LIFE CYCLE INVENTORY OF SLAG CEMENT CONCRETE

Jan R. Prusinski, Medgar L. Marceau and Martha G. VanGeem *

ABSTRACT

A life cycle inventory (LCI) was determined for concrete with slag cement used as a partial replacement for portland cement. The LCI includes materials, energy, and emissions from extraction of raw materials through the manufacture of one cubic yard of concrete. It does not include the upstream profiles of fuels, although it includes the quantity of fuel used.

Five concretes with different performance criteria were considered: 20 and 35 MPa (3000 and 5000 psi) ready mixed concrete, 50 and 70 MPa (7500 and 10,000 psi) precast concrete, and a concrete block mix. The LCI was determined for three combinations of cement for each concrete performance criteria: 100 percent portland cement, and 35 and 50 percent substitution of slag cement for the portland.

Energy, CO_2 emissions to air, and most other emissions to air are significantly reduced when slag cement is used as a partial replacement for portland cement in concrete. The slag cement mixtures produced an energy savings ranging from 21.1 to 48.4 percent; a savings in carbon dioxide emissions of 29.2 to 46.1 percent; and a virgin material savings of 4.3 to 14.6 percent when compared with 100 percent portland cement concrete mixtures.

Keywords: Slag cement, sustainability, life cycle inventory, environment

- ACI member **Jan Prusinski** is Executive Director, Slag Cement Association, Sugar Land, TX
- **Medgar Marceau** is Building Scientist, Building Science and Sustainability, Construction Technology Laboratories, Inc., Skokie, IL
- ACI member **Martha VanGeem** is Principal Engineer, Building Science and Sustainability, Construction Technology Laboratories, Inc., Skokie, IL

INTRODUCTION

Concrete and Sustainability

Concrete is an inherently sustainable material. It uses resources that are abundantly available and generally has a relatively small environmental footprint. Traditional concrete consists of portland cement, aggregates and water. Most modern concrete contains chemical admixtures to enhance various properties of concrete. Also, today's concrete often contains supplementary cementitious materials such as slag cement, fly ash and silica fume, which, if used properly, can enhance plastic and/or hardened properties of concrete. Certain aspects of concrete production are energy intensive and generate large amounts of greenhouse gasses, i.e. portland cement production. Utilizing a recovered industrial material, such as slag cement, to substitute for a portion of portland cement in concrete can substantially reduce the environmental footprint of concrete.

Slag Cement and "Green" Concrete

Slag is a by-product of iron produced in a blast furnace. Molten slag—the non-metallic minerals remaining after the iron is removed—is tapped from the blast furnace. At this point, slag can either become a waste, a construction aggregate or a hydraulic cement. If air cooled, slag can be recovered as a non-cementitious lightweight aggregate. Alternatively, if molten slag is rapidly quenched with large amounts of water in a controlled process, it becomes "granulated", the consistency of sand. The rapid cooling of molten slag prohibits formation of crystalline compounds, and produces instead glassy "granules" which, when ground to a fine powder, become a hydraulic cement, known as slag cement (also referred to as ground granulated blast furnace slag).

The worldwide use of slag cement to enhance the strength and durability of concrete is well documented.[1] Additionally, the use of slag cement significantly enhances the sustainability of concrete as a building material. This is done in several ways, including:

- Recovering an industrial material that otherwise might be disposed
- Reducing the amount virgin material required to produce concrete
- Reducing embodied greenhouse gasses in concrete
- Reducing embodied energy in concrete

The principal way slag cement achieves these benefits is through the direct replacement of portland cement in concrete. Slag cement substitution rates for portland cement (1:1, by mass) range from 25 to 80 percent (depending on application). Many U.S. State Departments of Transportation allow up to 50 percent substitution for paving and structural concrete, and numerous mass concrete structures utilize 65 to 80 percent slag cement to decrease heat generation. Additionally, high performance concrete mixtures can utilize large amounts of slag cement to decrease permeability and increase resistance to alkali-silica reaction, sulfate attack or corrosion of reinforcing steel. These high replacement rates in everyday concrete significantly reduce the largest contributor to embodied greenhouse gas emissions and energy in concrete: portland cement.

