aggregate production, fuel unit/production unit				
Crushed stone				
Diesel fuel, gallon	0.3	0.1	0.001	**
Electricity, kWh	10.3	5.3	0.051	**
Sand and gravel				
Diesel fuel, gallon	0.1	0.2	0.002	**
Electricity, kWh	3.8	7.0	0.067	**
Transporting materials to plant, fuel unit/production unit				
Diesel fuel, gallon				
Cement	0.1	0.1	0.001	†
Coarse aggregate	0.3	0.0	0.000	†
Fine aggregate	0.2	0.5	0.005	†
Concrete plant operations, fuel unit/production unit				
Diesel fuel, gallon	1.0	1.0	0.010	22
Natural gas, ft^3	29.5	29.5	0.291	22
Electricity, kWh	3.0	3.0	0.030	22
Concrete block curing, fuel unit/production unit				
Middle distillates, gallon	not applicable	0.176	0.002	29
Natural gas, ft^3	"	23.735	0.228	29
Electricity, kWh	"	0.000	0.000	29

*Production unit is 1 yd^3 for bulk (mix) concrete, and 1 CMU for concrete block.
**LCI assumptions and References 18 through 21.
†LCI assumptions and Reference 22.

Table 4-6. Air Emissions from Finished Goods Transport to Concrete Plant for Concrete Block Production

Concrete mix description	Ready Mixed 3	Block Mix	Block
28 day compressive strength, psi	3,000	Unspecified	Unspecified
Cement transportation, lb/production unit*			
Particulate Matter	0.004	0.003	0.000
CO_2	2.722	2.534	0.024
SO_2	0.004	0.004	0.000
NO_x	0.025	0.023	0.000
VOC**	0.005	0.004	0.000
CO	0.025	0.023	0.000
CH_4	0.001	0.001	0.000
Aggregate transportation, lb/production unit			
Particulate Matter	0.016	0.016	0.000
CO_2	11.946	12.406	0.119
SO_2	0.019	0.020	0.000
NO_x	0.110	0.114	0.001
VOC**	0.020	0.021	0.000
CO	0.110	0.114	0.001
CH_4	0.003	0.003	0.000
Total material transportation, lb/production unit			
Particulate Matter	0.019	0.020	0.000
CO_2	14.668	14.939	0.144
SO_2	0.023	0.024	0.000
NO_x	0.135	0.138	0.001
VOC**	0.024	0.025	0.000
CO	0.134	0.137	0.001
CH_4	0.004	0.004	0.000

*Production unit is 1 yd^3 for bulk (mix) concrete, and 1 CMU for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.
Source: LCI assumptions and Reference 22.

Table 4-7. Air Emissions by Process Step for Concrete Block Production

Concrete mix description	Ready Mixed 3	Block Mix	Block	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Cement manufacture, lb/production unit*				
Particulate Matter	0.913	0.850	0.008	17
CO_2	335	312	3.002	17
SO_2	1.467	1.366	0.013	17
NO_x	1.340	1.247	0.012	17
VOC**	0.023	0.022	0.000	17
CO	0.035	0.033	0.000	17
CH_4	0.021	0.020	0.000	17
Aggregate production, lb/production unit				
Particulate Matter	0.701	0.644	0.006	11, 13, 24
CO_2	7.923	6.934	0.067	22
SO_2	0.013	0.011	0.000	22
NO_x	0.073	0.064	0.001	22
VOC**	0.013	0.011	0.000	22
CO	0.073	0.064	0.001	22
CH_4	0.002	0.002	0.000	22
Transportation to ready mix plant, lb/production unit				
Particulate Matter	0.019	0.020	0.000	Table 4-6
CO_2	14.668	14.939	0.144	Table 4-6
SO_2	0.023	0.024	0.000	Table 4-6
NO_x	0.135	0.138	0.001	Table 4-6
VOC**	0.024	0.025	0.000	Table 4-6
CO	0.134	0.137	0.001	Table 4-6
CH_4	0.004	0.004	0.000	Table 4-6
Concrete plant operations, lb/production unit				
Particulate Matter	0.171	0.171	0.002	14
CO_2	23.913	23.913	0.236	26, 27
SO_2	0.141	0.141	0.001	26, 27
NO_x	0.024	0.024	0.000	26, 27
VOC**	0.000	0.000	0.000	26, 27
CO	0.006	0.006	0.000	26, 27
CH_4	no data	no data	no data	26, 27
Concrete block curing, lb/production unit				
Particulate Matter	not applicable	no data	no data	
CO_2	"	6.480	0.062	29
SO_2	"	0.025	0.000	29
NO_x	"	0.007	0.000	29
VOC**	"	0.000	0.000	29
CO	"	0.002	0.000	29
CH_4	"	0.000	0.000	29

