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PCA Portland Cement Association

Research & Development Information

PCA R&D SERIAL NO. 2137a

Environmental Life Cycle Inventory of Portland Cement Concrete

(Revised July, 2002)

by Michael A. Nisbet, Medgar L. Marceau, and Martha G. VanGeem

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DEFINITIONS

Ancillary material. Material input that is used by the system producing the product but is not used directly in product formation; for example, refractory brick in cement kilns.

Data quality. Quantitative and qualitative aspects of input data and the methods by which they are measured or calculated, collected, and integrated into the LCA model. The proposed use of the LCI establishes the quality standards.

Environmental impact. Consequences for human health, for the well-being of flora and fauna or for the future availability of natural resources.

Functional unit. Measure of the performance of the functional output of the product or services system; for example, in the cement LCI the functional unit is one metric ton of cement.

Impact assessment. Understanding and evaluating the magnitude and significance of environmental impacts.

Life cycle inventory (LCI) analysis. Quantification of the inputs and outputs—in this case materials, energy, and emissions—from a given product or service throughout its life cycle.

Life cycle. Consecutive and inter-linked stages of a product or service from the extraction of natural resources to final disposal.

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

Sensitivity analysis. Systematic procedure for estimating the effects of data uncertainties and variability on the outcome of an LCA model.

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

Upstream profiles. The resources consumed and emissions from extracting, processing, and transporting a material or energy source entering the system boundary; for example, the inputs and emissions incurred in delivering a metric ton of coal to a cement plant.

ACRONYMS AND ABBREVIATIONS

AP-42 United States Environmental Protection Agency Compilation of Air Pollution Emission Factors

CH_4 Methane

CKD Cement kiln dust

CMU Concrete masonry unit

CO Carbon monoxide

CO_2 Carbon dioxide

HCl Hydrogen chloride

GJ Gigajoule

KJ Kilojoule

kWh Kilowatt-hour

LCA Life cycle assessment

LCI Life cycle inventory

MBtu Million British thermal units

NO_x Nitrogen oxides

PM Total filterable airborne particulate matter

PM_{10} Particulate matter with an aerodynamic diameter of less than or equal to 10 micrometers

SI International System of Units

SO_2 Sulfur dioxide

VKT Vehicle kilometer traveled

VMT Vehicle miles traveled

VOC Volatile organic compounds (does not include methane in this case)

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Environmental Life Cycle Inventory of Portland Cement Concrete

by Michael A. Nisbet, Medgar L. Marceau, and Martha G. VanGeem*

EXECUTIVE SUMMARY

Purpose

This report is a revision of the report "Environmental Life Cycle Inventory of Portland Cement Concrete" (R&D Serial No. 2137) completed in 2000. It presents data on the life cycle inventories (LCIs) of eleven portland cement concrete mixes. The mixes represent (i) ready mix concrete exiting the plant gate, (ii) concrete block exiting the manufacturing plant, and (iii) precast concrete ready for placement in forms The purpose of this revision is to incorporated data that are more recent and to include SI units. Work on the project follows the guidelines proposed by the Society of Environmental Toxicity and Chemistry (SETAC). These guidelines parallel the standards proposed by the International Organization for Standardization (ISO) in ISO 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.

Goal and Scope

The goal of this concrete life cycle inventory (LCI) is to develop accurate data on the inputs and emissions associated with a specific range of concrete products. These LCIs will be used in turn to perform life cycle assessments (LCAs) of concrete products and competing construction materials. The data will be available for incorporation into existing and future LCA models, which are designed to improve a production process or to compare alternative construction materials.

The functional units, the basis for comparison, are (i) 1 cubic meter of ready mixed concrete, (ii) 100 concrete blocks, also referred to as concrete masonry units (CMUs), and (iii) 1 cubic meter of precast concrete. Results are also presented in U.S. customary units. A standard block is assumed to be 200×200×400 mm (8×8×16 in.) and to have 50% solid volume.

The system boundary is shown in figure ES-1. It includes all the inputs and outputs associated with producing concrete—from raw material extraction to producing concrete. 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

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† Although the two words "cement" and "concrete" are sometimes used interchangeably, cement is actually one of the ingredients in concrete. Cement is the fine gray powder that, in combination with water, binds sand and gravel or crushed stone into the rock-like mass know as concrete. Cement constitutes only 10 to 15 percent of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error.

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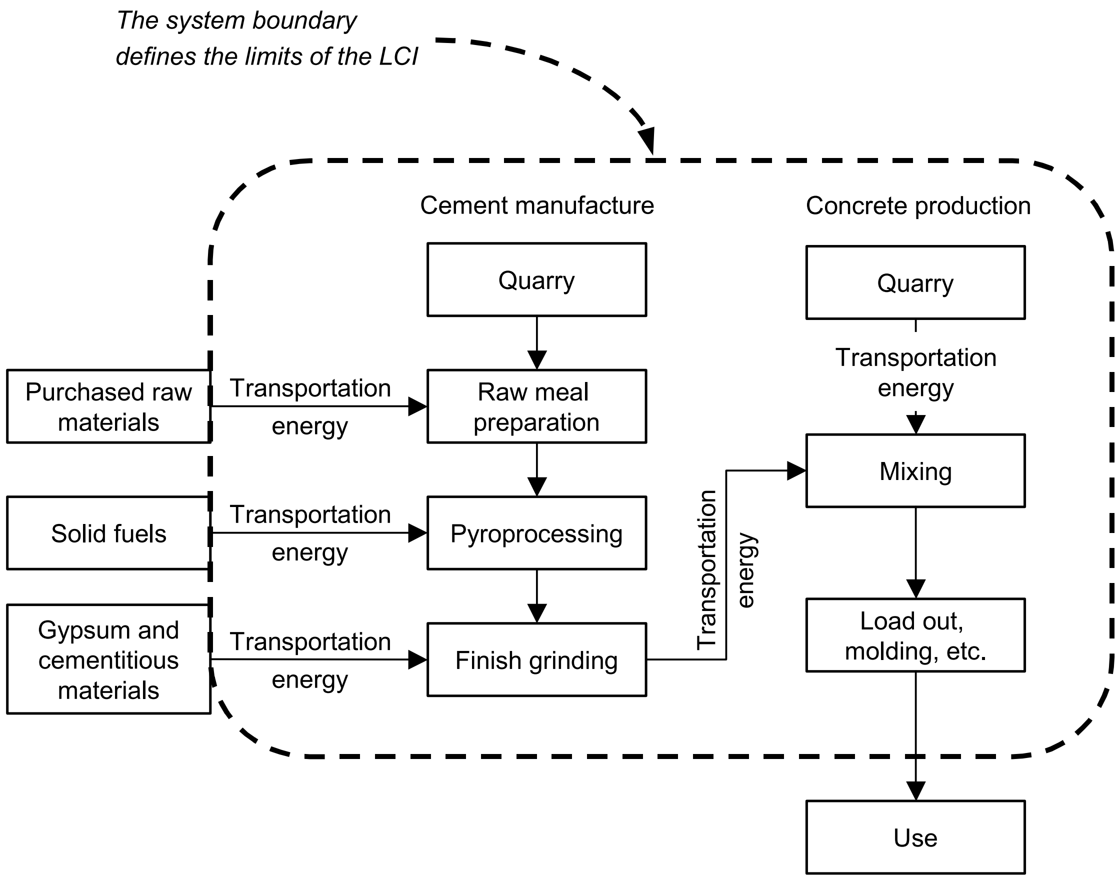

Figure ES-1. The generalized concrete production system boundary.

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.

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 35, 30, and 20 MPa (5,000, 4,000, and 3,000 psi), respectively. The different compressive strengths of concrete represent different broad use categories. Structural concrete for beams, columns, floors, slabs, and other uses often specify 30 or 35 MPa. Residential and other general use concrete is often 3,000 psi or less. Mixes 4 and 5 are for 20 MPa (3,000 psi) concrete where 15% and 20% of the cement is replaced with fly ash, respectively. The purpose of including the LCIs of these mixes is to demonstrate the reduction of energy and emissions resulting from replacement of cement with supplementary cementitious materials derived from waste products such as fly ash. It should be noted that approximately 90% of the ready mixed concrete market is in the 20-MPa range, approximately 8% is 30 to 35 MPa, and only 1 to 2% is higher strengths.

Table ES-1. Concrete Mix Designs Used for LCI

Mix	28-day compressive strength, MPa	28-day compressive strength, psi	Fly ash content, %	Silica fume content, %
Ready mixed 1	35	5,000	0	0
Ready mixed 2	30	4,000	0	0
Ready mixed 3	20	3,000	0	0
Ready mixed 4	20	3,000	15	0
Ready mixed 5	20	3,000	20	0
Ready mixed 6 (budget)	Not specified		14	0
CMUx	Not specified		0	0
100 CMUs	Not specified		0	0
Precast mix 1	50	7,500	0	0
Precast mix 2	70	10,000	0	11
Precast mix 3**	Not specified		0	0

Source: Portland Cement Association.
*200×200×400 mm (8×8×16 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 treated as fly ash in the LCI calculations.

The concrete mix used to make concrete block is expressed in terms of mass per volume and mass per 100 CMU. One cubic meter of mix makes approximately 136 CMUs and 1 cubic yard of mix makes approximately 104 CMUs. 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 originally carried out by the Portland Cement Association in 1996 and updated in 2002 with the most recent (1999) 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 consistent calculation of energy consumption and emissions to air for a wide range of mix designs.

Results

The amount of portland cement in a concrete mix has a major impact on the LCI results for concrete. For example, as shown in Table ES-2 for the 20 MPa (3,000 psi) mix, cement content accounts for approximately 70% 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 20 MPa (3,000 psi) Mix

Process step	Embodied energy		Percent of total
	GJ/metric ton	MBtu/yd^3	
Cement manufacturing	1.18	0.86	70
Aggregate production	0.13	0.10	8
Transportation	0.12	0.09	7
Concrete plant	0.25	0.18	15
Total	**1.69**	**1.22**	**100**

Conclusions

The concrete products LCI has been carried out according to SETAC guidelines and ISO standards 14040 and 14041 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 are an average of inputs and emissions from the production of one cubic meter (also one cubic yard) of concrete and 100 CMUs. The LCI does not provide information about the age and efficiency of plants or the scale of operations, nor about regional factors that 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.

We believe that the data on water consumption, solid waste generation, and recycling at the concrete plant are realistic estimates.

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:

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

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

Environmental Life Cycle Inventory of Portland Cement Concrete

by Michael A. Nisbet, Medgar L. Marceau, and Martha G. VanGeem*

1. INTRODUCTION

Section 1 of this report consists of a brief introduction to the concept of an environmental life cycle assessment (LCA) and the steps in developing an LCA. It also presents the objectives of the Portland Cement Association (PCA) LCA project. Section 2 deals with the goals, scope, and general aspects of the life cycle inventory (LCI) of concrete products. 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 masonry units (CMU) and precast concrete. Each product section contains a set of tables presenting the LCI results and the following:

- **i.** a brief description of the production process,
- **ii.** the relevant LCI assumptions,
- **iii.** information sources,
- **iv.** LCI results, and
- **v.** a sensitivity analysis.

1.1 Introduction to LCIs and LCAs

An LCA, as defined in ISO 14040,[1] is "a compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle." 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.

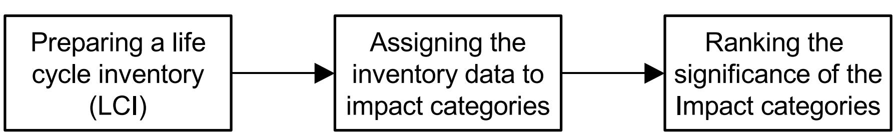

Figure 1-1. Process for developing an LCA.

An 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.

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

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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 supplementary cementitious materials (such as silica fume) or energy sources (such as the energy and emissions associated with generating electricity or mining coal). However, the quantities of these materials used are included. PCA plans to make data on concrete available to LCA models that contain the relevant upstream profiles and obtain upstream data from recognized databases.

In the LCA process, the data collected in the LCI phase are allocated to impact categories. For example, in its LCA model, Building for Environmental and Economic Sustainability (BEES),[4] the National Institute of Standards and Technology proposes the five categories shown 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%
Eutrophication	18%
Resource depletion	15%
Indoor air quality	12%
Solid waste	10%

If these categories are selected, the LCI data can be allocated to them in a scientific way. However, the number and types of impact categories are still under discussion by the groups standardizing LCA methodology. Weighting the relative importance of the impact categories cannot be done in a fully objective manner. Choice of the weightings involves subjective judgment 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.

1.2 Objectives of the PCA LCA Project

The PCA is in the process of developing an LCA of concrete products. The database developed by the project, and used in conjunction with available LCA models, should allow, for example, a comparison of:

1. structural components, such as concrete walls, with components of alternative materials,
2. roads made of portland cement concrete and asphalt cement concrete,
3. homes made of concrete walls with homes made from competing materials, and
4. 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 improving processes or comparing alternative materials.

2. GOALS, SCOPE AND GENERAL ASPECTS

2.1 Goal and Scope

The goal of this LCI is to develop accurate data on the inputs and emissions associated with a specific range of concrete products. This LCI will be used in turn to perform life cycle assessments (LCAs) of concrete and competing construction materials. The data will be available for incorporation into existing and future LCA models, which are designed to compare alternative construction materials or to improve a production process. Information on the target audience for this report and other related project reports is presented in Appendix A.

This report contains LCI data for producing concrete: from raw material extraction to producing concrete products. The three cases considered are (i) ready mix concrete exiting the plant gate, (ii) concrete block exiting the manufacturing plant, and (iii) precast concrete ready for placement in forms. The upstream profile of cement manufacturing is imported into the concrete production 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. The LCI data are presented for an average unit of product produced in the United States.

Embodied energy and emissions associated with construction of concrete plant equipment and buildings, and the heating and cooling of such buildings is not included in the LCI. This is generally acceptable because their materials, embodied energy, and associated emissions account for less than 1% of those in the process. The system boundary also excludes the creation of infrastructure, accidents, human resources, and environmental burdens caused by the work force.

2.2 Primary Materials

2.2.1 Cement. The materials used in the manufacture of cement have their own set of material inputs and these are imported into the concrete LCI. For example, approximately 1.6 metric tons of raw meal are needed to produce one metric ton of cement primarily because of calcination of calcium carbonate, which typically comprises 75% to 80% of the raw meal.

2.2.2 Supplementary cementitious materials. Fly ash, slag cement, and silica fume are supplementary 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.

2.2.3 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 & 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 & 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 & gravel[9]**	
	1000 metric ton	**1000 ton**	**1000 metric ton**	**1000 ton**
Total production	1,420,000	1,565,000	952,000	1,049,000
Amount used in construction, %	82.8		79.5	
Amount used in construction	1,176,000	1,296,000	757,000	834,000
Total aggregate used in construction, %	**61**		**39**	

Source: References 8 and 9.

The USGS identifies 82.8% of the total crushed stone production as being used in construction.[8] Furthermore, for sand & gravel, 42.8% is used for concrete aggregates, 23.3% for road base and coverings and road stabilization, and 13.4% for asphalt concrete.[9] 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 metric tons (1.3 billion tons) of crushed stone and 757 million metric tons (834 million tons) of sand & gravel were used in construction. Therefore, of the amount of aggregate used in construction, approximately 61% is crushed stone and 39% is sand & 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 & 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 report, the aggregates used in the mix are a combination of crushed stone and sand & gravel. For example, a mix design for 20 MPa (3,000 psi) concrete is show in Table 2-2.