SIGNIFICANCE OF RESEARCH

The availability of slag cement in the U.S. has increased tremendously in the past several years, and this has spurred utilization from 1.1 million tons in 1996 to 3.1 million tons in 2003. The market prevalence of this material, as well as the increased emphasis on sustainability by engineers and architects, makes it important to quantify the environmental benefits of using slag cement in concrete. The growth and success of the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED™) is evidence that green building is one of the most significant trends in the construction industry today. LEED, a "consensus-based voluntary rating system created to define and measure the standard for green building," [2] has captured 5 percent of U.S. commercial building market share and 15 percent of government buildings since inception just over 5 years ago. Over 1,300 commercial buildings are now LEED registered or certified.[3] Because of the significance of the green building movement, the Slag Cement Association, which represents shippers of over 95 percent of the product in the U.S., commissioned a study performed by Construction Technology Laboratories, Skokie, IL, to calculate the life cycle inventory (LCI) of concrete made with slag cement. This paper reports the results of this study and compares these results to a previous study by the Portland Cement Association (PCA) that documents the LCI of portland cement concrete mixtures (and some mixtures with fly ash and silica fume). [4]

LIFE CYCLE INVENTORY OF CONCRETE

Life Cycle Assessment (LCA) and Life Cycle Inventory (LCI)

An environmental life cycle assessment (LCA) is a "detailed, extensive tool used to systematically evaluate the environmental impacts of a product or system. An LCA considers environmental impacts from all possible sources—extraction of raw materials, manufacture, service life, and demolition…from 'cradle to grave.[5]'" The LCA is a tool that can be used by specifiers, manufacturers, suppliers, owners, and consumers to evaluate products and processes that have the least impact on the environment.   There are three phases to an LCA: inventory, impact assessment, and evaluation. LCAs are relatively new and quite complex; there is no established, generally accepted methodology at this time (although several organizations are developing procedures). However, the inventory phase, or life cycle inventory (LCI), is well defined, as detailed by the International Organization for Standardization (ISO) in ISO 14040 and 14041. This phase consists of detailing the energy use; raw material, water and fuel use; and air, solid and liquid waste and pollutants.

System Boundary

The system boundary defines the scope of an LCI. In this study, the system boundary is based on the boundary for portland and slag cement concrete. Figure 1 shows the system boundaries for manufacturing portland and slag cements. Figure 2 shows the system boundaries for concrete made with portland and slag cements. Figures 1 and 2 include all the inputs and outputs associated with producing concrete: Raw material extraction, manufacturing cements, processing aggregates, intermediate transportation and concrete production. The LCIs described in this paper represent:

- Ready-mixed concrete exiting the plant gate
- Precast concrete ready for placement in forms
- Concrete block exiting the manufacturing plant.

The system boundary does not include upstream profiles of energy sources, such as the energy and emissions associated with producing coal or generating electricity. However, the quantities of fuels used are included. In addition, the fuel used for transportation includes pre-combustion energy, i.e. the energy used to produce the fuels.

Methodology

CTL compiled information on the manufacture of slag cement from twelve questionnaires returned by member companies of the Slag Cement Association, representing over 95 percent of the slag cement shipped in the U.S. The data reported included materials, energy, and emissions to air, water, and land for each stage in the manufacture of slag cement. All fuels, energy and emissions associated with transportation were reported separately. These data were collected in 2001 and 2002. The data were evaluated for order-of-magnitude accuracy and completeness, and the data were clarified as needed with the responders. A data summary was produced by calculating a production weighted-average for the U.S., not traceable to a particular plant.[6]

The LCI of slag cement concrete was created by combining the data from the portland cement concrete LCI[4] and the slag cement LCI.[6] The basis for the slag cement concrete LCI[7] is the same as that for the portland cement concrete LCI. They are carried out in conformance with the requirement set by the International Organization for Standardization (ISO) in ISO 14040 and 14041.

Transportation of slag and slag cement to granulators, grinding facilities and distribution terminals is included in this LCI. In addition, transportation of slag cement from the distribution terminals to the concrete plant is also included in the slag cement concrete LCI, and it is assumed to be the same as for portland cement.

Mixture Proportions

Developing an LCI for concrete requires that the LCI for the individual components of concrete be known. The LCI values for all concrete components, excluding slag cement, are available in the PCA report[4]. The production weighted-average LCI values for slag cement are available in the slag cement LCI report[6]. These values were then used to develop LCIs for concrete mixtures utilizing various amounts of the individual components. Several mixtures were developed for concrete incorporating slag cement. The mixtures are equivalent to mixtures used in the PCA study, so that direct comparisons can be made between portland cement concrete, and concrete incorporating slag cement. Additionally, the PCA study included a mixture incorporating fly ash, which also can be compared.

Ten mixtures using slag cement were compared to five mixtures with portland cement only and one mixture with portland cement and fly ash. These mixtures encompass three types of concrete: Ready mixed concrete, precast concrete and concrete masonry units. The ready mixed concrete represents two strength levels. 20 MPa (3,000 psi) is indicative of many residential and general use concrete applications, while the 35 MPa (5,000 psi) level is typical of structural concrete for beams, columns floors and slabs. The precast mixtures show standard (50 MPa or 7,500 psi) and high-performance (70 MPa or 10,000 psi) mixture examples. The high-performance mixture contains 11 percent silica fume in all mixtures. The concrete masonry unit mixture is typical for concrete block. The cementitious materials percentages for each mixture are shown in Table 1.