*Production unit is 1 yd^3 for bulk (mix) concrete, and 1 CMU for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 4-8. Total Emissions from Concrete Block Production

Concrete mix description	Ready Mixed 3	Block Mix	Block	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Total emissions, lb/production unit*				
Particulate Matter	1.803	1.684	0.016	Table 4-7
CO_2	381	364	3.511	Table 4-7
SO_2	1.644	1.566	0.015	Table 4-7
NO_x	1.572	1.480	0.014	Table 4-7
VOC**	0.061	0.058	0.001	Table 4-7
CO	0.248	0.241	0.002	Table 4-7
CH_4	0.027	0.026	0.000	Table 4-7
Waste at cement plant, lb/production unit				
Cement kiln dust (CKD)	20	18	0.175	17

*Production unit is 1 yd^3 for bulk (mix) concrete, and 1 CMU for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 4-9. Range in Concrete Block Plant Curing Conditions

Assumptions	**High energy consumption case**	**Low energy consumption case**
Process	Batch	Continuous
Kiln type	Uninsulated	Insulated
Blocks per pallet	5	3
Ambient conditions	Winter	Summer
Curing temperature, °F	190	130
Energy before curing, Btu/CMU	11,375	11,375
Curing energy, Btu/CMU	2,729	468
Total energy, Btu/CMU	14,104	11,843
Curing energy as % of total	19.3	3.9

Source: Reference 29.

4.11 Sensitivity

The boundary for concrete block manufacture is essentially the same as the boundary for ready mixed concrete with the addition of a curing stage. The block LCI results have the same sensitivities as ready mixed concrete plus sensitivity to data relevant to the curing step.

Energy consumption in curing varies considerably with the underlying assumptions as shown in Table 4-9. Comparison of the two cases indicates that the higher curing energy case has a total energy requirement of 14,100 Btu/CMU which is 16% above the low curing energy case. Combustion gas emissions would increase by a similar percentage. The low energy consumption case was used in the concrete block LCI.

5. PRECAST CONCRETE

5.1 System boundary

Concrete has high compressive strength but low tensile strength. The strength of precast components is achieved by combining the properties of concrete with steel reinforcement.

Precast concrete components for walls, columns, floors, roofs and facades are made by pouring concrete into forms at a manufacturing plant, curing them and shipping, generally by truck, to the construction site.

Production procedures vary between the different categories of precast concrete products. Architectural precast concrete is usually made with conventional reinforcement in custom-made individual forms. These forms can be made of wood, fiberglass, concrete or steel. Wood or fiberglass forms can generally be used 40 to 50 times without major maintenance while concrete and steel have practically unlimited service lives. Form release agents are applied to forms prior to placing the concrete to prevent the concrete from sticking to the forms when they are removed[(30)].

The steps in the precast production process include:

- Concrete mixing.
- Conveying to the form in ready mix trucks, specially designed transporters with a dumping mechanism that places the concrete in the form or concrete buckets carried by overhead cranes.
- Placing the concrete in the form.
- Consolidation by vibration, leveling and surface finishing.
- Curing.
- Form stripping.

The functional unit in this LCI is one cubic yard of concrete ready for conveying and placement in a form.

The precast concrete system boundary used for this LCI is shown in Figure 5-1 and does not include conveying and placement or the subsequent steps in the process nor does it include reinforcing steel. The system boundary can be extended when more information becomes available.

5.2 Mix designs

Three mixes for precast concrete units, 7,500 psi, 10,000 psi, and architectural precast, are presented in Table 5-1. The table also provides the 3,000, 4,000 and 5,000 psi ready-mixed concrete mix designs for comparison purposes.