Table 2-2 Mix Design for 20 MPa (3,000 psi) Concrete

Raw material	**Amount**	
	kg/m^3	**lb/yd^3**
Cement	223	376
Water	141	237
Coarse aggregates	1,130	1,900
Fine aggregates	830	1,400
Total aggregates	1,360	2,300

Crushed stone in mix equals 1,360 $kg/m^3 \times 0.61 = 830\ kg/m^3$ (2,300 $lb/yd^3 \times 0.61 = 1,403\ lb/yd^3$)
Sand and gravel in mix equals 1,360 $kg/m^3 \times 0.39 = 530\ kg/m^3$ (2,300 $lb/yd^3 \times 0.39 = 897\ lb/yd^3$)

2.3 Ancillary Materials: Admixtures

The SETAC guidelines[3] indicate that inputs to a process do not need to be included in an LCI if (i) they are less than 1% of the total mass of the processed materials or product, (ii) they do not contribute significantly to a toxic emission, and (iii) they do not 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 2-3, 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 largely chemically bonded and retained in the concrete product.

Table 2-3. 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 35 MPa (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 - 5,200	6 - 80	0.053 - 0.705
Superplasticizers	390 - 630	6 - 25	0.053 - 0.220

Source: Grace Construction Products, Reference 10.

2.4 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 unpaved haul road equation.[12] The SCC AIRS factor for uncontrolled emissions is 15 kg of total suspended particulates per vehicle km traveled (52 lb/mile). With an assumed dust control factor of 70% resulting from water sprays, these haul road emissions per unit mass 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. In this study, tests were conducted in three quarries and it was found that the AP-42 equation overestimated PM_{10} (dust particles with 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 2-4.

The measured PM_{10} emissions resulted in an average emission factor for the three quarries of 0.47 kg/vehicle-km traveled (1.04 lb/vehicle-mile) as shown in Table 2-5. Multiplying the amount of PM_{10} (in lb/vehicle-mile traveled) by 2.1[14] gives an emission factor for total suspended particulates of 0.61 kg/vehicle-km traveled (2.18 lb/vehicle-mile traveled). This factor is used in this LCI to estimate dust emissions from unpaved haul-roads in crushed-stone operations and sand and gravel operations. However, data based on such a small sample is probably not 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. Therefore, efforts should be made to obtain more complete data on haul road emissions.

Table 2-4. 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, km/hr (mile/hr)	29.9 (18.55)	27.1 (16.87)	27.3 (16.94)
Average truck weight, metric ton (ton)	47.6 (52.5)	47.6 (52.5)	47.6 (52.5)
Average wind speed, km/hr (mile/hr)	9.2 (5.74)	8.2 (5.07)	2.6 (1.6)
Average watering interval, hour	2.97	3.98	2.29
Water application rates, L/m^2	0.846	0.846	0.846

Source: Reference 13.

Table 2-5. Test Results for Quarry Study of Particulate Emissions

Test location	Emission factor			
	kg/vehicle-km traveled		lb/vehicle-mile traveled	
	PM_{10}	Total suspended particles	PM_{10}	Total suspended particles
Quarry no. 1	0.08	0.17	0.29	0.61
Quarry no. 2	0.49	1.03	1.74	3.65
Quarry no. 3	0.30	0.64	1.08	2.27
Average	**0.29**	**0.61**	**1.04**	**2.18**

Source: Reference 13.

2.5 Hazardous Air Pollutants

The LCI data on emissions to air include particulate matter from point and fugitive sources and the combustion gases carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and methane (CH_4). Test data are available for emissions from cement kilns of hydrogen chloride, mercury and dioxins and furans.[15] 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.

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 functional unit, the basis for comparison, is 1 cubic meter of ready mixed concrete. The system boundary is shown in Figure 3-1. It includes all the inputs and outputs associated with producing concrete—from raw material extraction to producing ready mixed concrete. Concrete production consists of two linked operations, cement manufacture and concrete production.[‡] The upstream profile of cement manufacturing is imported into the concrete production 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. The boundary also includes energy and emissions associated with transportation of primary materials from their source to the concrete plant. However, it does not include upstream profiles of fuel, electricity, water, or supplementary cementitious materials; nor does it include energy and emissions from transportation of energy to the plant.

‡ Although the two words "cement" and "concrete" are sometimes used interchangeably, cement is actually one of the ingredients in concrete. Cement is the fine gray powder that, in combination with water, binds sand and gravel or crushed stone into the rock-like mass know as concrete. Cement constitutes only 10 to 15 percent of concrete's total mass by weight. Using cement LCI data incorrectly as concrete LCI data is a serious error.

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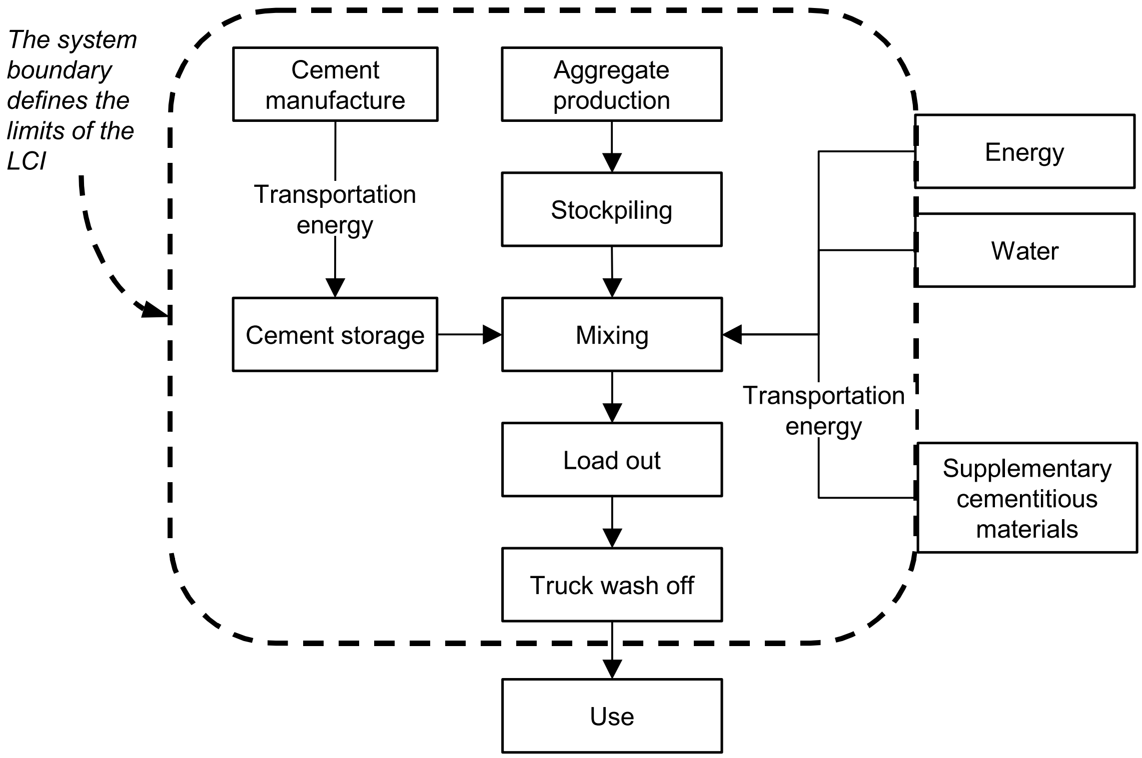

Figure 3-1. Ready mixed concrete system boundary.

3.2 Assumptions

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

i. Functional unit: 1 cubic meter of concrete.
ii. Cement data are based on the LCI of a weighted average unit of cement produced in the U.S.
iii. Aggregates, unless otherwise specified, are assumed to consist of 61% crushed stone and 39% sand and gravel (see Section 2.2.3).
iv. Energy consumption in concrete production is estimated for a central mix operation.
v. Round trip transportation distances to the concrete plant are 100 km (60 miles) for cement and fly ash, and 50 km (30 miles) for aggregates.
vi. 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.
vii. The amount of energy used is reported by energy-source such as coal, diesel fuel, and electricity, but the upstream profiles of the energy sources are not included in this LCI.
viii. 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 35, 25, and 20 MPa (5,000, 4,000, and 3,000 psi, respectively) concrete. Mixes 4 and 5 represent 20 MPa concrete with 15 and 20%, respectively,

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Table 3-1A. Concrete Mix Designs and Properties (SI Units)*

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, MPa	35	25	20	20	20	Budget
Fly ash, %	0	0	0	15	20	14
Unit weight, kg/m^3	2,386	2,390	2,294	2,294	2,294	2,312
Concrete raw material, kg/m^3 concrete						
Cement	335	279	223	190	179	267
Fly ash	0	0	0	33	44	42
Water	141	141	141	141	141	133
Coarse aggregate	1,200	1,200	1,100	1,100	1,100	1,100
Fine aggregate	710	770	830	830	830	770
Total	**2,386**	**2,390**	**2,294**	**2,294**	**2,294**	**2,312**

*Concretes with different compressive strengths represent different broad use categories. Structural concrete for beams, columns, floors, slabs, and other uses often specify 25 or 35 MPa. Residential and other general use concrete is often 20 MPa or less.
Source: Portland Cement Association.

Table 3-1B. Concrete Mix Designs and Properties (U.S. Customary Units)*

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.

of the cement replaced with fly ash. The purpose is to demonstrate the reduction of energy and emissions resulting from replacement of cement with supplementary cementitious materials, such as fly ash. Approximately 90% of the market for ready mixed concrete is in the 20 MPa range, approximately 8% is in the 25 to 30 MPa range, and only 1 to 2% is for higher strengths.[16]

Mix 6, provided by the National Ready Mixed Concrete Association (NRMCA), represents a "budget" mix.[17] This mix contains fly ash, blast furnace slag, and silica fume—all of which are assumed to be fly ash in the calculations. These supplementary cementitious materials account for 14% of the total mass of cementitious material in the mix. 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[18] (Appendix B of this report). 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, U.S. EPA emission factors, and information provided by the Environmental Council of Concrete Organizations (ECCO) members. Tables 3-2 and 3-3 show the references for the source of data on materials and energy consumption and on emissions, respectively.

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

Materials and energy consumption	Reference
Composition of portland cement concrete	LCI assumptions
Primary energy used to manufacture portland cement	18
Primary energy used to produce aggregates	19, 20, 21, 22
Primary energy used in the concrete plant	23
Primary energy used to transport materials to the concrete plant	Calculated from Ref. 24
Transportation energy factors	24
Electricity consumption in production of portland cement concrete	Calculated from Refs. 17 to 24

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 LCI of the portland cement manufacturing process[18] (Appendix B of this report).

Table 3-3. References for Sources of Data on Emissions

Emissions	Reference
Emissions from production of portland cement	18
Emissions from crushed stone quarry operations	11, 13
Emissions from crushed stone operations	25
Emissions from sand and gravel operations	26
Concrete plant particulate emissions	14
Transportation emission factors	24
Emissions from transportation of materials to concrete plant	Calculated from Ref. 24
Emissions from fuel used at concrete plant	27, 28

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 17,000 kJ/metric ton (15,000 Btu/ton) for sand to 240,000 kJ/metric ton (205,000 Btu/ton) for crushed and washed stone. A representative set of data is shown in Table 3-4. We realize that these data may not fully represent current practices, but they represent the most up-to-date and available information. The range of 67,000 to 210,000 kJ/metric ton (58,000 to 177,000 Btu/ton) for dry processed crushed stone reported in the Battelle study[19] was considered too wide to be of practical use. We therefore chose to use the conservative estimates of 81,000 kJ/metric ton (70,000 Btu/ton) for crushed stone and 47,000 kJ/metric ton (40,000 Btu/ton) for sand and gravel.

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

Data source	Type of aggregate	Embodied energy		Reference
		kJ/metric ton	Btu/ton	
Battelle Columbus Labs.	Dry processed crushed stone	67,000 to 210,000	58,000 to 177,000	19
	Crushed and washed gravel and washed sand	40,000	34,000	19
Texas AM	Crushed stone	81,000	70,000	21
	Crushed gravel	47,000	40,000	21
	Uncrushed aggregate	17,000	15,000	21
Asphalt Institute	Crushed stone	65,000	56,000	22
	Crushed gravel	47,000	40,000	22
	Uncrushed gravel	17,000	15,000	22
APCA	Crushed stone	81,000	70,000	20
	Sand	17,000	15,000	20

It is assumed for the purpose of this LCI that:

i. The energy required to produce crushed stone is 81,000 kJ/metric ton (70,000 Btu/ton.)

ii. The energy required to produce sand and gravel is 47,000 kJ/metric ton (40,000 Btu/ton).

iii. 50% of the energy used is diesel fuel and 50% is electricity.
iv. 61% of the aggregate in mixes 1 to 5 is crushed stone and 39% is sand and gravel.
v. 43% of the aggregate in mix 6 is crushed stone and 57% is sand and gravel.

3.5.3 Transportation energy. The energy to transport cement, fly ash, and aggregates from their source to the concrete plant is included in the LCI. 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 distance is assumed to be 100 km (60 miles) for both cement and fly ash, and 50 km (30 miles) for aggregates. The ECCO members accepted these distances as reasonable. The energy consumption of 1,060 kJ/metric ton-km (1,465 Btu/ton-mile) assumes that transportation energy efficiency is 24 L of diesel fuel per metric ton-km (9.4 gallon/1000 ton-miles).[24]

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.[23] These data are adapted from estimates of concrete plants in Canada, and they are considered to be similar to U.S. operations.

Table 3-5. Energy Used in the Concrete Plant

Energy source	SI units	U.S. customary units	Percent of total
	GJ/metric ton	MBtu/ton	
Electricity	0.0060	0.0052	5.8
Liquefied petroleum gas (LPG)	0.0175	0.0151	16.8
Natural gas	0.0175	0.0151	16.8
Middle distillates (diesel fuel)	0.0630	0.0543	60.6
Total	**0.1040**	**0.0896**	**100.0**

Source: Reference 22.

3.6 Water Consumption

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

i. 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.
ii. 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.
iii. Plant size: larger plants, particularly those in urban areas, are more likely to have water-recycling systems.

Reported estimates of the range of water consumption are presented in Table 3-6. The available data on water consumption show wide ranges for each of the applications. Rather than use an average, the NRMCA[16] 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 170 L/m^3 (35 gallon/yd^3), equivalent to 170 kg/m^3 (292 lb/yd^3), plus the amount used for the concrete mix from Table 3-1.

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

Water use	Quantity range	
	L/m^3 of concrete	$gallon/yd^3$ of concrete
Truck wash off	15 - 317	3 - 64
Truck wash out	5 - 69	1 - 14
Miscellaneous	15 - 129	3 - 26
Total	**35 - 515**	**7 - 104**

*Other than that used in the concrete mix.
Source: Reference 23.

3.7 Emissions to Air

The AP-42 emission factors[25] are assumed to apply to the production of coarse and fine aggregates from crushed stone. Emissions from sand and gravel operations are also based on AP-42 factors,[26] but because of wet processing, they are considerably less than those from crushed stone operations.

Aggregate quarries are assumed to be similar to cement plant quarries with an average of 3 kilometers (2 miles) from the quarry face to a paved road giving a round trip of 6 kilometers (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 this LCI, we assume stockpiles contain an average of 10% of the annual throughput at all times.

Emissions to air from diesel trucks are calculated from the energy consumption per metric ton-kilometer and emission factors provided by Franklin Associates[24] for combustion gases released per gigajoule of fuel consumed. Since these factors do not include methane emissions, we used the methane emission factor provided in Reference 23

3.8 Solid Wastes

An industry weighted average 69.8 kg of cement kiln dust is generated per metric ton of cement (139.7 lb/ton). Of this, 52.2 kg (104.5 lb) are landfilled and 17.6 kg (35.2 lb) are recycled in other applications.[18] The amount of cement kiln dust landfilled is included in this concrete LCI.

Waste from aggregate extraction is assumed to consist primarily of over-burden that remains in the quarry and can be used for reclamation. It is not regarded as a waste that requires disposal.

The concrete industry average for solid waste is about 2 to 5% of production.[16] About 90% of this is recycled. The high level of recycling is due to high landfill costs, which typically range from $28 to $55 per metric ton ($25 to $50 per ton). Assuming 90% recycling of the solid waste generated, total concrete waste is about 16 kg/m^3 (26 lb/yd^3). Table 3-7 shows estimates of solid wastes generated at a ready-mix concrete plant. Recycling options include (i) windrowing returned material, letting it harden, then crushing it and using it as fill or aggregate, (ii) using hydration control agents and re-shipping, (iii) pouring returned material into forms such as blocks or other shapes, (iv) using returned material to pave plant property, and (v) reclaiming and reusing the slurry.

