Generic Concrete Products with Portland Cement

Product Selection and Description

Portland cement concrete, typically referred to as “concrete,” is a mixture of portland cement (a fine powder), water, fine aggregate such as sand or finely crushed rock, and coarse aggregate such as gravel or crushed rock. Ground granulated blast furnace slag (slag cement), fly ash, silica fume, or limestone may be substituted for a portion of the portland cement in the concrete mix.

Concrete mixes modeled in the BEES software include compressive strengths of 21 MPa, 28 MPa, and 34 MPa (3 000 lb/in2, 4 000 lb/in2, and 5 000 lb/in2). Concrete with 21 MPa strength is used in applications such as residential slabs and basement walls, while strengths of 28 MPa and 34 MPa are used in structural applications such as beams and columns.

Portland cement concrete products like beams and columns are modeled based on volume of concrete (e.g., a functional unit of 1 ft3), while basement walls and slabs are modeled on an area basis (e.g., a functional unit of 1 ft2). The amount of concrete required depends on the dimensions of the product (e.g., thickness of slab or wall and surface area). Above-grade walls are typically 15 cm (6 in) thick. Basement walls are 20 cm (8 in) thick, slabs 10 cm (4 in) thick, and a typical column size is 51 cm by 51 cm (20 in by 20 in).

Manufacturing data for concrete products are taken from the Portland Cement Association’s LCA database, with extensive documentation provided by the Portland Cement Association for incorporating their LCA data into BEES.

Flow Diagram

The flow diagrams below show the major elements of the production of portland cement concrete products with and without cement substitutes such as fly ash, slag, and limestone.