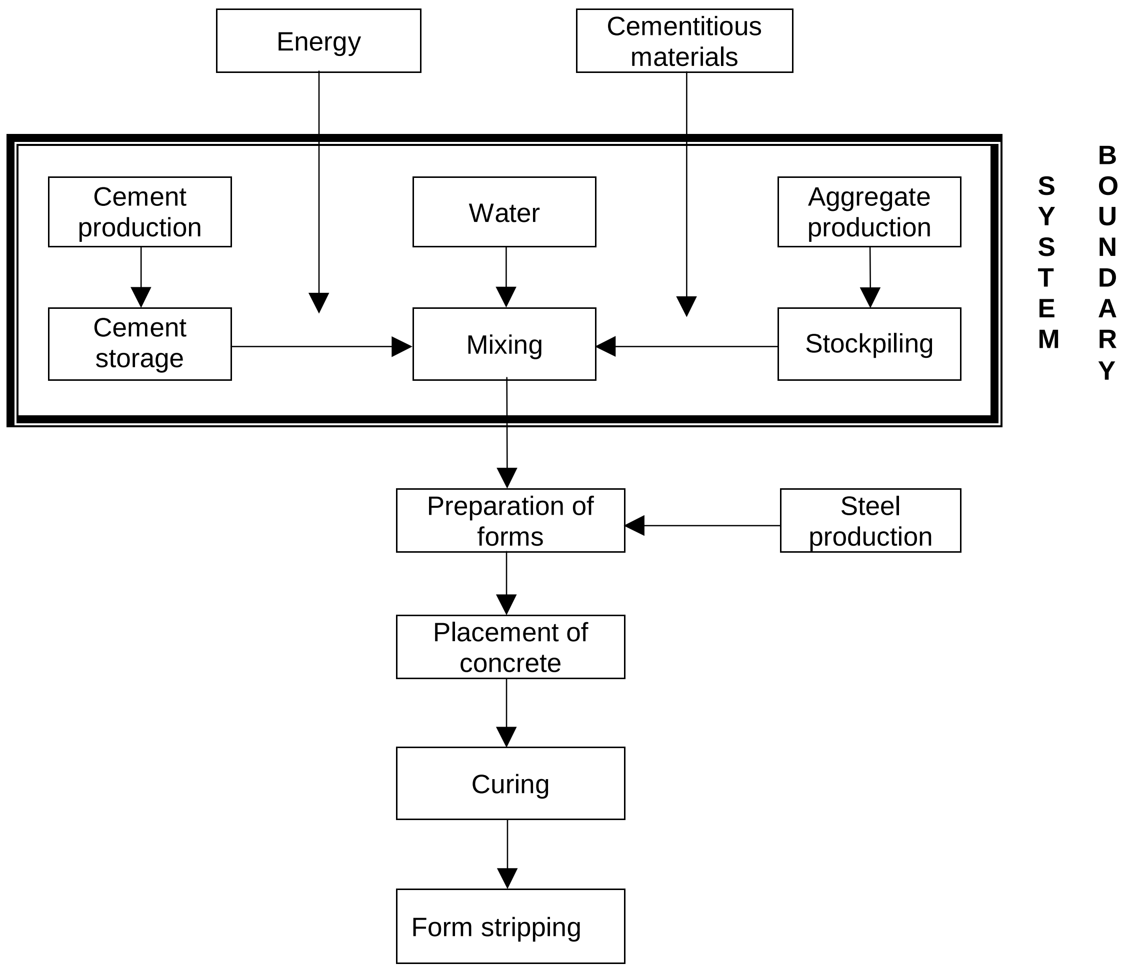

Figure 5-1. Precast concrete system boundary.

5.3 Information sources

The information sources are the same as for ready mixed concrete.

5.4 Assumptions

The primary assumptions for precast concrete are the same as those for ready mixed concrete. However, an exception is non-process water consumption, which is assumed to be 50% less than that used in ready mixed operations; and solid waste, which is assumed to be 95% recycled compared to 90% for ready mixed concrete. The round trip transportation distances to the concrete plant for silica fume are assumed to be 60 miles, the same as those for cement and fly ash.