The portland cement waste not used in concrete at the ready-mix plant is most likely due to losses during handling. Since cement is relatively expensive compared to the other materials, we assume this loss is minimized at the plant. Therefore, we assume it is less than 1% and not significant.

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

Activity	Wastes	
	kg/m^3 of concrete	lb/yd^3 of concrete
Returned concrete	126	212
Truck wash out	27	46
Mixer wash out	4	6
Subtotal (assuming no recycling)	157	264
Recycling (assuming 90%)	141	238
Total waste (assuming 90% recycling)	**16**	**26**

Source: Reference 23.

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

3.9 Waste Heat

The estimated waste heat from cement production to approximately 1.9 GJ/metric ton of cement (1.6 MBtu per ton).[18] 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 the stages of concrete production, but we consider it insignificant compared to the value for cement production. Waste heat is not included in the concrete LCI.

3.10 Ready Mixed Concrete LCI Results

3.10.1 Primary materials. The weight of materials, including cementitious materials, aggregates, and water remain relatively constant at about 2,000 kg/m^3 (3,500 lb/yd^3) 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 meter of concrete taking into account the fact that an average of 1.6 metric ton of raw material are needed to produce one metric ton of cement.

3.10.2 Energy input. Energy input data of each mix are presented in Tables 3-9 and 3-10 for cement manufacturing, aggregate production, transportation, and operations at the concrete plant. Table 3-9 presents the data in terms of energy consumption and Table 3-10 presents the data in terms of fuel and electricity use.

Energy consumption varies primarily with the cement content of a mix: ranging from 1.45 GJ/m^3 (1.05 MBtu/yd^3) for the 20 MPa (3,000 psi) concrete which has 179 kg/m^3 (301 lb/yd^3) of cement and 45 kg/m^3 (75 lb/yd^3) of fly ash to 2.28 GJ/m^3 (1.66 MBtu/yd^3) for the

Table 3-8A. Material Inputs for Ready Mixed Concrete Production (SI Units)*

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, MPa	35	30	20	20	20	Budget	Table 3-1
Cement, kg/m^3 concrete	335	279	223	190	179	267	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement raw material*, kg/m^3 concrete							
Limestone	399	332	266	226	213	318	18
Cement rock, marl	75	62	50	42	40	60	18
Shale	18	15	12	10	9	14	18
Clay	23	19	15	12	12	18	18
Bottom ash	1	0	0	0	0	0	18
Fly ash	2	2	1	1	1	1	18
Foundry sand	1	1	1	1	1	1	18
Sand	4	3	2	2	2	3	18
Iron, iron ore	2	2	2	2	1	2	18
Gypsum, anhydrite	17	14	11	9	9	14	18
Water	59	49	39	33	31	47	18
Subtotal**	**540**	**450**	**360**	**306**	**288**	**431**	
Other concrete raw material, kg/m^3 concrete							
Fly ash	0	0	0	33	44	42	Table 3-1
Water	141	141	141	141	141	133	Table 3-1
Coarse aggregate	1,200	1,200	1,100	1,100	1,100	1,100	Table 3-1
Fine aggregate	710	770	830	830	830	770	Table 3-1
Subtotal	**2,051**	**2,111**	**2,071**	**2,104**	**2,115**	**2,045**	

*U.S. and Canadian Labor-Energy Input Survey, Portland Cement Association, Skokie IL, January 2001.
**Approximately 1.6 metric tons of raw materials (excluding water) are needed to make 1 metric ton of cement due primarily to calcination of the limestone. Subtotal does not include water.

Table 3-8B. Material Inputs for Ready Mixed Concrete Production (U. S. Customary Units)*

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 concrete	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	672	560	448	381	359	536	18
Cement rock, marl	126	105	84	71	67	101	18
Shale	30	25	20	17	16	24	18
Clay	38	32	25	21	20	30	18
Bottom ash	1	0	0	0	0	0	18
Fly ash	3	3	2	2	2	2	18
Foundry sand	2	1	1	1	1	1	18
Sand	6	5	4	3	3	5	18
Iron, iron ore	4	3	3	3	2	4	18
Gypsum, anhydrite	29	24	19	16	15	23	18
Water	100	83	66	56	53	79	18
Subtotal**	**911**	**758**	**606**	**515**	**485**	**726**	
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, January 2001.

**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 3-9A. Energy Inputs for Ready Mixed Concrete Production in GJ (SI Units)

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, MPa	35	30	20	20	20	Unspecified	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacturing, GJ/m^3 concrete							
Coal	1.05	0.878	0.702	0.598	0.562	0.840	18
Gasoline	0.0008	0.0006	0.0005	0.0004	0.0004	0.0006	18
LPG	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	18
Middle distillates	0.016	0.013	0.011	0.009	0.008	0.013	18
Natural gas	0.116	0.096	0.077	0.066	0.062	0.092	18
Petroleum coke	0.264	0.220	0.176	0.150	0.141	0.211	18
Residual oil	0.001	0.001	0.001	0.001	0.001	0.001	18
Wastes	0.144	0.120	0.096	0.081	0.077	0.115	18
Electricity	0.183	0.152	0.122	0.104	0.097	0.146	18
Subtotal	**1.78**	**1.48**	**1.18**	**1.01**	**0.949**	**1.42**	
Aggregate production, GJ/m^3 concrete							
Crushed stone							
Diesel fuel	0.047	0.049	0.049	0.049	0.049	0.033	*
Electricity	0.047	0.049	0.049	0.049	0.049	0.033	*
Sand and gravel							
Diesel fuel	0.017	0.018	0.018	0.018	0.018	0.025	*
Electricity	0.017	0.018	0.018	0.018	0.018	0.025	*
Subtotal	**0.129**	**0.133**	**0.133**	**0.133**	**0.133**	**0.115**	
Transporting materials to plant, GJ/m^3 concrete							
Diesel fuel							
Cement	0.034	0.029	0.023	0.019	0.018	0.027	**
Coarse aggregate	0.061	0.061	0.058	0.058	0.058	0.056	**
Fine aggregate	0.036	0.039	0.042	0.042	0.042	0.039	**
Fly ash	0.000	0.000	0.000	0.003	0.005	0.004	**
Subtotal	**0.131**	**0.129**	**0.123**	**0.123**	**0.123**	**0.127**	
Concrete plant operations, GJ/m^3 concrete							
Diesel fuel	0.191	0.191	0.191	0.191	0.191	0.191	23
Natural gas	0.042	0.042	0.042	0.042	0.042	0.042	23
Electricity	0.014	0.014	0.014	0.014	0.014	0.014	23
Subtotal	**0.247**	**0.247**	**0.247**	**0.247**	**0.247**	**0.247**	
Total	**2.28**	**1.99**	**1.69**	**1.51**	**1.45**	**1.91**	

*LCI assumptions and References 19through 22

**LCI assumptions and Reference 24

Table 3-9B. Energy Inputs for Ready Mixed Concrete Production in MBtu (U.S. Customary Units)

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, MBtu/yd^3 concrete							
Coal	0.763	0.636	0.509	0.433	0.407	0.609	18
Gasoline	0.0006	0.0005	0.0004	0.0003	0.0003	0.0004	18
LPG	0.00008	0.00007	0.00005	0.00005	0.00004	0.00007	18
Middle distillates	0.011	0.010	0.008	0.006	0.006	0.009	18
Natural gas	0.084	0.070	0.056	0.048	0.045	0.067	18
Petroleum coke	0.191	0.160	0.128	0.109	0.102	0.153	18
Residual oil	0.001	0.001	0.001	0.001	0.000	0.001	18
Wastes	0.104	0.087	0.069	0.059	0.056	0.083	18
Electricity	0.132	0.110	0.088	0.075	0.071	0.106	18
Subtotal	**1.29**	**1.07**	**0.859**	**0.731**	**0.687**	**1.03**	
Aggregate production, MBtu/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, MBtu/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, MBtu/yd^3 concrete							
Diesel fuel	0.139	0.139	0.139	0.139	0.139	0.139	23
Natural gas	0.030	0.030	0.030	0.030	0.030	0.030	23
Electricity	0.010	0.010	0.010	0.010	0.010	0.010	23
Subtotal	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	
Total	**1.66**	**1.44**	**1.22**	**1.10**	**1.05**	**1.38**	

*LCI assumptions and References 19 through 22.
**LCI assumptions and Reference 24.

Table 3-10A. Energy Inputs for Ready Mixed Concrete Production by Fuel Type (SI Units)

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, MPa	35	30	20	20	20	Unspecified	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacturing, fuel unit/m^3 concrete							
Coal, kg	36.1	30.1	24.1	20.5	19.3	28.8	18
Gasoline, L	0.042	0.035	0.028	0.024	0.022	0.033	18
LPG, L	0.010	0.008	0.007	0.006	0.005	0.008	18
Middle distillates, L	0.321	0.267	0.214	0.182	0.171	0.256	18
Natural gas, m^3	3.07	2.56	2.05	1.74	1.64	2.45	18
Petroleum coke, kg	8.74	7.29	5.83	4.96	4.67	6.98	18
Residual oil, L	0.018	0.015	0.012	0.010	0.010	0.015	18
Wastes, kg	13.9	11.6	9.25	7.88	7.41	11.1	18
Electricity, kWh	30.3	25.2	20.2	17.2	16.2	24.2	18
Aggregate production, fuel unit/m^3 concrete							
Crushed stone							
Diesel fuel, L	1.22	1.26	1.26	1.26	1.26	0.85	*
Electricity, kWh	13.095	13.504	13.504	13.504	13.504	9.087	*
Sand and gravel							
Diesel fuel, L	0.447	0.461	0.461	0.461	0.461	0.643	*
Electricity, kWh	4.784	4.934	4.934	4.934	4.934	6.883	*
Transporting materials to plant, fuel unit/m^3 concrete							
Diesel fuel, L							
Cement	0.888	0.740	0.592	0.504	0.474	0.708	**
Coarse aggregate	1.57	1.57	1.50	1.50	1.50	1.46	**
Fine aggregate	0.94	1.02	1.10	1.10	1.10	1.02	**
Fly ash	0.000	0.000	0.000	0.088	0.118	0.112	**
Concrete plant operations, fuel unit/m^3 concrete							
Diesel fuel, L	4.97	4.97	4.97	4.97	4.97	4.97	23
Natural gas, m^3	1.09	1.09	1.09	1.09	1.09	1.09	23
Electricity, kWh	3.948	3.948	3.948	3.948	3.948	3.948	23

*LCI assumptions and References 19 through 22.
**LCI assumptions and Reference 24.

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Table 3-10B. Energy Inputs for Ready Mixed Concrete Production by Fuel Type (U.S. Customary Units)

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	60.8	50.7	40.5	34.5	32.5	48.5	18
Gasoline, gallon	0.008	0.007	0.006	0.005	0.005	0.007	18
LPG, gallon	0.002	0.002	0.001	0.001	0.001	0.002	18
Middle distillates, gallon	0.065	0.054	0.043	0.037	0.035	0.052	18
Natural gas, ft^3	83.0	69.2	55.3	47.1	44.3	66.2	18
Petroleum coke, lb	14.7	12.3	9.83	8.36	7.87	11.8	18
Residual oil, gallon	0.004	0.003	0.002	0.002	0.002	0.003	18
Wastes, lb	23.4	19.5	15.6	13.3	12.5	18.7	18
Electricity, kWh	23.1	19.3	15.4	13.1	12.4	18.5	18
Aggregate production, fuel unit/yd^3 concrete							
Crushed stone							
Diesel fuel, gallon	0.25	0.25	0.25	0.25	0.25	0.17	*
Electricity, kWh	10.012	10.325	10.325	10.325	10.325	6.947	*
Sand and gravel							
Diesel fuel, gallon	0.090	0.093	0.093	0.093	0.093	0.130	*
Electricity, kWh	3.658	3.772	3.772	3.772	3.772	5.262	*
Transporting materials to plant, fuel unit/yd^3 concrete							
Diesel fuel, gallon							
Cement	0.179	0.149	0.120	0.102	0.096	0.143	**
Coarse aggregate	0.318	0.318	0.302	0.302	0.302	0.294	**
Fine aggregate	0.191	0.207	0.223	0.223	0.223	0.207	**
Fly ash	0.000	0.000	0.000	0.018	0.024	0.023	**
Concrete plant operations, fuel unit/yd^3 concrete							
Diesel fuel, gallon	1.00	1.00	1.00	1.00	1.00	1.00	23
Natural gas, ft^3	29.5	29.5	29.5	29.5	29.5	29.5	23
Electricity, kWh	3.019	3.019	3.019	3.019	3.019	3.019	23

*LCI assumptions and References 19 through 22.
**LCI assumptions and Reference 24.

35 MPa (5,000 psi) concrete which has 335 kg/m^3 (564 lb/yd^3) of cement. The energy required to produce aggregate is relatively small: ranging from about 0.115 to 0.133 GJ/m^3 (0.083 to 0.096 $MBtu/yd^3$). Transportation energy ranges from 0.123 to 0.131 GJ/m^3 (0.089 to 0.095 $MBtu/yd^3$ for all the mixes, while energy used in the concrete plant is constant at 0.179 $MBtu/yd^3$ regardless of the mix design.

The effect on energy consumption of replacing cement with supplementary cementitious materials, such as fly ash, is shown in Table 3-11 using the 20 MPa (3,000 psi) mix 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 unit of concrete.

Table 3-11A. Effect on Embodied Energy of Addition of Fly Ash to the Mix (SI Units)

Concrete mix	**Ready mixed 3**	**Ready mixed 4**	**Ready mixed 5**
Compressive strength, MPa	20	20	20
Cement content, kg/m^3	223	190	179
Fly ash content, kg/m^3	0	33	44
Total cementitious material, kg/m^3	223	223	223
Percent replacement of cement with fly ash	0%	15%	20%
Embodied energy, GJ/m^3	1.69	1.51	1.45
Percent reduction in embodied energy	**0%**	**10%**	**14%**

Table 3-11B. Effect on Embodied Energy of Addition of Fly Ash to the Mix (U.S. Customary Units)

Concrete mix	**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, $MBtu/yd^3$	1.22	1.10	1.05
Percent reduction in embodied energy	**0%**	**10%**	**14%**

3.10.3 Emissions to air. Table 3-12 presents the emissions to air from transportation of purchased materials to the concrete plant. Table 3-13 presents the emissions to air for the process stages: cement manufacturing, aggregate production, transportation, and operations at the concrete plant. Table 3-14 shows total emissions to air. The CO_2 emissions from calcination are included in Table 3-13 and are approximately 60% of the total CO_2 emissions from cement manufacturing.

Aggregate production and cement manufacturing produce similar amounts of particulate matter. As shown in Table 3-13, particulate emissions from cement manufacturing range from 0.447 to 0.840 kg/m^3 (0.753 and 1.41 lb/yd^3). Particulate emissions from aggregate production are approximately 0.4 kg/m^3 (0.7 lb/yd^3). Particulate emissions in the concrete plant are approximately 0.1 kg/m^3 (0.2 lb/yd^3).