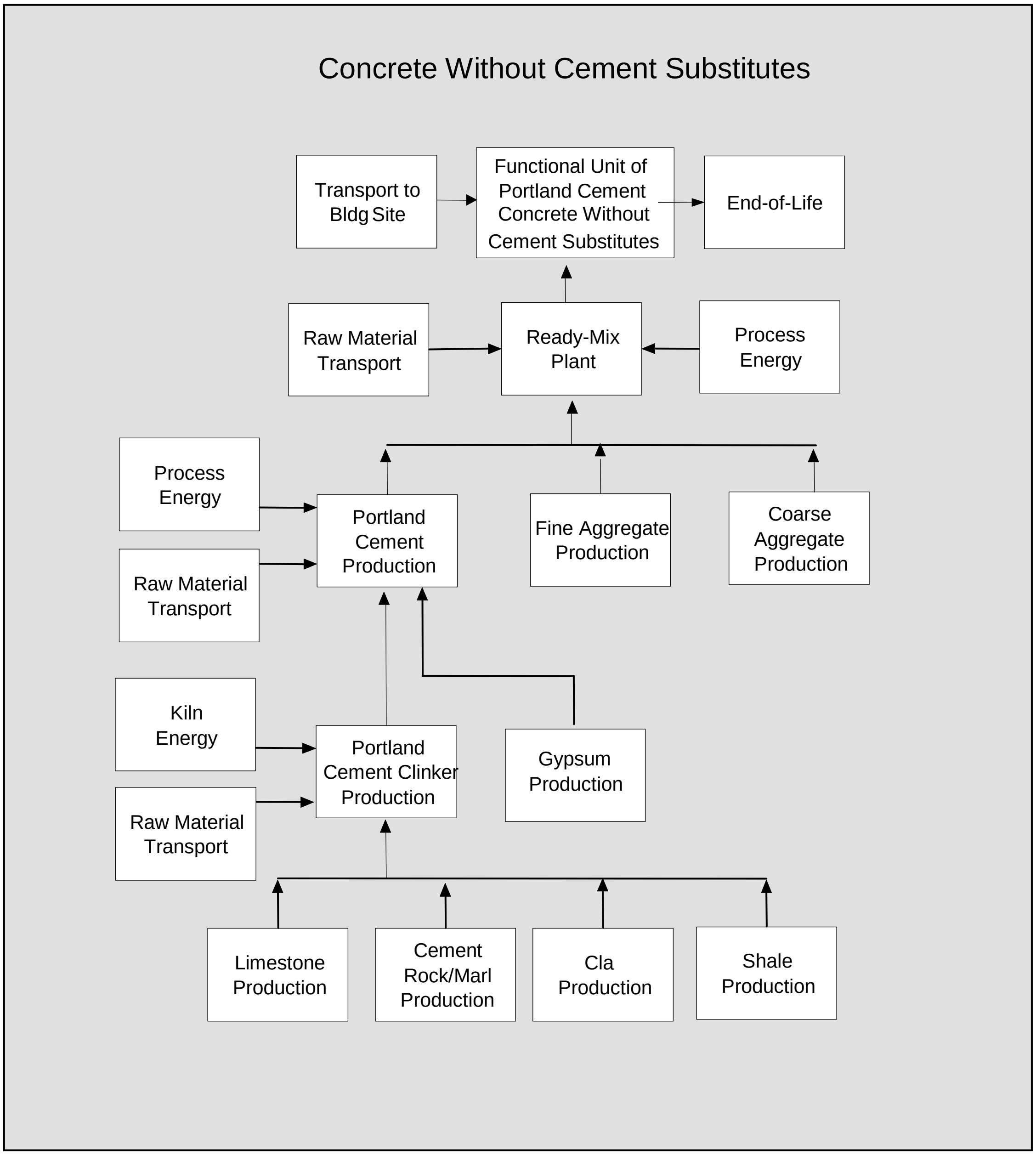

Figure 1: Concrete without Cement Substitutes System Boundaries

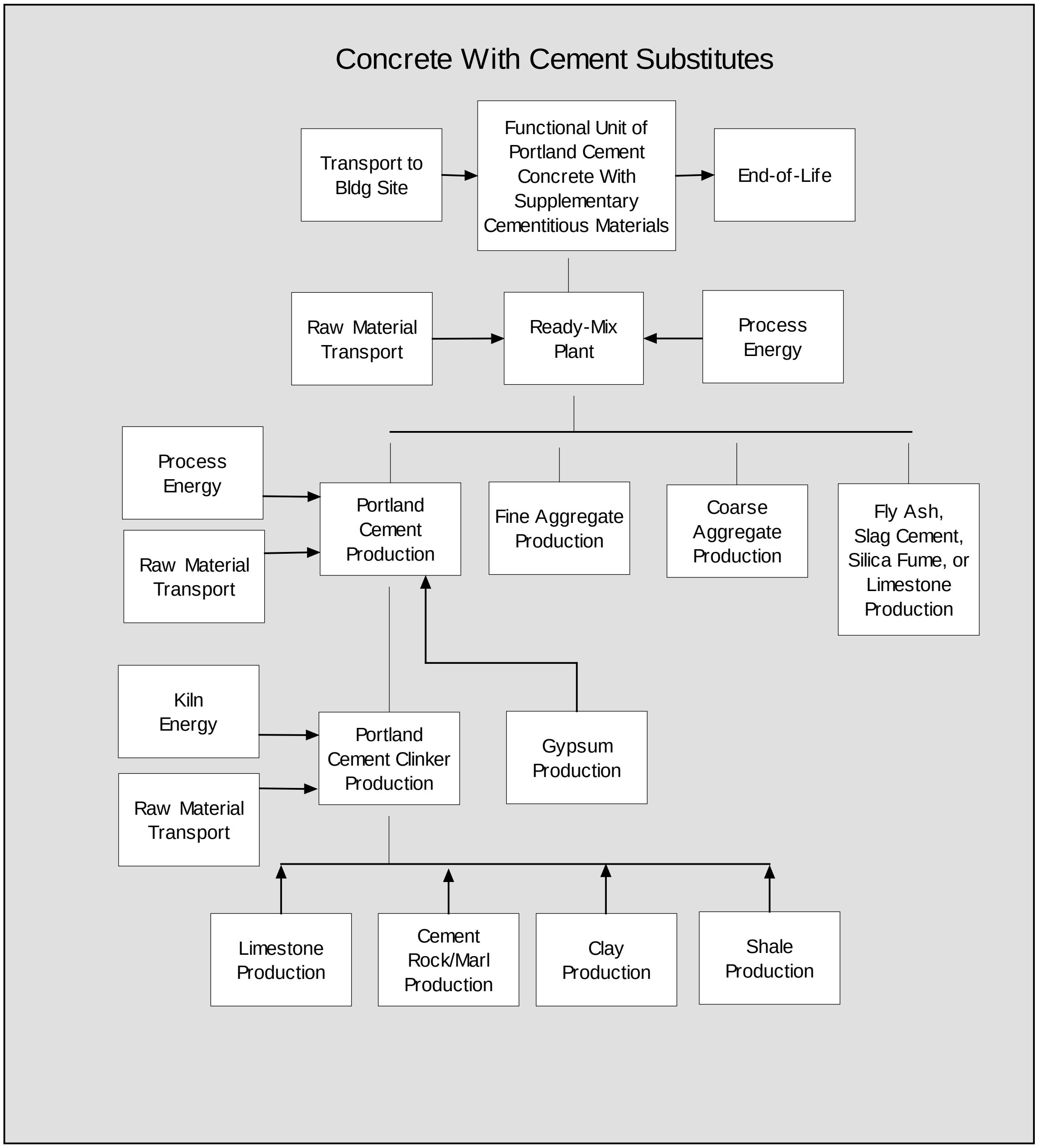

Figure 2: Concrete with Cement Substitutes System Boundaries

Raw Materials

As noted above, the constituents of portland cement concrete are portland cement (a fine powder), water, fine aggregate such as sand or finely crushed rock, and coarse aggregate such as gravel or crushed rock. Ground granulated blast furnace slag (slag cement), fly ash, silica fume, or limestone may be substituted for a portion of the portland cement in the concrete mix.

Typically, fly ash and slag are equal replacements by weight for cement. The same is true for a 5 % limestone blended cement, but at the 10 % and 20 % blend levels, more blended cement is needed in the concrete to achieve equivalent strength as mixes with no limestone replacements. Quantities of constituent materials used in an actual project will vary. Mix designs (that is, the constituent quantities) and strength will also vary depending on the aggregates and cement used.

The following Table shows quantities of concrete constituents for the three compressive strengths modeled. Other materials that are sometimes added, such as silica fume and chemical admixtures, are not considered.

Table 1: Concrete Constituent Quantities by Cement Blend and Compressive Strength of Concrete

Constituent	*Constituent Density in kg/m³(lb/yd³)*		
	21 MPa (3 000 lb/in²)	***28 MPa (4 000 lb/in²)***	***34 MPa (5 000 lb/in²)***
Cement and Fly Ash, Slag, or 5 % Limestone	223 (376)	279 (470)	335 (564)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	141 (237)	141 (237)	141 (237)