Table 5-1. Concrete Mix Designs and Properties

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*
Silica fume, %	0	0	0	0	11	0
Unit weight, lb/ft^3	148	148	145	143	147	147
Concrete raw material, lb/yd^3 concrete						
Cement	564	470	376	850	750	650
Silica fume	0	0	0	0	95	0
Water	237	237	237	300	230	260
Coarse aggregate	2,000	2,000	1,900	1,770	1,875	1,800
Fine aggregate	1,200	1,300	1,400	935	1,030	1,250
Total	**4,001**	**4,007**	**3,913**	**3,855**	**3,980**	**3,960**

*Architectural precast panels.
Source: Portland Cement Association.

5.5 Energy inputs

Energy use is the same as for ready mixed concrete.

5.6 Water consumption

The difference in water consumption between precast and ready mixed concrete is due to the fact that the precast product is placed in forms at the precast plant instead of loaded in trucks for shipment. This means that water is not needed for truck wash-off. Wash out of equipment used to transfer concrete to molds and the mixer would probably require similar amounts of water per cubic yard as used in a concrete plant to wash out the mixer and concrete trucks. The LCI assumes that precast concrete consumes 50% of the water used per cubic yard of ready mixed concrete, or 17.5 gallons per cubic yard of precast concrete.

Total water used at a precast concrete plant is assumed to be 17.5 gallons (146 lb) per cubic yard plus the amount used for the concrete mix from Table 5-1. Water used in the mix does not contribute to effluents.

5.7 Air emissions

Sources of air emissions in precast concrete production are the same as in ready mixed concrete production.

5.8 Solid wastes

It is assumed that 2.5% of the mass of precast concrete being processed is wasted, but since the waste is generated at the plant, 95% is beneficially recycled. Solid waste is approximately 5 lb/yd^3.

5.9 Waste heat

The available data on waste heat apply only to cement manufacture. There is no readily available information regarding waste heat in the other steps of the precast concrete manufacturing process included in the LCI boundary.

5.10 Precast concrete results

5.10.1 Primary materials. Table 5-1 shows that the cement content of the precast mixes ranges from 650 to 850 lb/yd^3 compared to 376 to 564 lb/yd^3 for the ready mixes. Precast Mix 2, in addition to 750 lb/yd^3 of cement, contains 95 lb/yd^3 of silica fume. Table 5-2 shows the total materials required to make a cubic yard of the precast mixes taking into account the fact that an average of 1.6 tons of raw material are needed to produce one ton of cement.

Table 5-2. Material Inputs for Precast Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3	Reference
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*	Table 5-1
Cement	564	470	376	850	750	650	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement raw material, lb/yd^3 concrete**							
Limestone	651	542	434	981	866	750	17
Cement rock, marl	104	87	69	157	138	120	17
Shale	53	44	35	80	70	61	17
Clay	27	22	18	40	36	31	17
Bottom ash	3	3	2	5	4	4	17
Fly ash	12	10	8	18	16	14	17
Foundry sand	3	2	2	4	4	3	17
Sand	8	6	5	11	10	9	17
Iron, iron ore	2	2	1	3	2	2	17
Gypsum, anhydrite	34	28	23	51	46	39	17
Water	462	385	308	696	614	532	17
Subtotal†	**897**	**746**	**597**	**1,350**	**1,192**	**1,033**	
Other concrete raw material, lb/yd^3 concrete							
Silica fume	0	0	0	0	95	0	Table 5-1
Water	237	237	237	300	230	260	Table 5-1
Coarse aggregate	2,000	2,000	1,900	1,770	1,875	1,800	Table 5-1
Fine aggregate	1,200	1,300	1,400	935	1,030	1,250	Table 5-1
Subtotal	**3,437**	**3,537**	**3,537**	**3,005**	**3,230**	**3,310**	

*Architectural precast panels

**Approximately 1.6 tons of raw materials (excluding water) are needed to make 1 ton of cement due primarily to calcination of the limestone.

†Subtotal does not include water.