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Table 3-12A. Emissions to Air from Transportation of Purchased Material to Concrete Plant for Concrete Production (SI Units)

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, MPa	35	30	20	20	20	Budget
Fly ash, %	0	0	0	15	20	14
Cement and fly ash transportation, kg/m^3 concrete						
Particulate matter	0.003	0.003	0.002	0.002	0.002	0.003
CO_2	2.42	2.02	1.62	1.62	1.62	2.24
SO_2	0.004	0.003	0.003	0.003	0.003	0.004
NO_x	0.022	0.019	0.015	0.015	0.015	0.021
VOC*	0.004	0.003	0.003	0.003	0.003	0.004
CO	0.022	0.019	0.015	0.015	0.015	0.021
CH_4	0.001	0.001	0.000	0.000	0.000	0.001
Aggregate transportation, kg/m^3 concrete						
Particulate matter	0.009	0.009	0.009	0.009	0.009	0.009
CO_2	6.88	7.09	7.09	7.09	7.09	6.77
SO_2	0.011	0.011	0.011	0.011	0.011	0.011
NO_x	0.063	0.065	0.065	0.065	0.065	0.062
VOC*	0.011	0.012	0.012	0.012	0.012	0.011
CO	0.063	0.065	0.065	0.065	0.065	0.062
CH_4	0.002	0.002	0.002	0.002	0.002	0.002
Total material transportation, kg/m^3 concrete						
Particulate matter	0.012	0.012	0.011	0.011	0.011	0.012
CO_2	9.30	9.12	8.71	8.71	8.71	9.01
SO_2	0.015	0.014	0.014	0.014	0.014	0.014
NO_x	0.086	0.084	0.080	0.080	0.080	0.083
VOC*	0.015	0.015	0.014	0.014	0.014	0.015
CO	0.085	0.084	0.080	0.080	0.080	0.083
CH_4	0.003	0.002	0.002	0.002	0.002	0.002

*Until data that are more precise are available, these VOC values also include some non-VOC, such as CH_4.
Source: Table 3-9, Table 3-10, and Reference 23.

Table 3-12B. Emissions to Air from Transportation of Purchased Material to Concrete Plant for Concrete Production (U.S. Customary Units)

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	4.09	3.41	2.72	2.72	2.72	3.78
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	11.6	12.0	12.0	12.0	12.0	11.4
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	15.7	15.4	14.7	14.7	14.7	15.2
SO_2	0.025	0.024	0.023	0.023	0.023	0.024
NO_x	0.144	0.142	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	0.135	0.135	0.135	0.139
CH_4	0.004	0.004	0.004	0.004	0.004	0.004

*Until data that are more precise are available, these VOC values also include some non-VOC, such as CH_4.
Source: Table 3-9, Table 3-10, and Reference 23.

Table 3-13A. Emissions to Air by Process Step for Ready Mix Concrete Production (SI Units)

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, MPa	35	30	20	20	20	Budget	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Cement manufacture, kg/m^3 concrete							
Particulate matter	0.84	0.70	0.558	0.475	0.447	0.67	18
CO_2	301	251	201	171	161	240	18
SO_2	0.66	0.550	0.440	0.374	0.352	0.526	18
NO_x	0.86	0.72	0.575	0.489	0.460	0.688	18
VOC*	0.014	0.012	0.009	0.008	0.007	0.011	18
CO	0.293	0.244	0.195	0.166	0.156	0.234	18
CH_4	0.012	0.010	0.008	0.007	0.006	0.009	18
Aggregate production, kg/m^3 concrete							
Particulate matter	0.403	0.416	0.416	0.416	0.416	0.397	11, 13, 25
CO_2	4.56	4.71	4.71	4.71	4.71	4.08	23
SO_2	0.007	0.007	0.007	0.007	0.007	0.006	23
NO_x	0.042	0.043	0.043	0.043	0.043	0.038	23
VOC*	0.008	0.008	0.008	0.008	0.008	0.007	23
CO	0.042	0.043	0.043	0.043	0.043	0.037	23
CH_4	0.001	0.001	0.001	0.001	0.001	0.001	23
Transportation to ready mix plant, kg/m^3 concrete							
Particulate matter	0.012	0.012	0.011	0.011	0.011	0.012	Table 3-12
CO_2	9.30	9.12	8.71	8.71	8.71	9.01	Table 3-12
SO_2	0.015	0.014	0.014	0.014	0.014	0.014	Table 3-12
NO_x	0.086	0.084	0.080	0.080	0.080	0.083	Table 3-12
VOC*	0.015	0.015	0.014	0.014	0.014	0.015	Table 3-12
CO	0.085	0.084	0.080	0.080	0.080	0.083	Table 3-12
CH_4	0.003	0.002	0.002	0.002	0.002	0.002	Table 3-12
Concrete plant operations, kg/m^3 concrete							
Particulate matter	0.101	0.101	0.101	0.101	0.101	0.101	14
CO_2	14.2	14.2	14.2	14.2	14.2	14.2	27, 28
SO_2	0.083	0.083	0.083	0.083	0.083	0.083	27, 28
NO_x	0.014	0.014	0.014	0.014	0.014	0.014	27, 28
VOC*	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	27, 28
CO	0.004	0.004	0.004	0.004	0.004	0.004	27, 28
CH_4	no data	no data	no data	no data	no data	no data	27, 28

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

Table 3-13B. Emissions to Air by Process Step for Ready Mix Concrete Production (U.S. Customary Units)

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/yd³ concrete							
Particulate matter	1.41	1.18	0.941	0.801	0.753	1.13	18
CO_2	508	423	339	288	271	405	18
SO_2	1.11	0.926	0.741	0.631	0.593	0.887	18
NO_x	1.45	1.21	0.969	0.824	0.776	1.159	18
VOC*	0.023	0.019	0.016	0.013	0.012	0.019	18
CO	0.494	0.412	0.329	0.280	0.264	0.394	18
CH_4	0.020	0.017	0.013	0.011	0.011	0.016	18
Aggregate production, lb/yd³ concrete							
Particulate matter	0.680	0.701	0.701	0.701	0.701	0.669	11, 13, 25
CO_2	7.69	7.93	7.93	7.93	7.93	6.87	23
SO_2	0.012	0.013	0.013	0.013	0.013	0.011	23
NO_x	0.071	0.073	0.073	0.073	0.073	0.063	23
VOC*	0.013	0.013	0.013	0.013	0.013	0.011	23
CO	0.070	0.073	0.073	0.073	0.073	0.063	23
CH_4	0.002	0.002	0.002	0.002	0.002	0.002	23
Transportation to ready mix plant, lb/yd³ concrete							
Particulate matter	0.020	0.020	0.019	0.019	0.019	0.020	Table 3-12
CO_2	15.7	15.4	14.7	14.7	14.7	15.2	Table 3-12
SO_2	0.025	0.024	0.023	0.023	0.023	0.024	Table 3-12
NO_x	0.144	0.142	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	0.135	0.135	0.135	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/yd³ concrete							
Particulate matter	0.171	0.171	0.171	0.171	0.171	0.171	14
CO_2	23.9	23.9	23.9	23.9	23.9	23.9	27, 28
SO_2	0.141	0.141	0.141	0.141	0.141	0.141	27, 28
NO_x	0.024	0.024	0.024	0.024	0.024	0.024	27, 28
VOC*	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	27, 28
CO	0.006	0.006	0.006	0.006	0.006	0.006	27, 28
CH_4	no data	no data	no data	no data	no data	no data	27, 28

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

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 188 kg/m^3 (318 lb/yd^3) for the 20 MPa (3,000 psi) concrete with 20% fly ash to 329 kg/m^3 (555 lb/yd^3) for the 35 MPa (5,000 psi) concrete. SO_2 ranges from 0.457 to 0.765 kg/m^3 (0.770 to 1.290 lb/yd^3) for the same mixes, while NO_X ranges from 0.598 to 1.00 kg/m^3 (1.01 to 1.69 lb/yd^3).

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. For example, as shown in Figure 3-2, cement manufacturing accounts for about 70% of total energy of the 20 MPa (3,000 psi) mix. Energy used in operations at the concrete plant contributes close to 15%, while aggregate processing and transportation each contribute about 7.5%. The relative importance of the energy contribution from cement increases as cement content in the mix increases.

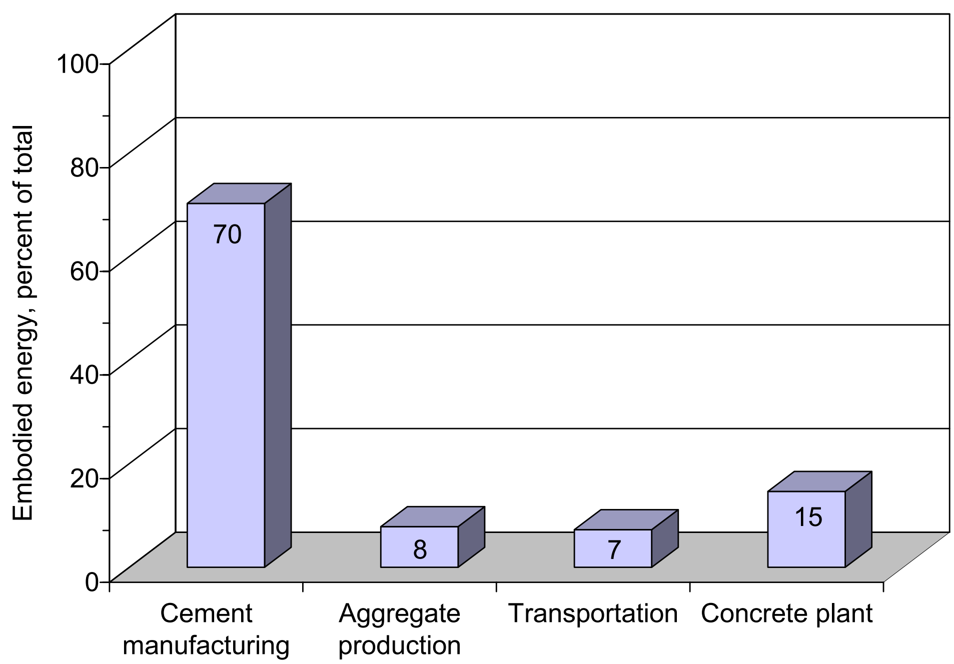

Figure 3-2. Embodied energy by process step for 20 MPa (3,000 psi) concrete with no fly ash.

Figure 3-3 shows that the embodied energy of a concrete mix increases 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 20 MPa (3,000 psi) mix is provided in Table 3-15.

Table 3-14A. Total Emissions from Ready Mix Concrete Production (SI Units)

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, MPa	35	30	20	20	20	Budget	Table 3-1
Fly ash, %	0	0	0	15	20	14	Table 3-1
Total emissions, kg/m^3 concrete							
Particulate matter	1.35	1.23	1.09	1.00	0.98	1.18	Table 3-13
CO_2	329	279	228	199	188	268	Table 3-13
SO_2	0.765	0.655	0.544	0.479	0.457	0.630	Table 3-13
NO_x	1.004	0.860	0.713	0.627	0.598	0.823	Table 3-13
VOC*	0.037	0.035	0.032	0.030	0.030	0.033	Table 3-13
CO	0.424	0.375	0.322	0.293	0.283	0.357	Table 3-13
CH_4	0.016	0.014	0.012	0.010	0.010	0.013	Table 3-13
Waste at cement plant, kg/m^3 concrete							
Cement kiln dust (CKD)	17.4	14.5	11.6	9.87	9.29	13.9	18

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

Table 3-14B. Total Emissions from Ready Mix Concrete Production (U.S. Customary Units)

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	2.282	2.067	1.831	1.691	1.644	1.985	Table 3-13
CO_2	555	470	385	335	318	451	Table 3-13
SO_2	1.289	1.104	0.918	0.807	0.770	1.062	Table 3-13
NO_x	1.693	1.450	1.201	1.057	1.008	1.387	Table 3-13
VOC*	0.062	0.058	0.053	0.051	0.050	0.056	Table 3-13
CO	0.714	0.631	0.543	0.494	0.477	0.602	Table 3-13
CH_4	0.026	0.023	0.019	0.017	0.017	0.022	Table 3-13
Waste at cement plant, lb/yd^3 concrete							
Cement kiln dust (CKD)	29.3	24.4	19.6	16.6	15.7	23.4	18

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

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

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 for the 20 MPa (3,000 psi) mix. Thus, concrete LCI results are significantly influenced by mix cement content and cement LCI carbon dioxide data.

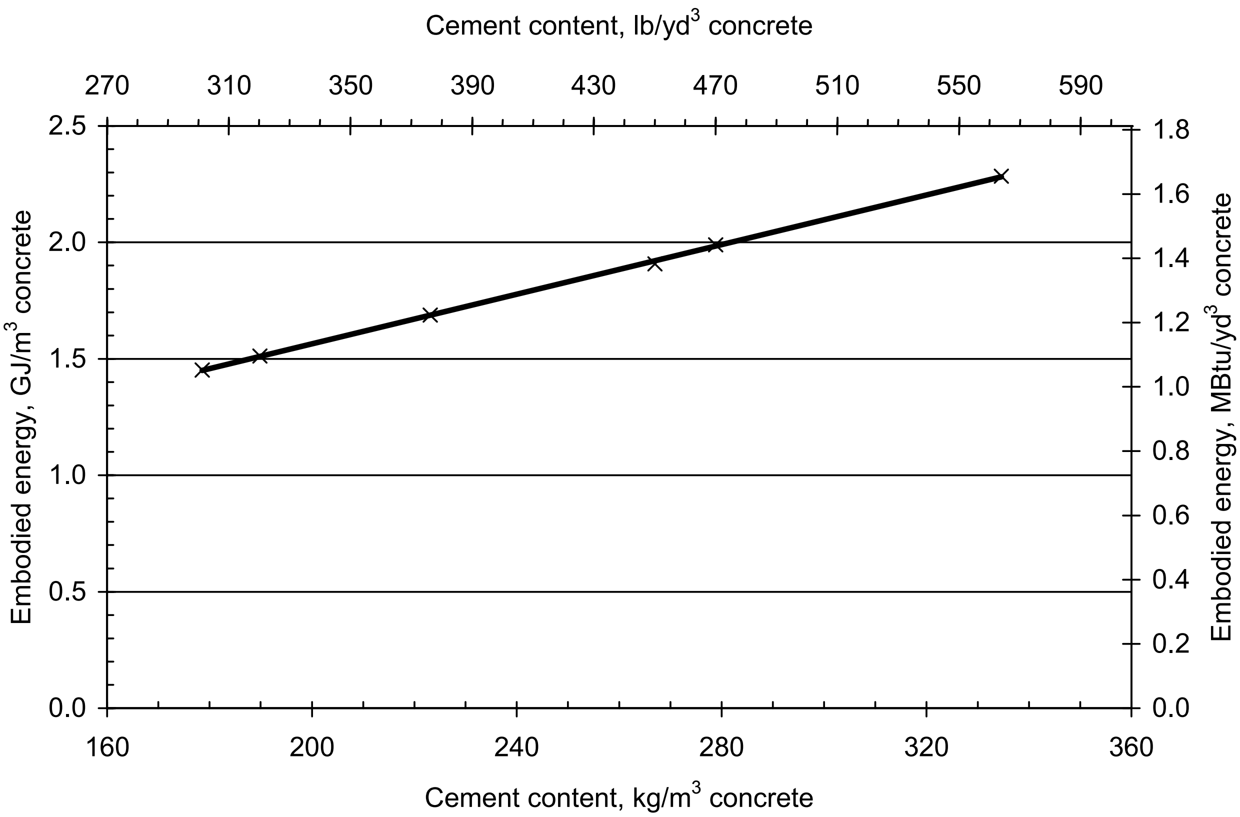

Figure 3-3. Relationship between cement content and embodied energy per unit volume of concrete.

Table 3-15. Fuel Consumption by Process Step for Energy Sources other than Electricity for 20 MPa (3,000 psi) concrete

Process step	**GJ/m³**	**MBtu/yd³**	**Percent of total**
Cement manufacturing	1.063	0.770	72
Aggregate production	0.066	0.048	4
Transportation	0.123	0.089	8
Concrete plant operations	0.233	0.169	16
Total	**1.485**	**1.076**	**100.0**

3.11.3 Particulate emissions. The single largest contributor to particulate emissions in both cement manufacture and aggregate production is quarry operations. These operations include blasting, haul roads, unloading, and stockpiling. In cement manufacture, quarry operations account for approximately 61% of total particulate emissions. In aggregate production, quarry operations are responsible for approximately 92% of particulate emissions. Figure 3-4 shows the particulate emissions by process step for the 20 MPa (3,000 psi) mix. Approximately 38% of the particulate emissions associated with concrete manufacture are from aggregate production and approximately 51% are embodied in the cement. Although not specifically addressed in this study, it should be noted that the impact of particulate emissions depends on the grain size.