Cement and 10 % Limestone	236 (397)	294 (496)	353 (595)
Coarse Aggregate	1 127 (1 900)	1 187 (2 000)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	712 (1 200)
Water	148 (250)	147 (248)	148 (250)
Cement and 20 % Limestone	265 (447)	331 (558)	397 (670)
Coarse Aggregate	1 127 (1 900)	1 127 (1 900)	1 187 (2 000)
Fine Aggregate	831 (1 400)	771 (1 300)	653 (1 100)
Water	167 (281)	166 (279)	167 (281)

Portland Cement Production. Cement plants are located throughout North America at locations with adequate supplies of raw materials. Major raw materials for cement manufacture include limestone, cement rock/marl, shale, and clay. These raw materials contain various proportions of calcium oxide, silicon dioxide, aluminum oxide, and iron oxide, with oxide content varying widely across North America. Since portland cement must contain the appropriate proportion of these oxides, the mixture of the major raw materials and minor ingredients (as required) varies among cement plants.

BEES data for cement manufacture is based on the average raw material mix and oxide content for all U.S. cement plants for ASTM C150 Type I/II cement, the most commonly used cement in North America. The average raw materials for U.S. cement include limestone, cement rock/marl, shale, clay, bottom ash, fly ash, foundry sand, sand, and iron/iron ore. For the BEES model, the raw materials listed in the Table below are used.[1]

[1] The weight of inputs is greater than the weight of portland cement output, as a significant percentage of the weight of limestone is released as CO_2.