5.10.2 Energy input. Energy consumption data per cubic yard of each mix are presented for cement manufacturing, aggregate production, transportation and operation of the precast concrete plant. Table 5-3 presents energy consumption for all aspects of the manufacturing process in terms of million Btu and Table 5-4 presents energy consumption in terms of energy units. Table 5-5 summarizes the embodied energy at each stage of the precast concrete manufacturing process.

Energy consumption varies primarily with cement content of the mix ranging from 1.236 million Btu/yd^3 for the 3,000 psi mix which contains 376 lb of cement to 2.326 million Btu/yd^3 for Precast Mix 1 which contains 850 lb of cement. Energy required to produce aggregate is relatively small ranging from approximately 0.08 to 0.10 million Btu/yd^3. Transportation energy is relatively constant at about 0.10 million Btu/yd^3 for all the mixes while energy used in the concrete plant is constant at 0.18 million Btu/yd^3 regardless of the mix design.

5.10.3 Air emissions. Table 5-6 presents the air emissions from transportation of raw materials to the precast concrete plant. Table 5-7 presents the air emissions data per cubic yard of each mix for the process stages: cement manufacture, aggregate production, transportation and operation of the concrete plant. Table 5-8 shows total emissions. The amounts of CO_2 and other combustion gases emissions associated with concrete production are primarily a function of the cement content in the mix designs. For example, total CO_2 emissions range from 381 lb/yd^3 for the 3,000 psi mix to 804 lb/yd^3 for Precast Mix 1. SO_2 ranges from 1.64 to 3.49 lb/yd^3 for the same mixes, while NO_x ranges from 1.57 to 3.26 lb/yd^3.

Table 5-8 shows that particulate emissions range from 1.8 to 2.8 lb/yd^3 depending on the mix and are not as dependent on cement content as CO_2. Table 5-7 shows that particulate emissions from aggregate production are 0.70 lb/yd^3 for the 3,000 psi mix and 0.58 lb/yd^3 for Precast Mix 1. Particulate emissions associated with cement manufacture range from are 0.91 and 2.06 lb/yd^3, respectively, for the same mixes.

5.11 Sensitivity

The current boundary for precast concrete treats the product like ready mixed concrete that is made for use on site instead of shipment. For this reason the LCI results for precast will have the same sensitivities as ready mixed concrete (Section 3.11).

Table 5-3. Energy Inputs for Precast Concrete Production in Million Btu

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3	Reference
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*	Table 4-1
Fly ash, %	0	0	0	0	11	0	Table 4-1
Cement manufacturing, million Btu/yd^3 concrete							
Coal	0.767	0.639	0.511	1.156	1.020	0.884	17
Gasoline	0.000	0.000	0.000	0.001	0.001	0.001	17
LPG	0.000	0.000	0.000	0.000	0.000	0.000	17
Middle distillates	0.011	0.009	0.007	0.016	0.014	0.012	17
Natural gas	0.095	0.079	0.064	0.144	0.127	0.110	17
Petroleum coke	0.190	0.159	0.127	0.287	0.253	0.219	17
Residual oil	0.002	0.001	0.001	0.003	0.002	0.002	17
Wastes	0.106	0.088	0.071	0.159	0.141	0.122	17
Electricity	0.135	0.113	0.090	0.204	0.180	0.156	17
Subtotal	**1.306**	**1.088**	**0.871**	**1.970**	**1.738**	**1.506**	
Aggregate production, million Btu/yd^3 concrete							
Crushed stone							
Diesel fuel	0.034	0.035	0.035	0.029	0.031	0.033	**
Electricity	0.034	0.035	0.035	0.029	0.031	0.033	**
Sand and gravel							
Diesel fuel	0.012	0.013	0.013	0.011	0.011	0.012	**
Electricity	0.012	0.013	0.013	0.011	0.011	0.012	**
Subtotal	**0.092**	**0.096**	**0.096**	**0.080**	**0.084**	**0.090**	
Transporting materials to plant, million Btu/yd^3 concrete							
Diesel fuel							
Cement	0.025	0.021	0.017	0.037	0.033	0.029	†
Coarse aggregate	0.044	0.044	0.042	0.039	0.041	0.040	†
Fine aggregate	0.026	0.029	0.031	0.021	0.023	0.027	†
Silica fume	0.000	0.000	0.000	0.000	0.004	0.000	†
Subtotal	**0.095**	**0.094**	**0.090**	**0.097**	**0.101**	**0.096**	
Concrete plant operations, million Btu/yd^3 concrete							
Diesel fuel	0.139	0.139	0.139	0.139	0.139	0.139	22
Natural gas	0.030	0.030	0.030	0.030	0.030	0.030	22
Electricity	0.010	0.010	0.010	0.010	0.010	0.010	22
Subtotal	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	
Total	**1.672**	**1.457**	**1.236**	**2.326**	**2.102**	**1.870**	