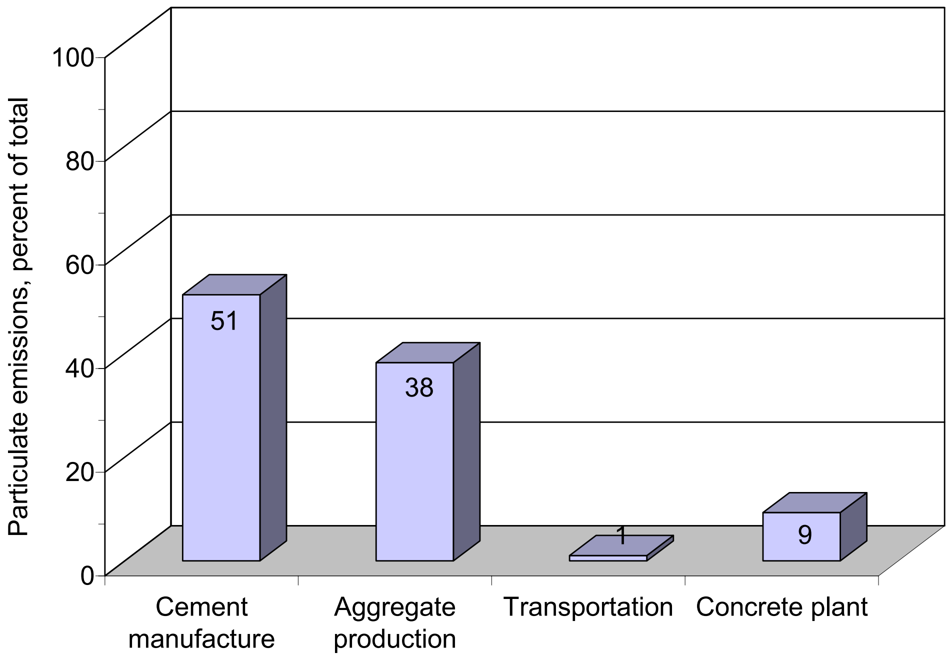

Figure 3-4. Particulate emissions by process step for 20 MPa (3,000 psi) concrete.

3.12 Data Quality

The energy data used for cement refer to 1999 and are national in scope. They include the four main cement manufacturing technologies: wet, long dry, dry with preheater, and dry with preheater and precalciner. The data are reported from plants representing approximately 70% of the U.S. cement industry. We believe the data that have a significant impact on results have a good level of accuracy. A set of industry-standard data-quality indicators complying with ISO 14401 has not yet been developed. Emissions to air, with the exception of CO_2, are based largely on EPA AP-42 emission factors for which qualitative quality indicators are available. Emissions of CO_2 are calculated from energy and calcination data.

The data referring to aggregate production and the operations at the 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.

4. CONCRETE MASONRY UNITS

4.1 System Boundary

The operations at a concrete masonry unit (CMU) plant (more commonly called a concrete block plant) are similar to those of a central-mixer ready-mixed-plant with the addition of molding and curing stages prior to shipment of the product. Concrete block plants usually produce a wide range of units for different specialty applications; however, the standard 200×200×400 mm (8×8×16 in.) CMU is the dominant product. Concrete block is produced by placing very dry, no-slump concrete in molds. After removal from the molds, the blocks are subjected to accelerated curing. As a general practice, concrete block is molded 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 the production of cement and aggregates and their transportation to the concrete block plant. The boundary includes operations at the block plant up to the point where the product is ready for shipment at the plant gate.

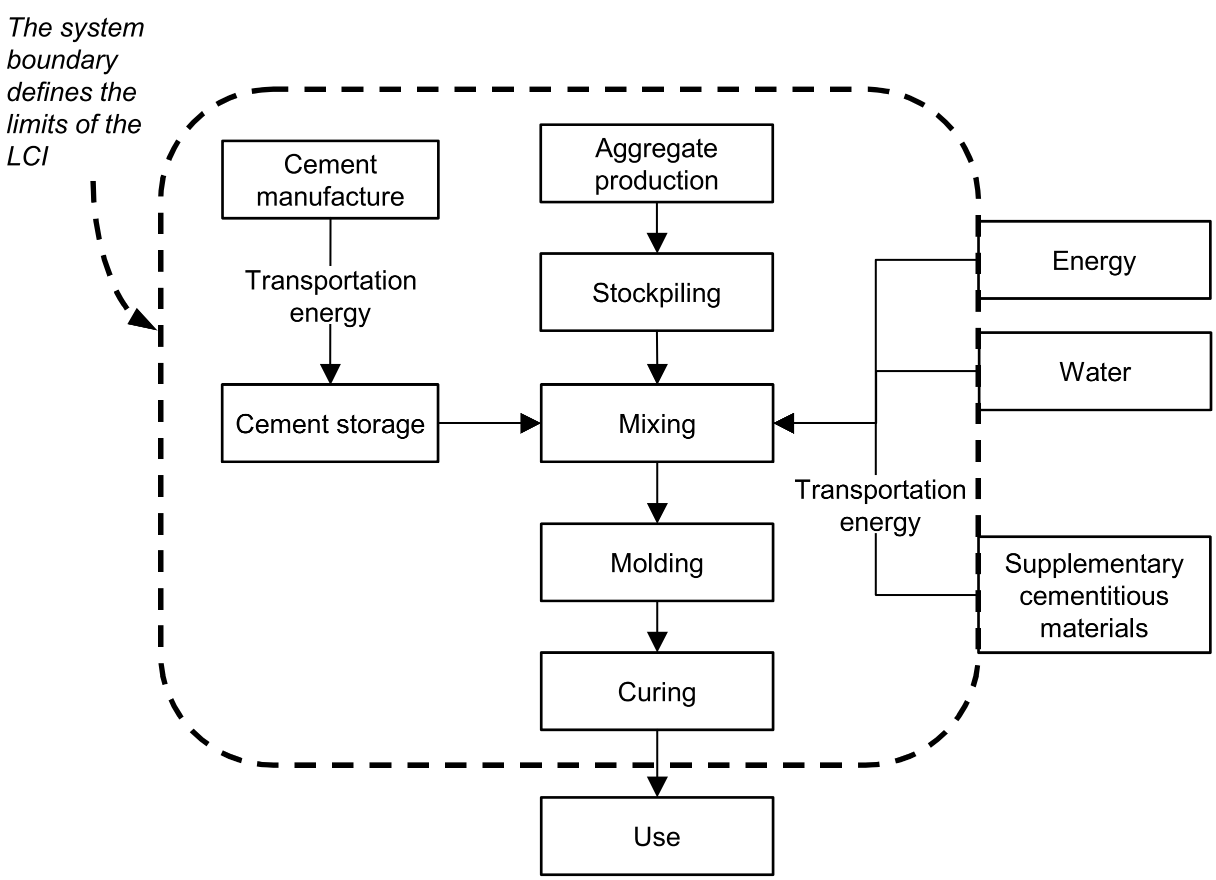

Figure 4-1. Concrete block system boundary.

4.2 Assumptions

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

1. The functional unit is 100 CMUs. A standard CMU is assumed to measure 200×200×400 mm (8×8×16 in.) and have 50% solid volume.
2. An average CMU contains 0.0074 m^3 (0.26 ft^3) of concrete. One cubic meter of mix represents approximately 135 CMUs (1 yd^3 of mix represents approximately 104 CMUs).
3. Estimates of curing energy are based on 3 blocks per pallet in an insulated kiln at 54°C (130°F) under summer conditions.[29]
4. On average, 50% of the fuel used in curing is natural gas and 50% is fuel oil.
5. Crushed stone accounts for 30% of the aggregate in the block mixes, and sand and gravel accounts for 70%.

4.3 Mix Designs

Table 4-1 presents three mix designs. The first is for the 20 MPa (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 unit weight of the bulk mix and for 100 CMUs.

Table 4-1A. Concrete Block Mix Design and Properties (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs**
28 day compressive strength, MPa	20	Unspecified	Unspecified
Fly ash, %	0	0	0
Unit weight, kg/m^3	2,294	2,350	2,337
Concrete raw material, kg/production unit*			
Cement	223	208	200
Fly ash	0	0	0
Water	141	142	137
Coarse aggregate	1,100	0	0
Fine aggregate	830	2,000	2,000
Total	**2,294**	**2,350**	**2,337**

*Production unit is 1 m^3 for ready mix and CMU concrete, and 100 CMUs for concrete block.
**The concrete mixes for CMU mix and CMUs 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]

Table 4-1B. Concrete Block Mix Design and Properties (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs**
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	337
Fly ash	0	0	0
Water	237	240	231
Coarse aggregate	1,900	0	0
Fine aggregate	1,400	3,400	3,300
Total	**3,913**	**3,990**	**3,900**

*Production unit is 1 yd^3 for ready mix and CMU concrete, and 100 CMUs for concrete block.
**The concrete mixes for CMU mix and CMUs are identical, but expressed in different units.
Source: Portland Cement Association.

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 90°C (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 (i) kiln design and insulation, (ii) curing process, whether continuous or batch, (iii) climate, whether summer or winter, and (iv) 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 NCMA.[29] The conditions are presented in Table 4-2.

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

Curing	Continuous
CMU per pallet	3
Temperature	54°C (130°F)
Conditions	Summer, insulated
Energy consumption per block	490 kJ (470 Btu)

Source: Reference 29.

4.6 Water Consumption

Block operations do not have the truck wash-off and wash-out requirements that ready mix plants have. Therefore, for the purposes of this LCI, it is assumed that block plants consume 25% of the water used in ready mix plants (not including water used in the concrete mix). Block operations are assumed to use 44 L/m^3 (8.8 gallon/yd^3), equivalent to 44 kg/m^3 (73 lb/yd^3), plus the amount used in the block mix from Table 4-1.

4.7 Emissions to Air

Sources of emissions to air 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. However, since the waste from block production consists primarily of damaged units that are generally crushed and recycled as aggregate or fill, 95% is beneficially reused. Based on this assumption, solid waste is approximately 3.0 kg/m^3 (5 lb/yd^3), which is equal to 23 kg (50 lb) per 100 CMU.

4.9 Waste Heat

The available data on waste heat apply only to cement manufacture, and average 1.9 GJ/metric ton (1.6 MBtu per ton).[18] There is no readily available information regarding waste heat in the other steps in the block manufacturing process, therefore waste heat is not included in the LCI.

4.10 Concrete Block LCI Results

The LCI results are presented as inputs and emissions per 100 CMU and as inputs and emissions per cubic meter of the mix used to make the block. The inputs and emissions for a standard 20 MPa (3,000 psi) concrete mix are provided as a benchmark.

4.10.1 Primary materials. Table 4-1 shows that the block mix contains 208 kg of cement per m^3 (337 lb/ yd^3) compared to 223 kg of cement per m^3 (376 lb/yd^3) for 20 MPa (3,000 psi) concrete. Table 4-3 shows the total materials required to make concrete and concrete block. An average of 1.6 metric tons of raw material are needed to produce one metric ton of cement.

4.10.2 Energy input. The energy data are expressed as units per cubic meter, units per cubic yard and units per 100 blocks. 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 1.66 GJ/m^3 (1.20 MBtu/yd^3) compared to 1.69 GJ/m^3 (1.22 MBtu/yd^3) for the 20 MPa (3,000 psi) mix. Embodied energy per 100 CMU is 1.23 GJ (1.16 MBtu). Table 4-5 presents the consumption of fuel and electricity.

As indicated in Section 3, energy consumption of the mixes varies primarily with cement content. Energy to produce cement for the block mix, 1.10 GJ/m^3 (0.799 MBtu/yd^3), dominates energy from other steps of the block production process. Energy required to produce aggregate is relatively small: 0.116 GJ/m^3 (0.084 MBtu/yd^3). Transportation energy is relatively constant at approximately 0.12 GJ/m^3 (0.09 MBtu/yd^3) for both mixes while energy used in the batch plant is 0.067 GJ/m^3 (0.179 MBtu/yd^3) regardless of the mix design.

Estimated curing energy is 494 J (468 Btu) per block assuming a continuous curing system with three blocks per pallet in an insulated kiln at 54°C (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.

4.10.3 Emissions to air. Table 4-6 presents the emissions to air from transportation of finished goods to the concrete block plant. Table 4-7 presents the emissions data per unit 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 4-3A. Material Inputs for Concrete Block Production (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, MPa	20	Unspecified	Unspecified	Table 3-1
Cement, kg/production unit*	223	208	200	Table 3-1
Fly ash, %	0	0	0	Table 3-1
Cement raw material, kg/production unit**				
Limestone	266	247	238	18
Cement rock, marl	50	46	45	18
Shale	12	11	11	18
Clay	15	14	13	18
Bottom ash	0	0	0	18
Fly ash	1	1	1	18
Foundry sand	1	1	1	18
Sand	2	2	2	18
Iron, iron ore	2	1	1	18
Gypsum, anhydrite	11	11	10	18
Water	39	37	35	18
Subtotal†	**360**	**335**	**323**	
Other concrete raw material, kg/production unit				
Fly ash	0	0	0	Table 3-1
Water	141	142	137	Table 3-1
Coarse aggregate	1,127	0	0	Table 3-1
Fine aggregate	831	2,033	1,955	Table 3-1
Subtotal	**2,098**	**2,176**	**2,092**	

*Production unit is 1 m^3 for ready mix and CMU mix concrete and 100 CMUs for concrete block.
**Approximately 1.6 metric ton of raw materials (excluding water) are needed to make 1 metric 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 0.416 kg/m^3 (0.701 lb/yd^3) for the 20 MPa (3,000 psi) mix and 0.382 GJ/m^3 (0.644 lb/yd^3) for the block mix. Particulate emissions associated with cement manufacture are 0.558 and 0.519 kg/m^3 (0.941 and 0.876 lb/yd^3) for the same mixes.

Table 4-3B. Material Inputs for Concrete Block Production (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 3-1
Cement, lb/production unit*	376	350	337	Table 3-1
Fly ash, %	0	0	0	Table 3-1
Cement raw material, lb/production unit**				
Limestone	448	417	402	18
Cement rock, marl	84	78	75	18
Shale	20	19	18	18
Clay	25	24	23	18
Bottom ash	0	0	0	18
Fly ash	2	2	2	18
Foundry sand	1	1	1	18
Sand	4	4	4	18
Iron, iron ore	3	2	2	18
Gypsum, anhydrite	19	18	17	18
Water	66	62	59	18
Subtotal†	**606**	**565**	**545**	
Other concrete raw material, lb/production unit				
Fly ash	0	0	0	Table 3-1
Water	237	240	231	Table 3-1
Coarse aggregate	1,900	0	0	Table 3-1
Fine aggregate	1,400	3,427	3,295	Table 3-1
Subtotal	**3,537**	**3,667**	**3,526**	

*Production unit is 1 yd^3 for ready mix and CMU mix concrete and 100 CMUs for concrete block.
**Approximately 1.6 ton 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.

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 14,600 kJ/CMU (13,900 Btu/CMU), which is 19% higher than 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.