Table 2: Portland Cement Constituents

Constituent	***Mass of inputs in kg***	***Mass Fraction***
Limestone	1.17	72.2 %
Cement rock, marl	0.21	12.8 %
Clay	0.06	3.7 %
Shale	0.05	3.2 %
Sand	0.04	2.5 %
Slag	0.02	1.2 %
Iron/iron ore	0.01	0.9 %
Fly ash	0.01	0.8 %
Bottom ash	0.01	0.6 %
Foundry sand	0.004	0.2 %
Slate	0.001	0.1 %

In the manufacturing process, major raw materials are blended with minor ingredients, as required, and processed at high temperatures in a cement kiln to form an intermediate material known as clinker. Gypsum is interground with clinker to form portland cement. Gypsum content is assumed to be added at 3.0 % (by mass fraction) of portland cement.

Portland cement is manufactured using one of four processes: wet, long dry, preheater, or precalciner. The wet process is the oldest and uses the most energy due to the energy required to evaporate the water. New cement manufacturing plants are being constructed, and older plants converted, to use the more energy efficient preheater and precalciner processes. The mix of production processes modeled is 16.5 % wet, 14.4 % dry, 15.8 % preheater, and 53.3 % precalciner.[2]

The following Table presents U.S. industry-average energy use by process and fuel type, and, for all processes combined, average energy use weighted by the process mix. The production of the different types of fuel is based on the U.S. LCI Database; however, production of "wastes" used as fuel is assumed to be free of any environmental burdens to portland cement production.

[2] Portland Cement Association, *U.S. and Canadian Labor-Energy Input Survey 2002* (Skokie, IL: Portland Cement Association, 2005).

Table 3: Energy Requirements for Portland Cement Manufacturing

Energy Carrier	***Cement Manufacturing Process****[*]*				
	Wet	***Long Dry***	***Preheater***	***Precalciner***	***Weighted Average***
Coal	50 %	50 %	70 %	63 %	60 %
Petroleum Coke	18 %	33 %	11 %	11 %	15 %
Electricity	8 %	10 %	12 %	12 %	11 %
Wastes	23 %	3 %	2 %	6 %	8 %
Natural Gas	1 %	4 %	3 %	7 %	5 %
Liquid Fuels[**]	1 %	1 %	1 %	1 %	1 %
All Fuels	100 %	100 %	100 %	100 %	100 %
Total Energy - kJ/kg of cement (Btu/lb)	6 400 (2 749)	5 591 (2 402)	4 357 (1 872)	4 220 (1 813)	4 798 (2 061)

* Cement constitutes 10 % to 15 % by mass fraction of the total mass of concrete.
** Liquid fuels include gasoline, middle distillated, residual oil, and light petroleum gas

Emissions for portland cement manufacturing are from the Portland Cement Association cement LCA database.[3] Emissions include particulate matter, carbon dioxide (CO_2), carbon monoxide (CO), sulfur oxides (SO_X), nitrogen oxides (NO_X), total hydrocarbons, and hydrogen chloride (HCl). Emissions vary for the different combinations of compressive strength and blended cements.

The major waste material from cement manufacturing is cement kiln dust (CKD). There is no breakdown of CKD by process type. An industry average of 38.6 kg of CKD is generated per metric ton (93.9 lb/ton) of cement. Of this, 30.7 kg (74.6 lb) is landfilled and 7.9 kg (19.3 lb) is reused on-site or enters commerce as inputs to the agricultural, construction, and waste treatment industries.[4]

Aggregate Production. Aggregate is a general term that describes a filler material in concrete. Aggregate generally provides 60 % to 75 % of the concrete volume. Typically, aggregate consists of a mixture of coarse and fine rocks. Aggregate is either mined or manufactured. Sand and gravel are examples of mined aggregate. These materials are dug or dredged from a pit, river bottom, or lake bottom and require little or no processing. Crushed rock is an example of manufactured aggregate. Crushed rock is produced by crushing and screening quarry rock, boulders, or large-sized gravel. Approximately half of the coarse aggregate used in the United States is crushed rock.