*Architectural precast concrete panels.
**LCI assumptions and References 18 through 21.
†LCI assumptions and Reference 22.

Table 5-4. Energy Inputs for Precast Concrete Production by Fuel Type

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3	Reference
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement manufacturing, fuel unit/yd^3 concrete							
Coal, lb	65.5	54.6	43.7	98.7	87.1	75.5	17
Gasoline, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
LPG, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
Middle distillates, gallon	0.1	0.1	0.1	0.1	0.1	0.1	17
Natural gas, ft^3	86.8	72.3	57.8	130.8	115.4	100.0	17
Petroleum coke, lb	13.0	10.8	8.7	19.6	17.3	15.0	17
Residual oil, gallon	0.0	0.0	0.0	0.0	0.0	0.0	17
Wastes, lb	10.6	8.8	7.1	16.0	14.1	12.2	17
Electricity, kWh	39.6	33.0	26.4	59.7	52.7	45.7	17
Aggregate production, fuel unit/yd^3 concrete							
Crushed stone							
Diesel fuel, gallon	0.2	0.3	0.3	0.2	0.2	0.2	**
Electricity, kWh	10.0	10.3	10.3	8.5	9.1	9.5	**
Sand and gravel							
Diesel fuel, gallon	0.1	0.1	0.1	0.1	0.1	0.1	**
Electricity, kWh	3.7	3.8	3.8	3.1	3.3	3.5	**
Transporting materials to plant, fuel unit/yd^3 concrete							
Diesel fuel, gallon							
Cement	0.2	0.1	0.1	0.3	0.2	0.2	†
Coarse aggregate	0.3	0.3	0.3	0.3	0.3	0.3	†
Fine aggregate	0.2	0.2	0.2	0.1	0.2	0.2	†
Silica fume, %	0.0	0.0	0.0	0.0	0.0	0.0	†
Concrete plant operations, fuel unit/yd^3 concrete							
Diesel fuel, gallon	1.0	1.0	1.0	1.0	1.0	1.0	22
Natural gas, ft^3	29.5	29.5	29.5	29.5	29.5	29.5	22
Electricity, kWh	3.0	3.0	3.0	3.0	3.0	3.0	22

*Architectural precast concrete panels.
**LCI assumptions and References 18 through 21.
†LCI assumptions and Reference 22.

Table 5-5. Summary of Embodied Energy at Each Stage of Precast Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3
28 day compressive strength, psi	5000	4000	3000	7,500	10,000	Unspecified*
Energy use, million Btu/yd^3 concrete						
Cement manufacturing	1.306	1.088	0.871	1.970	1.738	1.506
Aggregate production	0.092	0.096	0.096	0.080	0.084	0.090
Transporting materials to plant	0.095	0.094	0.090	0.097	0.101	0.096
Concrete plant operations	0.179	0.179	0.179	0.179	0.179	0.179
Total	**1.672**	**1.457**	**1.236**	**2.326**	**2.102**	**1.870**

*Architectural precast concrete panels.
Source: Table 5-4.