Table 4-4A. Energy Inputs for Concrete Block Production (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, MPa	20	Unspecified	Unspecified	Table 4-1
Cement manufacturing, GJ/functional unit*				
Coal	0.702	0.654	0.481	18
Gasoline	0.0005	0.0005	0.0003	18
LPG	0.0001	0.0001	0.0001	18
Middle distillates	0.011	0.010	0.007	18
Natural gas	0.077	0.072	0.053	18
Petroleum coke	0.176	0.164	0.121	18
Residual oil	0.001	0.001	0.001	18
Wastes	0.096	0.089	0.066	18
Electricity	0.122	0.113	0.083	18
Subtotal	**1.18**	**1.10**	**0.812**	
Aggregate production, GJ/functional unit				
Crushed stone				
Diesel fuel	0.049	0.025	0.019	**
Electricity	0.049	0.025	0.019	**
Sand and gravel				
Diesel fuel	0.018	0.033	0.024	**
Electricity	0.018	0.033	0.024	**
Subtotal	**0.133**	**0.116**	**0.085**	
Transporting materials to plant, GJ/functional unit				
Diesel fuel				
Cement	0.023	0.021	0.016	†
Coarse aggregate	0.058	not applicable	not applicable	†
Fine aggregate	0.042	0.104	0.076	†
Subtotal	**0.123**	**0.125**	**0.092**	†
Concrete plant operations, GJ/functional unit				
Diesel fuel	0.191	0.191	0.144	23
Natural gas	0.042	0.042	0.031	23
Electricity	0.014	0.014	0.011	23
Subtotal	**0.247**	**0.247**	**0.187**	
Concrete block curing, GJ/functional unit				
Middle distillates	not applicable	0.034	0.025	29
Natural gas	"	0.034	0.025	29
Electricity	"	0.000	0.000	29
Subtotal	"	**0.067**	**0.049**	
Total	**1.69**	**1.66**	**1.23**	

*Functional unit is 1 m^3 for ready mix and CMU mix concrete, and 100 CMUs for concrete block.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 4-4B. Energy Inputs for Concrete Block Production in (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Cement manufacturing, MBtu/functional unit*				
Coal	0.509	0.474	0.456	18
Gasoline	0.0004	0.0003	0.0003	18
LPG	0.0001	0.0001	0.0000	18
Middle distillates	0.008	0.007	0.0068	18
Natural gas	0.056	0.052	0.0501	18
Petroleum coke	0.128	0.119	0.1144	18
Residual oil	0.001	0.001	0.0005	18
Wastes	0.069	0.065	0.0622	18
Electricity	0.088	0.082	0.0791	18
Subtotal	**0.859**	**0.799**	**0.770**	
Aggregate production, MBtu/functional unit				
Crushed stone				
Diesel fuel	0.035	0.018	0.018	**
Electricity	0.035	0.018	0.018	**
Sand and gravel				
Diesel fuel	0.013	0.024	0.023	**
Electricity	0.013	0.024	0.023	**
Subtotal	**0.096**	**0.084**	**0.081**	
Transporting materials to plant, MBtu/functional unit				
Diesel fuel				
Cement	0.017	0.015	0.015	†
Coarse aggregate	0.042	not applicable	not applicable	†
Fine aggregate	0.031	0.075	0.072	†
Subtotal	**0.089**	**0.091**	**0.087**	†
Concrete plant operations, MBtu/functional unit				
Diesel fuel	0.139	0.139	0.137	23
Natural gas	0.030	0.030	0.030	23
Electricity	0.010	0.010	0.010	23
Subtotal	**0.179**	**0.179**	**0.177**	
Concrete block curing, MBtu/functional unit				
Middle distillates	not applicable	0.024	0.023	29
Natural gas	"	0.024	0.023	29
Electricity	"	0.000	0.000	29
Subtotal	"	**0.049**	**0.047**	
Total	**1.22**	**1.20**	**1.16**	

*Functional unit is 1 yd^3 for ready mix and CMU mix concrete and 100 CMUs for concrete block.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 4-5A. Energy Inputs for Concrete Block Production by Fuel Type (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, MPa	20	Unspecified	Unspecified	
Cement manufacturing, fuel unit/functional unit*				
Coal, kg	24.1	22.4	16.5	18
Gasoline, L	0.028	0.026	0.019	18
LPG, L	0.007	0.006	0.005	18
Middle distillates, L	0.214	0.199	0.147	18
Natural gas, m^3	2.05	1.91	1.40	18
Petroleum coke, kg	5.83	5.43	3.99	18
Residual oil, L	0.012	0.011	0.008	18
Wastes, kg	9.25	8.61	6.34	18
Electricity, kWh	20.2	18.8	13.8	18
Aggregate production, fuel unit/functional unit				
Crushed stone				
Diesel fuel, L	1.261	0.654	0.481	†
Electricity, kWh	13.504	6.997	5.144	†
Sand and gravel				
Diesel fuel, L	0.461	0.854	0.627	†
Electricity, kWh	4.934	9.139	6.717	†
Transporting materials to plant, fuel unit/functional unit				
Diesel fuel, L				
Cement	0.592	0.551	0.405	††
Coarse aggregate	1.50	not applicable	not applicable	††
Fine aggregate	1.10	2.70	1.38	††
Concrete plant operations, fuel unit/functional unit				
Diesel fuel, L	4.97	4.97	3.75	23
Natural gas, m^3	1.09	1.09	0.824	23
Electricity, kWh	3.948	3.948	2.980	23
Concrete block curing, fuel unit/functional unit				
Diesel fuel, L	not applicable	0.871	0.641	29
Natural gas, m^3	"	0.880	0.647	29
Electricity, kWh	"	0.000	0.000	29

*Production unit is 1 m^3 for bulk (mix) concrete, and 100 CMUs for concrete block.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 4-5B. Energy Inputs for Concrete Block Production by Fuel Type (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	
Cement manufacturing, fuel unit/functional unit*				
Coal, lb	40.5	37.7	36.3	18
Gasoline, gallon	0.006	0.005	0.005	18
LPG, gallon	0.001	0.001	0.001	18
Middle distillates, gallon	0.043	0.040	0.039	18
Natural gas, ft^3	55.3	51.5	49.6	18
Petroleum coke, lb	9.83	9.15	8.81	18
Residual oil, gallon	0.002	0.002	0.002	18
Wastes, lb	15.6	14.5	14.0	18
Electricity, kWh	15.4	14.4	13.8	18
Aggregate production, fuel unit/functional unit				
Crushed stone				
Diesel fuel, gallon	0.255	0.132	0.127	**
Electricity, kWh	10.325	5.350	5.144	**
Sand and gravel				
Diesel fuel, gallon	0.093	0.172	0.166	**
Electricity, kWh	3.772	6.987	6.717	**
Transporting materials to plant, fuel unit/functional unit				
Diesel fuel, gallon				
Cement	0.120	0.111	0.107	†
Coarse aggregate	0.302	not applicable	not applicable	†
Fine aggregate	0.223	0.545	0.366	†
Concrete plant operations, fuel unit/functional unit				
Diesel fuel, gallon	1.00	1.00	0.99	23
Natural gas, ft^3	29.5	29.5	29.1	23
Electricity, kWh	3.019	3.019	2.980	23
Concrete block curing, fuel unit/functional unit				
Middle distillates, gallon	not applicable	0.176	0.169	29
Natural gas, ft^3	"	23.75	22.84	29
Electricity, kWh	"	0.000	0.000	29

*Production unit is 1 yd^3 for bulk (mix) concrete, and 100 CMUs for concrete block.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

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Table 4-6A. Emissions to Air for Transportation of Purchased Materials to Concrete Plant for Concrete Block Production (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs
28 day compressive strength, MPa	20	Unspecified	Unspecified
Cement transportation, kg/functional unit*			
Particulate matter	0.002	0.002	0.001
CO_2	1.62	1.50	1.11
SO_2	0.003	0.002	0.002
NO_x	0.015	0.014	0.010
VOC**	0.003	0.002	0.002
CO	0.015	0.014	0.010
CH_4	0.000	0.000	0.000
Aggregate transportation, kg/functional unit			
Particulate matter	0.009	0.010	0.007
CO_2	7.09	7.37	5.42
SO_2	0.011	0.012	0.009
NO_x	0.065	0.068	0.050
VOC**	0.012	0.012	0.009
CO	0.065	0.068	0.050
CH_4	0.002	0.002	0.001
Total material transportation, kg/functional unit			
Particulate matter	0.011	0.012	0.009
CO_2	8.71	8.87	6.52
SO_2	0.014	0.014	0.010
NO_x	0.080	0.082	0.060
VOC**	0.014	0.015	0.011
CO	0.080	0.081	0.060
CH_4	0.002	0.002	0.002

*Production unit is 1 m^3 for bulk (mix) concrete, and 100 CMUs 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 23.

Table 4-6B. Emissions to Air for Transportation of Purchased Materials to Concrete Plant for Concrete Block Production (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs
28 day compressive strength, psi	3,000	Unspecified	Unspecified
Cement transportation, lb/functional unit*			
Particulate matter	0.004	0.003	0.003
CO_2	2.72	2.54	2.44
SO_2	0.004	0.004	0.004
NO_x	0.025	0.023	0.022
VOC**	0.005	0.004	0.004
CO	0.025	0.023	0.022
CH_4	0.001	0.001	0.001
Aggregate transportation, lb/functional unit			
Particulate matter	0.016	0.016	0.016
CO_2	12.0	12.4	11.9
SO_2	0.019	0.020	0.019
NO_x	0.110	0.114	0.110
VOC**	0.020	0.021	0.020
CO	0.110	0.114	0.109
CH_4	0.003	0.003	0.003
Total material transportation, lb/functional unit			
Particulate matter	0.019	0.020	0.019
CO_2	14.7	15.0	14.4
SO_2	0.023	0.024	0.023
NO_x	0.135	0.138	0.132
VOC**	0.024	0.025	0.024
CO	0.135	0.137	0.132
CH_4	0.004	0.004	0.004

*Production unit is 1 yd^3 for bulk (mix) concrete and 100 CMUs 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 23.

Table 4-7A. Emissions to Air by Process Step for Concrete Block Production (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	20	Unspecified	Unspecified	Table 4-1
Cement manufacture, kg/functional unit*				
Particulate matter	0.558	0.519	0.382	18
CO_2	201	187	138	18
SO_2	0.440	0.409	0.301	18
NO_x	0.575	0.535	0.394	18
VOC**	0.009	0.009	0.006	18
CO	0.195	0.182	0.134	18
CH_4	0.008	0.007	0.005	18
Aggregate production, kg/functional unit				
Particulate matter	0.416	0.382	0.281	11, 13, 25
CO_2	4.71	4.12	3.03	23
SO_2	0.007	0.007	0.005	23
NO_x	0.043	0.038	0.028	23
VOC**	0.008	0.007	0.005	23
CO	0.043	0.038	0.028	23
CH_4	0.001	0.001	0.001	23
Transportation to ready mix plant, kg/functional unit				
Particulate matter	0.011	0.012	0.009	Table 4-6
CO_2	8.7	8.9	6.5	Table 4-6
SO_2	0.014	0.014	0.010	Table 4-6
NO_x	0.080	0.082	0.060	Table 4-6
VOC**	0.014	0.015	0.011	Table 4-6
CO	0.080	0.081	0.060	Table 4-6
CH_4	0.002	0.002	0.002	Table 4-6
Concrete plant operations, kg/functional unit				
Particulate matter	0.101	0.101	0.076	14
CO_2	14.2	14.2	10.7	27, 28
SO_2	0.083	0.083	0.063	27, 28
NO_x	0.014	0.014	0.011	27, 28
VOC**	0.0003	0.0003	0.0002	27, 28
CO	0.004	0.004	0.003	27, 28
CH_4	no data	no data	no data	27, 28
Concrete block curing, kg/functional unit				
Particulate matter	not applicable	no data	no data	
CO_2	"	3.84	2.83	29
SO_2	"	0.015	0.011	29
NO_x	"	0.004	0.003	29
VOC**	"	0.0001	0.00004	29
CO	"	0.001	0.001	29
CH_4	"	0.0001	0.00004	29

*Production unit is 1 m^3 for bulk (mix) concrete, and 100 CMUs for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 4-7B. Emissions to Air by Process Step for Concrete Block Production (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Cement manufacture, lb/functional unit*				
Particulate matter	0.941	0.876	0.843	18
CO_2	339	315	303	18
SO_2	0.741	0.690	0.664	18
NO_x	0.969	0.902	0.868	18
VOC**	0.016	0.014	0.014	18
CO	0.329	0.307	0.295	18
CH_4	0.013	0.012	0.012	18
Aggregate production, lb/functional unit				
Particulate matter	0.701	0.644	0.619	11, 13, 25
CO_2	7.93	6.94	6.67	23
SO_2	0.013	0.011	0.011	23
NO_x	0.073	0.064	0.061	23
VOC**	0.013	0.011	0.011	23
CO	0.073	0.064	0.061	23
CH_4	0.002	0.002	0.002	23
Transportation to ready mix plant, lb/functional unit				
Particulate matter	0.019	0.020	0.019	Table 4-6
CO_2	14.7	15.0	14.4	Table 4-6
SO_2	0.023	0.024	0.023	Table 4-6
NO_x	0.135	0.138	0.132	Table 4-6
VOC**	0.024	0.025	0.024	Table 4-6
CO	0.135	0.137	0.132	Table 4-6
CH_4	0.004	0.004	0.004	Table 4-6
Concrete plant operations, lb/functional unit				
Particulate matter	0.171	0.171	0.168	14
CO_2	23.9	23.9	23.6	27, 28
SO_2	0.141	0.141	0.139	27, 28
NO_x	0.024	0.024	0.024	27, 28
VOC**	0.0004	0.0004	0.0004	27, 28
CO	0.006	0.006	0.006	27, 28
CH_4	no data	no data	no data	27, 28
Concrete block curing, lb/functional unit				
Particulate matter	not applicable	no data	no data	
CO_2	"	6.48	6.23	29
SO_2	"	0.025	0.024	29
NO_x	"	0.007	0.007	29
VOC**	"	0.0001	0.0001	29
CO	"	0.002	0.002	29
CH_4	"	0.0001	0.0001	29

*Production unit is 1 yd^3 for bulk (mix) concrete, and 100 CMUs for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 4-8A. Total Emissions from Concrete Block Production (SI Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	20	Unspecified	Unspecified	Table 4-1
Total emissions, kg/functional unit*				
Particulate matter	1.09	1.01	0.75	Table 4-7
CO_2	228	218	161	Table 4-7
SO_2	0.544	0.528	0.390	Table 4-7
NO_x	0.71	0.67	0.50	Table 4-7
VOC**	0.032	0.030	0.022	Table 4-7
CO	0.322	0.306	0.225	Table 4-7
CH_4	0.012	0.011	0.008	Table 4-7
Waste at cement plant, kg/functional unit				
Cement kiln dust (CKD)	11.6	10.8	7.9	18

*Production unit is 1 m^3 for bulk (mix) concrete, and 100 CMUs for concrete block.
**Until more precise data are available, these VOC values also include some non-VOC, such as CH_4.

Table 4-8B. Total Emissions from Concrete Block Production (U.S. Customary Units)

Concrete mix description	Ready mixed 3	CMU mix	100 CMUs	Reference
28 day compressive strength, psi	3,000	Unspecified	Unspecified	Table 4-1
Total emissions, lb/functional unit*				
Particulate matter	1.83	1.71	1.65	Table 4-7
CO_2	385	367	354	Table 4-7
SO_2	0.918	0.890	0.860	Table 4-7
NO_x	1.20	1.13	1.09	Table 4-7
VOC**	0.053	0.051	0.049	Table 4-7
CO	0.543	0.515	0.496	Table 4-7
CH_4	0.019	0.018	0.018	Table 4-7
Waste at cement plant, lb/functional unit				
Cement kiln dust (CKD)	19.6	18.2	17.5	18

*Production unit is 1 yd^3 for bulk (mix) concrete, and 100 CMUs 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
CMU per pallet	5	3
Ambient conditions	Winter	Summer
SI units		
Curing temperature, °C	88	54
Energy before curing, kJ/CMU	11,760	11,760
Curing energy, kJ/CMU	2,879	494
Total energy, kJ/CMU	14,639	12,254
U.S. Customary units		
Curing temperature, °F	190	130
Energy before curing, Btu/CMU	11,147	11,147
Curing energy, Btu/CMU	2,729	468
Total energy, Btu/CMU	13,876	11,615
Curing energy as % of total	**20**	**4**

Source: Reference 29.

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:

1. Concrete mixing.
2. 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.
3. Placing the concrete in the form.
4. Consolidation by vibration, leveling, and surface finishing.
5. Curing.
6. Form stripping.