Concrete contains 25 % coarse and fine aggregate from crushed rock and 75 % coarse and fine aggregate from sand and gravel.[5] The energy to produce coarse and fine aggregate from crushed rock is 81 kJ/kg (35 Btu/lb), and the energy to produce coarse and fine aggregate from uncrushed aggregate is 17 kJ/kg (7.3 Btu/lb).[6] The energy for aggregate production is a 50:50 mix of diesel oil and electricity.

Fly Ash Production. Fly ash is a waste material that results from burning coal to produce electricity. In LCA terms, fly ash is an environmental outflow of coal combustion, and an environmental inflow of concrete production. This waste product is assumed to be an environmentally "free" input material.[7] However, transport

[3] Nisbet, M.A., Marceau, M.L., and VanGeem, M.G. "Life Cycle Inventory of Portland Cement Manufacture" (an appendix to Environmental Life Cycle Inventory of Portland Cement Concrete), *PCA R&D Serial No. 2095a* (Skokie, IL: Portland Cement Association, 2002).

[4] Bhatty, J., et al., *Innovations in Portland Cement Manufacturing* (Skokie, IL: Portland Cement Association, 2004).

[5] U.S. Geological Survey. *USGS Minerals Yearbook—2003, Volume I. Metals and Minerals* (Washington, DC: Interior Dept., Geological Survey, 2003), pp 64.1-2; 71.1-3.

[6] Nisbet, M., et al. "Environmental Life Cycle Inventory of Portland Cement Concrete." *PCA R&D Serial No. 2137a*(Skokie, IL: Portland Cement Association, 2002).

[7] The environmental burdens associated with the production of waste materials are typically allocated to the intended product(s) of the process from which the waste results.

of the fly ash to the ready mix plant is included.

Ground Granulated Blast Furnace Slag (Slag Cement) Production. Slag cement is a waste material that is a result of the production of steel. Similar to fly ash, slag is an environmental outflow of steel production and an environmental inflow of concrete production. Therefore, slag is considered to be an environmentally "free" input material. Unlike fly ash, slag must be processed prior to inclusion in concrete. Processing consists of quenching and granulating at the steel mill, transport to the grinding facility, and finish grinding. This production energy (an assumed 75:25 mix of electricity and natural gas) is assumed to be 722 kJ/kg of slag cement (311 Btu/lb). Transportation to the ready mix plant is included.

Limestone Production. While not common practice in the United States, limestone is used as a partial replacement for portland cement in most European countries. The concrete mix designs used in BEES are estimates based on available literature and have not been tested in the laboratory. Mixes at the higher limestone replacement levels are based on limited data. Energy burdens for limestone production are taken from the U.S. LCI Database.

Manufacturing

Energy Requirements and Emissions. Most portland cement concrete is produced at a central ready mix plant. Energy use in the batch plant includes electricity and fuel used for heating and mobile equipment.[8]

Table 4: Energy Requirements for Ready Mix Concrete Production

Energy Carrier	*MJ/m3 (MBtu/yd3)*	*MJ/kg (Btu/lb)*
Heavy Fuel Oil	124 (0.09)	0.05 (22)
Electricity	124 (0.09)	0.05 (22)
Total	**247 (0.179)**	**0.1 (43)**

Transportation**.** Round-trip distances for transport of concrete raw materials to the ready-mix plant are assumed to be 97 km (60 mi) for portland cement and fly ash, 216 km (134 mi) for slag, and 80 km (50 mi) for aggregate and limestone. The method of transport is truck. A small

percentage of the above materials, assumed to be 10 %, may be transported more than 3 219 km (2 000 mi). When this is the case, transport is assumed to be by rail.

Transportation

Transportation of concrete products with portland cement by heavy-duty truck to the building site is modeled as a variable of the BEES system.