Table 5-6. Air Emissions from Finished Goods Transport to Concrete Plant for Precast Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*
Silica fume, %	0	0	0	0	11	0
Cement and silica fume transportation, lb/yd^3 concrete						
Particulate Matter	0.005	0.004	0.004	0.008	0.008	0.006
CO_2	4.083	3.403	2.722	6.154	6.118	4.706
SO_2	0.006	0.005	0.004	0.010	0.010	0.007
NO_x	0.038	0.031	0.025	0.057	0.056	0.043
VOC**	0.007	0.006	0.005	0.010	0.010	0.008
CO	0.037	0.031	0.025	0.056	0.056	0.043
CH_4	0.001	0.001	0.001	0.002	0.002	0.001
Aggregate transportation, lb/yd^3 concrete						
Particulate Matter	0.015	0.016	0.016	0.013	0.014	0.014
CO_2	11.584	11.946	11.946	9.792	10.516	11.041
SO_2	0.018	0.019	0.019	0.016	0.017	0.018
NO_x	0.107	0.110	0.110	0.090	0.097	0.102
VOC**	0.019	0.020	0.020	0.016	0.017	0.018
CO	0.106	0.110	0.110	0.090	0.096	0.101
CH_4	0.003	0.003	0.003	0.003	0.003	0.003
Total material transportation, lb/yd^3 concrete						
Particulate Matter	0.020	0.020	0.019	0.021	0.022	0.021
CO_2	15.667	15.349	14.668	15.946	16.634	15.747
SO_2	0.025	0.024	0.023	0.025	0.026	0.025
NO_x	0.144	0.141	0.135	0.147	0.153	0.145
VOC**	0.026	0.025	0.024	0.026	0.028	0.026
CO	0.144	0.141	0.134	0.146	0.152	0.144
CH_4	0.004	0.004	0.004	0.004	0.005	0.004

*Architectural precast concrete panels.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 5-7. Air Emissions by Process Step for Precast Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3	Reference
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement manufacture, lb/yd^3 concrete							
Particulate Matter	1.369	1.141	0.913	2.064	1.821	1.578	17
CO_2	502	419	335	757	668	579	17
SO_2	2.201	1.834	1.467	3.317	2.926	2.536	17
NO_x	2.010	1.675	1.340	3.029	2.672	2.316	17
VOC**	0.035	0.029	0.023	0.052	0.046	0.040	17
CO	0.053	0.044	0.035	0.080	0.071	0.061	17
CH_4	0.032	0.026	0.021	0.047	0.042	0.036	17
Aggregate production, lb/yd^3 concrete							
Particulate Matter	0.680	0.701	0.701	0.575	0.617	0.648	11, 13, 24
CO_2	7.683	7.923	7.923	6.495	6.975	7.323	22
SO_2	0.012	0.013	0.013	0.010	0.011	0.012	22
NO_x	0.071	0.073	0.073	0.060	0.064	0.067	22
VOC**	0.013	0.013	0.013	0.011	0.012	0.012	22
CO	0.070	0.073	0.073	0.060	0.064	0.067	22
CH_4	0.002	0.002	0.002	0.002	0.002	0.002	22
Transportation to ready mix plant, lb/yd^3 concrete							
Particulate Matter	0.020	0.020	0.019	0.021	0.022	0.021	Table 5-6
CO_2	15.667	15.349	14.668	15.946	16.634	15.747	Table 5-6
SO_2	0.025	0.024	0.023	0.025	0.026	0.025	Table 5-6
NO_x	0.144	0.141	0.135	0.147	0.153	0.145	Table 5-6
VOC**	0.026	0.025	0.024	0.026	0.028	0.026	Table 5-6
CO	0.144	0.141	0.134	0.146	0.152	0.144	Table 5-6
CH_4	0.004	0.004	0.004	0.004	0.005	0.004	Table 5-6
Concrete plant operations, lb/yd^3 concrete							
Particulate Matter	0.171	0.171	0.171	0.171	0.171	0.171	14
CO_2	23.913	23.913	23.913	23.913	23.913	23.913	26, 27
SO_2	0.141	0.141	0.141	0.141	0.141	0.141	26, 27
NO_x	0.024	0.024	0.024	0.024	0.024	0.024	26, 27
VOC**	0.000	0.000	0.000	0.000	0.000	0.000	26, 27
CO	0.006	0.006	0.006	0.006	0.006	0.006	26, 27
CH_4	no data	no data	no data	no data	no data	no data	26, 27

*Architectural precast concrete panels.