The functional unit in this LCI is one cubic meter and 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, 50 MPa (7,500 psi), 70 MPa (10,000 psi), and architectural precast, are presented in Table 5-1. The table also provides the 20 MPa (3,000 psi) 30 MPa (4,000 psi) and 35 MPa (5,000 psi) ready-mixed concrete mix designs for comparison purposes.

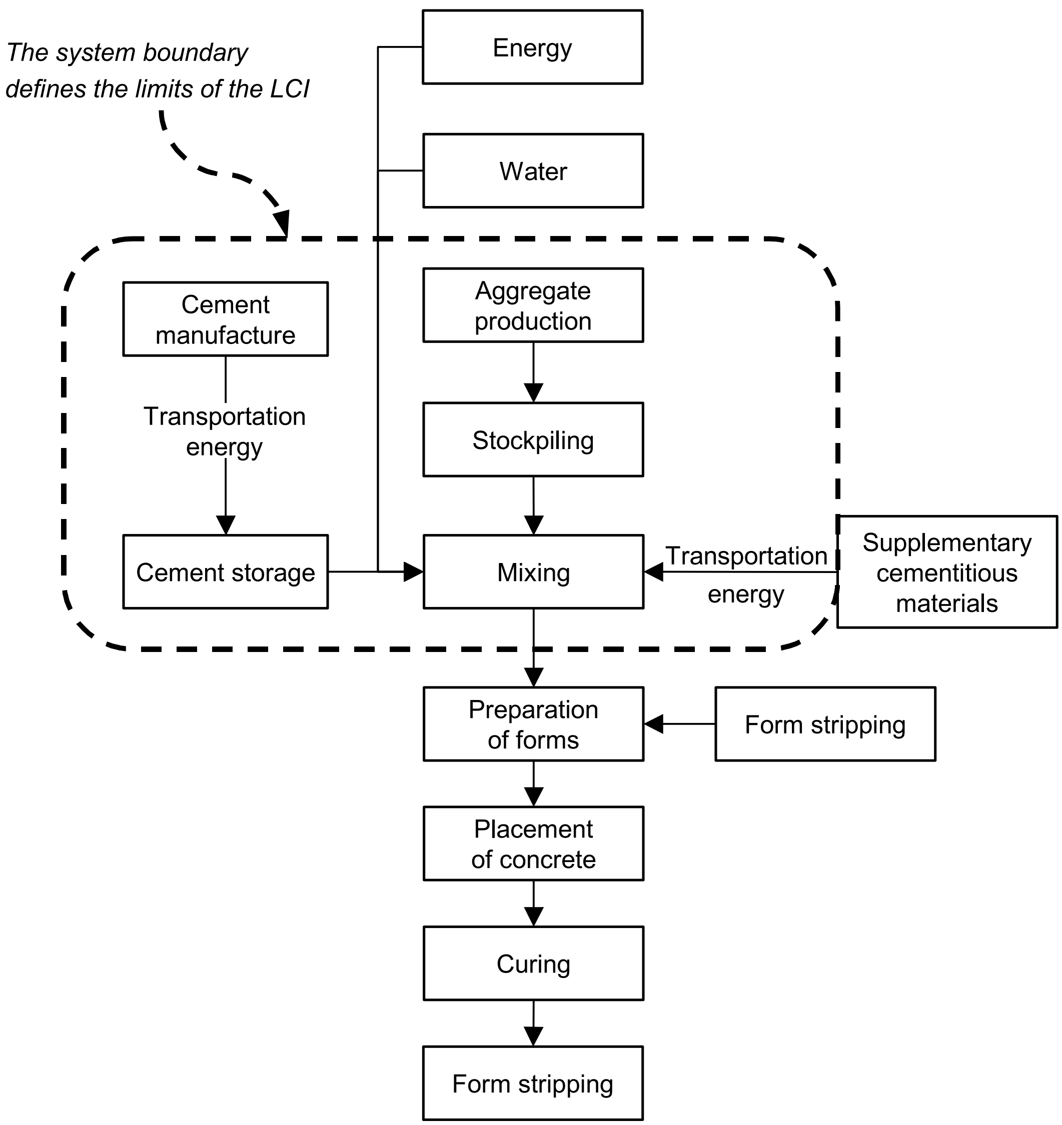

Figure 5-1. Precast concrete system boundary.

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, two exceptions are (i) non-process water consumption, which is assumed to be 50% less than that used in ready mixed operations; and (ii) solid waste, which is assumed to be 95% recycled compared to 90% for ready mixed concrete. The round trip transportation distances to the precast concrete plant for silica fume are assumed to be 100 kilometers (60 miles), the same as those for cement and fly ash.

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 because 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 unit of ready mixed concrete, which is equivalent to 85 L/m^3 (17.5 gallon/yd^3) of precast concrete.

Total water used at a precast concrete plant is assumed to be 85 L/m^3 (17.5 gallon/yd^3), which is equivalent to 85 kg/m^3 (146 lb/yd^3), plus the amount used for the concrete mix from Table 5-1. Water used in the mix does not contribute to effluents.

5.7 Emissions to Air

Sources of emissions to air 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 reused. Solid waste is approximately 3 kg/m^3 (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, therefore waste heat is not included in the LCI.

5.10 Precast Concrete Results

5.10.1 Primary materials. Table 5-1 shows that the cement content of the precast mixes ranges from 386 to 504 kg/m^3 (650 to 850 lb/yd^3) compared to 650 to 850 kg/m^3 (376 to 564 lb/yd^3) for the ready mixes. Precast mix 2, in addition to 445 kg/m^3 (750 lb/yd^3) of cement, contains 56 kg/m^3 (95 lb/yd^3) of silica fume. Table 5-2 shows the total materials required to make a cubic meter and a cubic yard of the precast mixes taking into account the fact that an average of 1.6 metric tons of raw material are needed to produce one metric ton of cement.

5.10.2 Energy input. Energy consumption data per unit of each mix are presented for cement manufacturing, aggregate production, transportation, and operations at the precast concrete plant. Table 5-3 presents energy consumption for all aspects of the manufacturing process in terms of energy and Table 5-4 presents energy consumption in terms of fuel and electricity. 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 1.69 GJ/m^3 (1.22 MBtu/yd3) for the 20 MPa (3,000 psi) mix, which contains 223 kg (376 lb) of cement, to 3.17 GJ/m^3 (2.30 MBtu/yd^3) for precast mix 1, which contains 504 kg (850 lb) of cement. Energy required to produce aggregate is relatively small ranging from approximately 0.109 to 0.123 GJ/m^3 (0.079 to 0.089 MBtu/yd^3). Transportation energy is relatively constant at approximately 0.135 GJ/m^3 (0.098 MBtu/yd^3) for all the mixes while energy used in the concrete plant is constant at 0.247 GJ/m^3 (0.179 MBtu/yd^3) regardless of the mix design.

5.10.3 Emissions to air. Table 5-6 presents the emissions from transportation of raw materials to the precast concrete plant. Table 5-7 presents the emissions data per cubic meter and per cubic yard of each mix for the process stages: cement manufacture, aggregate production, transportation, and operations at the concrete plant. Table 5-8 shows total emissions. The amounts of CO_2 and other emissions of combustion gases associated with concrete production are primarily a function of the cement content in the mix designs. For example, total CO_2 emissions range from 228 kg/m^3 (385 lb/yd^3) for the 20 MPa (3,000 psi) mix to 482 kg/m^3 (812 lb/yd^3) for precast mix 1. SO_2 ranges from 0.54 to 1.10 kg/m^3 (0.92 to 1.85 lb/yd^3) for the same mixes, while NO_x ranges from .71 to 1.44 kg/m^3 (1.20 to 2.42 lb/yd^3).

Table 5-8 shows that particulate emissions range from 1.09 to 1.72 kg/m^3 (1.83 to 2.89 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 0.42 kg/m^3 (0.70 lb/yd^3) for the 20 MPa (3,000 psi) mix and 0.341 kg/m^3 (0.58 lb/yd^3) for precast mix 1. Particulate emissions associated with cement manufacture range from are 0.56 to 1.26 kg/m^3 (0.94 and 2.13 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 for shipment. For this reason the LCI results for precast will have the same sensitivities as ready mixed concrete (see Section 3.11).

Table 5-1A. Concrete Mix Designs and Properties (SI Units)

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, MPa	35	30	20	50	70	Unspecified*
Silica fume, %	0	0	0	0	11	0
Unit weight, kg/m^3	2,374	2,377	2,321	2,287	2,361	2,349
Concrete raw material, kg/m^3 concrete						
Cement	335	279	223	504	445	386
Silica fume	0	0	0	0	56	0
Water	141	141	141	178	136	154
Coarse aggregate	1,200	1,200	1,100	1,100	1,100	1,100
Fine aggregate	710	770	830	550	610	740
Total	**2,385**	**2,389**	**2,294**	**2,332**	**2,348**	**2,380**

*Architectural precast panels.
Source: Portland Cement Association.

Table 5-1B. Concrete Mix Designs and Properties (U.S. Customary Units)

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.

Table 5-2A. Material Inputs for Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*	Table 5-1
Cement, kg/m^3 concrete	335	279	223	504	445	386	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement raw material, kg/m^3 concrete**							
Limestone	399	332	266	601	530	460	18
Cement rock, marl	75	62	50	113	100	86	18
Shale	18	15	12	27	24	21	18
Clay	23	19	15	34	30	26	18
Bottom ash	1	0	0	1	0	1	18
Fly ash	2	2	1	3	2	2	18
Foundry sand	1	1	1	2	1	1	18
Sand	4	3	2	6	5	4	18
Iron, iron ore	2	2	2	4	4	3	18
Gypsum, anhydrite	17	14	11	26	23	20	18
Water	59	49	39	89	78	68	18
Subtotal†	**540**	**450**	**360**	**815**	**718**	**624**	
Other concrete raw material, kg/m^3 concrete							
Silica fume	0	0	0	0	56	0	Table 5-1
Water	141	141	141	178	136	154	Table 5-1
Coarse aggregate	1,200	1,200	1,100	1,100	1,100	1,100	Table 5-1
Fine aggregate	710	770	830	550	610	740	Table 5-1
Subtotal	**2,051**	**2,111**	**2,071**	**1,828**	**1,903**	**1,994**	

*Architectural precast panels
**Approximately 1.6 metric ton of raw materials (excluding water) are needed to make 1 metric ton of cement due primarily to calcination of the limestone.
†Subtotal does not include water.

Table 5-2B. Material Inputs for Precast Concrete Production (U.S. Customary Units)

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, lb/yd^3 concrete	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	672	560	448	1,013	894	775	18
Cement rock, marl	126	105	84	190	168	145	18
Shale	30	25	20	46	40	35	18
Clay	38	32	25	57	50	44	18
Bottom ash	1	0	0	1	0	1	18
Fly ash	3	3	2	5	4	4	18
Foundry sand	2	1	1	3	2	2	18
Sand	6	5	4	10	8	7	18
Iron, iron ore	4	3	3	6	6	5	18
Gypsum, anhydrite	29	24	19	43	38	33	18
Water	100	83	66	150	132	115	18
Subtotal†	**911**	**758**	**606**	**1,374**	**1,210**	**1,051**	
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 ton 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.

Table 5-3A. Energy Inputs for Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*	Table 4-1
Silica fume, %	0	0	0	0	11	0	Table 4-1
Cement manufacturing, GJ/m^3 concrete							
Coal	1.05	0.878	0.702	1.59	1.40	1.21	18
Gasoline	0.001	0.001	0.001	0.001	0.001	0.001	18
LPG	0.0001	0.0001	0.0001	0.0002	0.0002	0.0001	18
Middle distillates	0.016	0.013	0.011	0.024	0.021	0.018	18
Natural gas	0.116	0.096	0.077	0.174	0.154	0.133	18
Petroleum coke	0.264	0.220	0.176	0.398	0.351	0.304	18
Residual oil	0.001	0.001	0.001	0.002	0.002	0.001	18
Wastes	0.144	0.120	0.096	0.216	0.191	0.165	18
Electricity	0.183	0.152	0.122	0.275	0.243	0.210	18
Subtotal	**1.78**	**1.48**	**1.18**	**2.68**	**2.36**	**2.05**	
Aggregate production, GJ/m^3 concrete							
Crushed stone							
Diesel fuel	0.047	0.049	0.049	0.040	0.043	0.045	**
Electricity	0.047	0.049	0.049	0.040	0.043	0.045	**
Sand and gravel							
Diesel fuel	0.017	0.018	0.018	0.015	0.016	0.016	**
Electricity	0.017	0.018	0.018	0.015	0.016	0.016	**
Subtotal	**0.129**	**0.133**	**0.133**	**0.109**	**0.117**	**0.123**	
Transporting materials to plant, GJ/m^3 concrete							
Diesel fuel							
Cement	0.034	0.029	0.023	0.052	0.045	0.039	†
Coarse aggregate	0.061	0.061	0.058	0.054	0.057	0.055	†
Fine aggregate	0.036	0.039	0.042	0.028	0.031	0.038	†
Silica fume	0.000	0.000	0.000	0.000	0.006	0.000	†
Subtotal	**0.131**	**0.129**	**0.123**	**0.134**	**0.139**	**0.132**	
Concrete plant operations, GJ/m^3 concrete							
Diesel fuel	0.191	0.191	0.191	0.191	0.191	0.191	23
Natural gas	0.042	0.042	0.042	0.042	0.042	0.042	23
Electricity	0.014	0.014	0.014	0.014	0.014	0.014	23
Subtotal	**0.247**	**0.247**	**0.247**	**0.247**	**0.247**	**0.247**	
Total	**2.28**	**1.99**	**1.69**	**3.17**	**2.87**	**2.55**	

*Architectural precast concrete panels.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 5-3B. Energy Inputs for Precast Concrete Production (U.S. Customary Units)

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
Silica fume, %	0	0	0	0	11	0	Table 4-1
Cement manufacturing, MBtu/yd^3 concrete							
Coal	0.763	0.636	0.509	1.15	1.02	0.880	18
Gasoline	0.001	0.000	0.000	0.001	0.001	0.001	18
LPG	0.00008	0.00007	0.00005	0.00012	0.00011	0.00009	18
Middle distillates	0.011	0.010	0.008	0.017	0.015	0.013	18
Natural gas	0.084	0.070	0.056	0.126	0.112	0.097	18
Petroleum coke	0.191	0.160	0.128	0.289	0.255	0.221	18
Residual oil	0.001	0.001	0.001	0.001	0.001	0.001	18
Wastes	0.104	0.087	0.069	0.157	0.138	0.120	18
Electricity	0.132	0.110	0.088	0.199	0.176	0.152	18
Subtotal	**1.29**	**1.07**	**0.86**	**1.94**	**1.71**	**1.48**	
Aggregate production, MBtu/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	**0.093**	**0.096**	**0.096**	**0.079**	**0.085**	**0.089**	
Transporting materials to plant, MBtu/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**	**0.093**	**0.089**	**0.097**	**0.101**	**0.096**	
Concrete plant operations, MBtu/yd^3 concrete							
Diesel fuel	0.139	0.139	0.139	0.139	0.139	0.139	23
Natural gas	0.030	0.030	0.030	0.030	0.030	0.030	23
Electricity	0.010	0.010	0.010	0.010	0.010	0.010	23
Subtotal	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	**0.179**	
Total	**1.66**	**1.44**	**1.22**	**2.30**	**2.08**	**1.85**	

*Architectural precast concrete panels.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

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Table 5-4A. Energy Inputs for Precast Concrete Production by Fuel Type (SI Units)