Installation

Installing each of the BEES concrete applications requires different quantities of plywood forms and steel reinforcement as shown in the Table below.[9]

[8] Nisbet, M., et. al, "Environmental Life Cycle Inventory of Portland Cement Concrete."
[9] R. S. Means Co., Inc., *2007 Building Construction Cost Data* (Kingston, MA: 2006), pp. 711-713.

Table 5: Concrete Form and Reinforcing Requirements

Building Element	*Compressive Strength MPa (lb/in^2)*	*Plywood Forms (SFCA/functional unit)*	*Steel Reinforcing (lb/ft^2 for slabs, lb/yd^3 for rest)*	*Comment*
Slabs	21 (3 000)	1.03	1.67	For 7.62 m (25 ft) span, 4 in thick.
Above grade walls, precast concrete	34 (5000)	0	135	Assume 6 in thick. Plywood wall forms are reused over 75 times; hence their environmental burdens are not taken into account.
Above grade walls, ICF	21 (3000)	0	135	Assume 6 in thick. The insulation board used as formwork becomes part of the wall; hence no forms are used.
Above grade walls, cast-in-place	28 (4000)	0	135	Assume 6 in thick. Plywood wall forms are reused over 75 times; hence they are not taken into account.
Basement Walls	21 (3 000)	0	44	For 0.20 m (8 in) thick, 2.44 m (8 ft) high walls. Plywood wall forms are reused over 75 times; hence they are not taken into account.
Columns	28 (4 000)	65	290	For 0.51 m x 0.51 m (20 in x 20 in) columns with a 7.62 m (25 ft) span. Approximately 65 ft^2 of plywood is required per cubic yard of concrete. Plywood forms are reused four times, each time with 10 % installation waste. Steel reinforcements are added to the concrete forms at 290 lb of steel per cubic yard of concrete. The steel value is twice the amount for beams.
Columns	34 (5 000)	65	290	Values for forms and reinforcement provided for 28 MPa (4 000 lb/in^2) columns are used for 34 MPa (5 000 lb/in^2) columns.
Beams	28 (4 000)	54	145	For 7.62 m (25 ft) span beams. Steel reinforcements are added to the concrete forms at 145 lb of steel per cubic yard of concrete (half of the amount required for columns). Plywood forms are reused four times, each time with 10 % installation waste. Values for forms and reinforcement provided for 28 MPa (4 000 lb/in^2) beams are used for
Beams	34 (5 000)	54	145	34 MPa (5 000 lb/in^2) beams.

Notes: 1. Plywood forms are 12.7 mm (0.5 in) thick and their surface density is 5.88 kg/m^2 (1.17 lb/ft^2). Plywood production impacts are the same as those reported for the BEES Plywood Wall Sheathing product.
2. SFCA=0.09 m^2 (1 ft^2) contact area.
3. Steel reinforcing is made from 100 % recycled steel.

The industry average for steel reinforcement is 5 lb of steel reinforcement/ft^3 of concrete (135 lb steel/yd^3 concrete). Installation materials are assumed to be transported by truck 161 km (100 mi) to the point of installation.

Use

With general maintenance, quality concrete in buildings will generally last more than 100 years. This is a performance-based lifetime.

Interior concrete not exposed to weather (such as beams, columns, foundations, and footings) generally does not require maintenance. For exterior concrete, maintenance will vary depending on weather conditions, but usually consists of minimal repairs that can be done by hand. Maintenance is not included within the system boundaries of the BEES model.

End of Life

The majority of concrete in the U.S. is used in urban areas where concrete is not accepted at landfills. Concrete is recycled as fill and road base, and steel used in concrete reinforcement is recycled. Plywood forms are assumed to be disposed of in a landfill at end of life.

References

Life Cycle Data

National Renewable Energy Laboratory (NREL): *U.S. Life-Cycle Inventory Database*. 2005. Golden, CO. Found at: http://www.nrel.gov/lci/database.

PRé Consultants: *SimaPro 6.0 LCA Software*. 2005. The Netherlands.