**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 5-8. Total Emissions from Precast Concrete Production

Concrete mix description	Ready Mixed 1	Ready Mixed 2	Ready Mixed 3	Precast Mix 1	Precast Mix 2	Precast Mix 3	Reference
28 day compressive strength, psi	5,000	4,000	3,000	7,500	10,000	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Total emissions, lb/yd^3 concrete							
Particulate Matter	2.240	2.033	1.803	2.830	2.630	2.417	Table 5-7
CO_2	550	466	381	804	716	626	Table 5-7
SO_2	2.378	2.012	1.644	3.493	3.105	2.714	Table 5-7
NO_x	2.249	1.913	1.572	3.259	2.914	2.553	Table 5-7
VOC*	0.074	0.068	0.061	0.090	0.086	0.079	Table 5-7
CO	0.273	0.264	0.248	0.292	0.293	0.279	Table 5-7
CH_4	0.038	0.033	0.027	0.054	0.049	0.043	Table 5-7
Waste at cement plant, lb/yd^3 concrete							
Cement kiln dust (CKD)	29	24	20	44	39	34	17

*Architectural precast concrete panels.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

6. CONCLUSIONS

The concrete products LCI has been carried out according to SETAC guidelines and ISO standards 14040 and 14041.

The energy data used for cement refer to 1998, and are national in scope. They include the four main technologies: wet, long dry, preheater and preheater/precalciner kilns. The data are reported from plants representing approximately 70% of the U.S. cement industry and have been collected annually for 25 years. We believe these data have a good level of accuracy but have not yet developed quantitative indicators of data quality. A set of industry standard data quality indicators complying with ISO 14041 has not yet been developed. Air emissions are based largely on EPA AP-42 emission factors for which qualitative quality indicators are available.

The data referring to aggregate production and the operations of concrete plants come from published reports and other sources provided by concrete industry associations. These data do not come from industry-wide surveys and in some cases the sources are 20 years old. However, because aggregate production and concrete technology have not changed rapidly, we believe the data are reasonably representative of current technology.

The LCI data and results have been peer reviewed by the PCA membership and by industry associations that are members of ECCO.

The LCI contains a set of internally consistent calculations generated by a transparent input/output model. The results of the LCI can be readily updated to accommodate new input or emission data or modified assumptions.

Data used in the cement manufacturing LCI are based on industry-wide surveys of energy consumption, raw material use and transportation distances. Emissions are calculated using test data and US EPA emission factors.

Data relevant to energy consumption in ready mixed concrete, precast, and block operations come from reports and other information provided by concrete industry associations. Estimates are made of transportation distances. Data sources are limited and therefore it is not clear whether these data are fully representative. The data sources on concrete plant water consumption and recycling, and solid waste generation and recycling are also limited and the data may not adequately reflect current operations.

The results are the average of inputs and emissions associated with 1 cubic yard of concrete produced in the United States and, in the case of block, from 1 CMU. The average does not take into account scale of operations or regional factors that may affect transportation distances and concrete plant fuel use.

7. RECOMMENDATIONS

There is a lack of representative data on water consumption and lack of information on the percentage of recycling of returned materials. More information regarding water use and effluent composition needs to be collected. If representative data on water effluents are not available, an average could be assumed based on permitted levels.

The LCI results are based on readily available information. In order to refine the results it is recommended that more data be obtained in the following areas:

- Water consumption and recycling at central mixer and transit mixer operations.
- Concrete plant solid waste generation and recycling.
- Transportation distances for cement, aggregates, fly ash, and silica fume.
- Energy consumption in concrete plants.
- Quarry haul road distances and unpaved road emissions.

Upstream profiles of energy sources are not included in the LCI results. PCA's intention is to provide LCI data for use in LCA models that include upstream profiles. It is recommended that PCA consider a parallel course of action and evaluate sources of upstream data that could be included in the PCA concrete LCI.

Representatives of the cement and concrete industries have reviewed the data used in the report. However, the LCI report does not contain indicators of data quality. It is recommended that suitable indicators be developed in compliance with the requirements of ISO 14041; however, a set of industry standard data quality indicators complying with ISO 14041 has not yet been developed.

8. ACKNOWLEDGEMENT

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