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, MPa	35	30	20	50	70	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement manufacturing, fuel unit/m^3 concrete							
Coal, kg	36.1	30.1	24.1	54.4	48.0	41.6	18
Gasoline, L	0.042	0.035	0.028	0.063	0.056	0.048	18
LPG, L	0.010	0.008	0.007	0.015	0.013	0.011	18
Middle distillates, L	0.321	0.267	0.214	0.484	0.427	0.370	18
Natural gas, m^3	3.07	2.56	2.05	4.63	4.09	3.54	18
Petroleum coke, kg	8.74	7.29	5.83	13.2	11.6	10.1	18
Residual oil, L	0.018	0.015	0.012	0.027	0.024	0.021	18
Wastes, kg	13.9	11.6	9.3	20.9	18.5	16.0	18
Electricity, kWh	30.3	25.2	20.2	45.6	40.3	34.9	18
Aggregate production, fuel unit/m^3 concrete							
Crushed stone							
Diesel fuel, L	1.22	1.26	1.26	1.03	1.11	1.17	**
Electricity, kWh	13.095	13.504	13.504	11.069	11.888	12.481	**
Sand and gravel							
Diesel fuel, L	0.447	0.461	0.461	0.378	0.406	0.426	**
Electricity, kWh	4.784	4.934	4.934	4.044	4.343	4.560	**
Transporting materials to plant, fuel unit/m^3 concrete							
Diesel fuel, L							
Cement	0.888	0.740	0.592	1.34	1.18	1.02	†
Coarse aggregate	1.57	1.57	1.50	1.39	1.48	1.42	†
Fine aggregate	0.944	1.02	1.10	0.736	0.810	0.984	†
Silica fume, %	0.000	0.000	0.000	0.000	0.150	0.000	†
Concrete plant operations, fuel unit/m^3 concrete							
Diesel fuel, L	4.97	4.97	4.97	4.97	4.97	4.97	23
Natural gas, m^3	1.09	1.09	1.09	1.09	1.09	1.09	23
Electricity, kWh	3.948	3.948	3.948	3.948	3.948	3.948	23

*Architectural precast concrete panels.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 5-4B. Energy Inputs for Precast Concrete Production by Fuel Type (U.S. Customary Units)

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	60.8	50.7	40.5	91.7	80.9	70.1	18
Gasoline, gallon	0.008	0.007	0.006	0.013	0.011	0.010	18
LPG, gallon	0.002	0.002	0.001	0.003	0.003	0.002	18
Middle distillates, gallon	0.06	0.05	0.04	0.10	0.09	0.07	18
Natural gas, ft^3	83.0	69.2	55.3	125.1	110.4	95.6	18
Petroleum coke, lb	14.7	12.3	9.8	22.2	19.6	17.0	18
Residual oil, gallon	0.004	0.003	0.002	0.006	0.005	0.004	18
Wastes, lb	23.4	19.5	15.6	35.3	31.1	27.0	18
Electricity, kWh	23.1	19.3	15.4	34.9	30.8	26.7	18
Aggregate production, fuel unit/yd^3 concrete							
Crushed stone							
Diesel fuel, gallon	0.247	0.255	0.255	0.209	0.224	0.235	**
Electricity, kWh	10.012	10.325	10.325	8.463	9.089	9.542	**
Sand and gravel							
Diesel fuel, gallon	0.090	0.093	0.093	0.076	0.082	0.086	**
Electricity, kWh	3.658	3.772	3.772	3.092	3.320	3.486	**
Transporting materials to plant, fuel unit/yd^3 concrete							
Diesel fuel, gallon							
Cement	0.179	0.149	0.120	0.270	0.238	0.207	†
Coarse aggregate	0.318	0.318	0.302	0.281	0.298	0.286	†
Fine aggregate	0.191	0.207	0.223	0.149	0.164	0.199	†
Silica fume, %	0.000	0.000	0.000	0.000	0.030	0.000	†
Concrete plant operations, fuel unit/yd^3 concrete							
Diesel fuel, gallon	1.00	1.00	1.00	1.00	1.00	1.00	23
Natural gas, ft^3	29.5	29.5	29.5	29.5	29.5	29.5	23
Electricity, kWh	3.019	3.019	3.019	3.019	3.019	3.019	23

*Architectural precast concrete panels.
**LCI assumptions and References 19 through 22.
†LCI assumptions and Reference 24.

Table 5-5A. Summary of Embodied Energy at Each Stage of Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*
Energy use, GJ/m^3 concrete						
Cement manufacturing	1.78	1.48	1.18	2.68	2.36	2.05
Aggregate production	0.129	0.133	0.133	0.109	0.117	0.123
Transporting materials to plant	0.131	0.129	0.123	0.134	0.139	0.132
Concrete plant operations	0.247	0.247	0.247	0.247	0.247	0.247
Total	**2.28**	**1.99**	**1.69**	**3.17**	**2.87**	**2.55**

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

Table 5-5B. Summary of Embodied Energy at Each Stage of Precast Concrete Production (U.S. Customary Units)

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	1.288	1.073	0.859	1.941	1.713	1.484
Aggregate production	0.093	0.096	0.096	0.079	0.085	0.089
Transporting materials to plant	0.095	0.093	0.089	0.097	0.101	0.096
Concrete plant operations	0.179	0.179	0.179	0.179	0.179	0.179
Total	**1.66**	**1.44**	**1.22**	**2.30**	**2.08**	**1.85**

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

Table 5-6A. Emissions to Air from Transportation of Purchased Materials to Concrete Plant for Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*
Silica fume, %	0	0	0	0	11	0
Cement and silica fume transportation, kg/m^3 concrete						
Particulate matter	0.003	0.003	0.002	0.005	0.005	0.004
CO_2	2.42	2.02	1.62	3.65	3.63	2.79
SO_2	0.004	0.003	0.003	0.006	0.006	0.004
NO_x	0.022	0.019	0.015	0.034	0.033	0.026
VOC**	0.004	0.003	0.003	0.006	0.006	0.005
CO	0.022	0.019	0.015	0.034	0.033	0.026
CH_4	0.001	0.001	0.000	0.001	0.001	0.001
Aggregate transportation, kg/m^3 concrete						
Particulate matter	0.009	0.009	0.009	0.008	0.008	0.009
CO_2	6.88	7.09	7.09	5.82	6.25	6.56
SO_2	0.011	0.011	0.011	0.009	0.010	0.010
NO_x	0.063	0.065	0.065	0.054	0.058	0.060
VOC**	0.011	0.012	0.012	0.010	0.010	0.011
CO	0.063	0.065	0.065	0.053	0.057	0.060
CH_4	0.002	0.002	0.002	0.002	0.002	0.002
Total material transportation, kg/m^3 concrete						
Particulate matter	0.012	0.012	0.011	0.012	0.013	0.012
CO_2	9.30	9.12	8.71	9.47	9.88	9.35
SO_2	0.015	0.014	0.014	0.015	0.016	0.015
NO_x	0.086	0.084	0.080	0.087	0.091	0.086
VOC**	0.015	0.015	0.014	0.016	0.016	0.015
CO	0.085	0.084	0.080	0.087	0.091	0.086
CH_4	0.003	0.002	0.002	0.003	0.003	0.003

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

Table 5-6B. Emissions to Air from Transportation of Purchased Materials to Concrete Plant for Precast Concrete Production (U.S. Customary Units)

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	4.09	3.41	2.72	6.16	6.12	4.71
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	11.6	12.0	12.0	9.80	10.5	11.1
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	15.7	15.4	14.7	16.0	16.7	15.8
SO_2	0.025	0.024	0.023	0.025	0.026	0.025
NO_x	0.144	0.142	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	0.135	0.146	0.153	0.144
CH_4	0.004	0.004	0.004	0.004	0.005	0.004

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

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Table 5-7A. Emissions to Air by Process Step for Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Cement manufacture, kg/m^3 concrete							
Particulate matter	0.84	0.70	0.56	1.26	1.11	0.96	18
CO_2	301	251	201	454	401	347	18
SO_2	0.66	0.550	0.440	0.99	0.88	0.76	18
NO_x	0.86	0.72	0.575	1.30	1.15	0.99	18
VOC**	0.014	0.012	0.009	0.021	0.018	0.016	18
CO	0.293	0.244	0.195	0.442	0.390	0.338	18
CH_4	0.012	0.010	0.008	0.018	0.016	0.014	18
Aggregate production, kg/m^3 concrete							
Particulate matter	0.403	0.416	0.416	0.341	0.366	0.384	11, 13, 25
CO_2	4.56	4.71	4.71	3.86	4.14	4.35	23
SO_2	0.007	0.007	0.007	0.006	0.007	0.007	23
NO_x	0.042	0.043	0.043	0.036	0.038	0.040	23
VOC**	0.008	0.008	0.008	0.006	0.007	0.007	23
CO	0.042	0.043	0.043	0.035	0.038	0.040	23
CH_4	0.001	0.001	0.001	0.001	0.001	0.001	23
Transportation to ready mix plant, kg/m^3 concrete							
Particulate matter	0.012	0.012	0.011	0.012	0.013	0.012	Table 5-6
CO_2	9.30	9.12	8.71	9.47	9.88	9.35	Table 5-6
SO_2	0.015	0.014	0.014	0.015	0.016	0.015	Table 5-6
NO_x	0.086	0.084	0.080	0.087	0.091	0.086	Table 5-6
VOC**	0.015	0.015	0.014	0.016	0.016	0.015	Table 5-6
CO	0.085	0.084	0.080	0.087	0.091	0.086	Table 5-6
CH_4	0.003	0.002	0.002	0.003	0.003	0.003	Table 5-6
Concrete plant operations, kg/m^3 concrete							
Particulate matter	0.101	0.101	0.101	0.101	0.101	0.101	14
CO_2	14.2	14.2	14.2	14.2	14.2	14.2	27, 28
SO_2	0.083	0.083	0.083	0.083	0.083	0.083	27, 28
NO_x	0.014	0.014	0.014	0.014	0.014	0.014	27, 28
VOC**	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	27, 28
CO	0.004	0.004	0.004	0.004	0.004	0.004	27, 28
CH_4	no data	no data	no data	no data	no data	no data	27, 28

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

Table 5-7B. Emissions to Air by Process Step for Precast Concrete Production (U.S. Customary Units)

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	1.41	1.18	0.94	2.13	1.88	1.63	18
CO_2	508	423	339	765	675	585	18
SO_2	1.11	0.926	0.741	1.68	1.48	1.28	18
NO_x	1.45	1.21	0.969	2.19	1.93	1.67	18
VOC**	0.023	0.019	0.016	0.035	0.031	0.027	18
CO	0.494	0.412	0.329	0.745	0.657	0.570	18
CH_4	0.020	0.017	0.013	0.030	0.027	0.023	18
Aggregate production, lb/yd^3 concrete							
Particulate matter	0.680	0.701	0.701	0.575	0.617	0.648	11, 13, 25
CO_2	7.69	7.93	7.93	6.50	6.98	7.33	23
SO_2	0.012	0.013	0.013	0.010	0.011	0.012	23
NO_x	0.071	0.073	0.073	0.060	0.064	0.068	23
VOC**	0.013	0.013	0.013	0.011	0.012	0.012	23
CO	0.070	0.073	0.073	0.060	0.064	0.067	23
CH_4	0.002	0.002	0.002	0.002	0.002	0.002	23
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	15.7	15.4	14.7	16.0	16.7	15.8	Table 5-6
SO_2	0.025	0.024	0.023	0.025	0.026	0.025	Table 5-6
NO_x	0.144	0.142	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	0.135	0.146	0.153	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	23.9	23.9	23.9	23.9	23.9	23.9	27, 28
SO_2	0.141	0.141	0.141	0.141	0.141	0.141	27, 28
NO_x	0.024	0.024	0.024	0.024	0.024	0.024	27, 28
VOC**	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	27, 28
CO	0.006	0.006	0.006	0.006	0.006	0.006	27, 28
CH_4	no data	no data	no data	no data	no data	no data	27, 28

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

Table 5-8A. Total Emissions from Precast Concrete Production (SI Units)

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, MPa	35	30	20	50	70	Unspecified*	Table 5-1
Silica fume, %	0	0	0	0	11	0	Table 5-1
Total emissions, kg/m³ concrete							
Particulate matter	1.35	1.23	1.09	1.72	1.59	1.46	Table 5-7
CO_2	329	279	228	482	429	375	Table 5-7
SO_2	0.765	0.655	0.544	1.098	0.983	0.865	Table 5-7
NO_x	1.004	0.860	0.713	1.436	1.290	1.134	Table 5-7
VOC*	0.037	0.035	0.032	0.043	0.042	0.039	Table 5-7
CO	0.424	0.375	0.322	0.568	0.522	0.467	Table 5-7
CH_4	0.016	0.014	0.012	0.022	0.020	0.017	Table 5-7
Waste at cement plant, kg/m³ concrete							
Cement kiln dust (CKD)	17.4	14.5	11.6	26.2	23.1	20.1	18

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

Table 5-8B. Total Emissions from Precast Concrete Production (U.S. Customary Units)

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/yd³ concrete							
Particulate matter	2.28	2.07	1.83	2.89	2.69	2.47	Table 5-7
CO_2	555	470	385	812	723	632	Table 5-7
SO_2	1.29	1.10	0.918	1.85	1.66	1.46	Table 5-7
NO_x	1.69	1.45	1.20	2.42	2.17	1.91	Table 5-7
VOC*	0.062	0.058	0.053	0.073	0.071	0.066	Table 5-7
CO	0.714	0.631	0.543	0.957	0.880	0.787	Table 5-7
CH_4	0.026	0.023	0.019	0.037	0.033	0.029	Table 5-7
Waste at cement plant, lb/yd³ concrete							
Cement kiln dust (CKD)	29.3	24.4	19.6	44.2	39.0	33.8	18

*Architectural precast concrete panels.
**Until data that are more precise 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.

Cement data are taken from the cement manufacturing LCI originally carried out by the Portland Cement Association in 1996 and updated in 2002 with the most recent (1999) energy data. They include the four main technologies: wet, long dry, dry with preheater, and dry with preheater and precalciner. The data are reported from plants representing approximately 90% of the U.S. cement industry. We believe these data have a good level of accuracy. A set of industry standard data quality indicators complying with ISO 14041 has not yet been developed. Emissions to air are based largely on EPA AP-42 emission factors for which qualitative quality indicators are available.

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). 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 one unit volume of concrete produced in the United States and, in the case of block, from 100 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:

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

The LCI results contain quantities of energy sources used (for example, coal, natural gas, etc.) but not their upstream profiles. The intention of PCA is to provide LCI data for use in LCA models that include upstream profiles. The PCA may also 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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APPENDIX A – TARGET AUDIENCES AND INFORMATION TO BE COMMUNICATED

This report is one of many for the Environmental Life Cycle Assessment (LCA) of Portland Cement Concrete project sponsored by the Portland Cement Association.
The objectives of publishing reports and disseminating information are to:

- Determine the environmental life cycle benefits associated with the use of these products.
- Produce comparisons of concrete and other building materials.
- Provide information about these benefits to manufacturers and users of these products.
- Provide life cycle inventory (LCI) and LCA information to practitioners and others, such as data base providers in need of accurate data on cement and concrete.

The contents of the reports will provide information for the following audiences:

- Members of the Portland Cement Association (PCA) and other organizations that promote the use of cement and concrete, generally called “allied industries.”
- Members of the Environmental Council of Concrete Organizations (ECCO).
- LCA practitioners and database developers.
- Engineers, architects, and designers.
- Public agencies (Departments of Transportation [DOTs], Energy Star, Environmentally Preferable Purchasing Program).
- General public.

The report formats are not particularly suited for all audiences. The reports are intended to document the particular partial LCI, LCI, or LCA. They provide data in a transparent, traceable format for documentation purposes. The intent is that abbreviated papers, brochures, data packages, presentations, or press releases can be developed from the project reports. The materials presenting the results of this project will be matched, in form and format, to the needs of the target audience. The materials have been categorized as follows:

- General Information:
    - Purpose of life cycle assessments (LCAs) and how they are done.
    - Limited life cycle results of portland cement concrete products from production through use to demolition and recycling.
- Summary Results:
    - Presentation of selected life cycle inventory (LCI) data in the form of summary information, bar charts or other diagrams; for example PowerPoint™ presentations.
    - Published papers or articles.
- Detailed Results:
    - LCI results for databases or LCA models, such as BEES or Athena.
    - Description of the LCI methodology used in the project and specific assumptions, information sources/references, and detailed results.