Kosmatka, S.H., Kerkhoff, B., and Panarese W.C., *Design and Control of Concrete Mixtures*, *14th Ed.*, (Skokie, IL: Portland Cement Association, 2002). p. 327

Portland Cement Association, *U.S. and Canadian Labor-Energy Input Survey 2002*, (Skokie, IL: Portland Cement Association, 2005).

Construction Technology Laboratories, Inc, “Completed BEES Site Questionnaire for Portland Cement,” *CTL Project No. 312006*, (Skokie, IL: Construction Technology Laboratories, Inc, June 2002).

Construction Technology Laboratories, Inc, “Theoretical Concrete Mix Designs for Cement with Limestone as a Partial Replacement for Portland Cement,” *CTL Project 312006*, (Skokie, IL: Construction Technology Laboratories, Inc, June 2002).

Construction Technology Laboratories, Inc. and JAN Consultants, “Data Transmittal for Incorporation of Slag Containing Concrete Mixes into Version 2.0 of the BEES Software,” *PCA R&D Serial No. 2168a*/*PCA Project 94-04*, (Skokie, IL: Portland Cement Association, 2000).

Nisbet, M., et al. “Concrete Products Life Cycle Inventory (LCI) Data Set for Incorporation into the NIST BEES Model.” *PCA R&D Serial No. 2168/PCA Project 94-04a*, (Skokie, IL: Portland Cement Association, 1998).

Nisbet, M.A., Marceau, M.L., and VanGeem, M.G. "Life Cycle Inventory of Portland Cement Manufacture (an Appendix to Environmental Life Cycle Inventory of Portland Cement Concrete)," *PCA R&D Serial No. 2095a* (Skokie, IL: Portland Cement Association, 2002).

Bhatty, J., et al. *Innovations in Portland Cement Manufacturing*, (Skokie, IL: Portland Cement Association, 2004).

U.S. Geological Survey. *USGS Minerals Yearbook—2003, Volume I. Metals and Minerals* (Washington, DC: Interior Dept., Geological Survey, 2003). pp 64.1-2; 71.1-3. Found at: http://minerals.usgs.gov/minerals/pubs/commodity/myb/index.html

Nisbet, M., et al. “Environmental Life Cycle Inventory of Portland Cement Concrete.” *PCA R&D Serial No. 2137a*, (Skokie, IL: Portland Cement Association, 2002).

R. S. Means Co., Inc., *2007 Building Construction Cost Data* (Kingston, MA: 2006), pp. 711-713.

Industry Contacts

Martha VanGeem, P.E., Construction Technology Laboratories, Inc. (on behalf of the Portland Cement Association), August-October 2005

Medgar Marceau, P.E., Construction Technology Laboratories, Inc. (on behalf of the Portland Cement Association), August-October 2005

1 The weight of inputs is greater than the weight of portland cement output, as a significant percentage of the weight of limestone is released as CO_2.
2 Portland Cement Association, U.S. and Canadian Labor-Energy Input Survey 2002 (Skokie, IL: Portland Cement Association, 2005).
3 Nisbet, M.A., Marceau, M.L., and VanGeem, M.G. "Life Cycle Inventory of Portland Cement Manufacture" (an appendix to Environmental Life Cycle Inventory of Portland Cement Concrete), PCA R&D Serial No. 2095a (Skokie, IL: Portland Cement Association, 2002).

4 Bhatty, J., et al., Innovations in Portland Cement Manufacturing (Skokie, IL: Portland Cement Association, 2004).
5 U.S. Geological Survey. USGS Minerals Yearbook—2003, Volume I. Metals and Minerals (Washington, DC: Interior Dept., Geological Survey, 2003), pp 64.1-2; 71.1-3.
6 Nisbet, M., et al. "Environmental Life Cycle Inventory of Portland Cement Concrete." PCA R&D Serial No. 2137a(Skokie, IL: Portland Cement Association, 2002).
7 The environmental burdens associated with the production of waste materials are typically allocated to the intended product(s) of the process from which the waste results.

8 Nisbet, M., et. al, "Environmental Life Cycle Inventory of Portland Cement Concrete."
9 R. S. Means Co., Inc., 2007 Building Construction Cost Data (Kingston, MA: 2006), pp. 711-713