The proportions for the mixtures not containing slag cement were defined by the original PCA study. These were adjusted to include a slag cement component of 35 and 50 percent (by mass) because these percentages are commonly found and easily achievable in mainstream concrete mixtures. The 20 percent fly ash mixture was included in the original PCA study, and represents a common 20 MPa (3,000 psi) ready mixed concrete substitution level for fly ash. This mixture is useful for comparison to the ordinary portland and slag cement mixtures. The 70 MPa (10,000 psi) precast mixtures include 11 percent silica fume (as developed in the original study). No attempt was made to account for the increased compressive strengths and performance levels achievable with a one-to-one mass substitution of slag cement for portland cement. In performance-based mixtures, often total cementitious materials can be reduced when slag cement is incorporated, thus further increasing the environmental benefits of using slag cement. The LCI comparisons, therefore, are deemed to be conservative.

Table 2 shows the complete mixture proportions assumed for each of the mixtures.

Assumptions

Several assumptions were made to calculate the LCI of concrete.

- The functional unit for concrete is one cubic yard.
- The slag and portland cement data are based on production weighted-average units of these materials produced in the U.S.[4,6]
- Round trip transportation distances to the concrete plant are 100 km (60 miles) for portland and slag cements and fly ash, and 50 km (30 miles) for aggregates
- Road transportation is assumed in all cases, which is conservative from an energy consumption and emissions standpoint (i.e. higher energy and emissions than rail or barge transportation).
- Energy used is reported by energy source (e.g. coal, diesel fuel and electricity), but the upstream profiles of energy sources are not included in the LCI
- Upstream profiles for fly ash and silica fume are not included in this LCI. This is a liberal assumption since energy and emissions are expended in the processing of fly ash and silica fume (i.e. energy and emissions are understated)
- Information sources for portland cement, aggregates, concrete production facilities,

and transportation energy can be found in reference 4. Information on slag cement can be found in reference 6.

Raw Materials, Fuel, Energy and Emissions

Table 3 lists the material inputs for portland and slag cement concrete. The mass of raw material to manufacture portland cement is 1.6 times as much as the mass of finished portland cement; this higher amount of material is reflected in the "portland cement manufacturing" inputs in Table 3. The LCI assumes that one ton of slag granules yields one ton of slag cement. Although some material is lost in the form of particulate matter and suspended solids, the amount is significantly less than one tenth of one percent. Also, the water used in manufacturing slag cement is not incorporated into slag cement, whereas the water used in producing portland cement and concrete is incorporated into the concrete.

Table 4 shows the amount of embodied energy used per process step for concrete production. These energy values were converted from fuel and electricity use for concrete.

Emissions from manufacturing processes and transporting finished goods to the concrete plant include carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), metals, methane (CH_4), nitrogen oxides (NOx), volatile organic compounds (VOC), particulate matter, and sulfur dioxide (SO_2). The emissions from fuel combustion during manufacturing of slag cement are based on the slag cement LCI except for CO_2 emissions. The CO_2 emissions are calculated from EPA AP-42 emission factors.[8] Table 5 summarizes emissions, with carbon dioxide by far being the greatest in both quantity and in importance to the environment, as it is a greenhouse gas that contributes to global warming. In general, emissions to air decrease with increasing level of slag cement replacement.

DISCUSSION OF RESULTS

The LCI for concrete is important because it provides one of the building blocks for a life cycle assessment of a complete structure. The information from this paper provides architects, engineers and owners with the ability to evaluate a wide range of concrete mixture designs and their impact on the environment. Not only can one mixture be compared with an equivalent mixture using different components, but also, once a mixture is selected, the LCI information can be used to compare one system to competing systems (e.g. concrete compared to steel or wood). Additionally, this information can be used to document a recently-approved LEED Innovation and Design Process credit for reducing the embodied carbon dioxide emissions by 40 percent in cast-in-place concrete.[9] The LCI data for carbon dioxide presented in the tables below is actually conservative with regard to the LEED credit, as LEED allows a 1:1 mass of carbon dioxide to mass of portland assumption, whereas the data below is based on a 0.9:1 ratio.

In concrete, cement is the most energy intensive of all the materials used. Even though it only makes up about 10 to 20 percent of an entire concrete mixture, it is responsible for up to 85 percent of the total embodied energy and 94% of the carbon dioxide emissions of concrete. Figures 3 and 4 show the relative amounts of emissions and energy attributed to manufacturing portland cement and aggregate, transportation, and concrete plant operations for mixtures with the lowest and highest levels of energy and emissions.

Effect of Slag Cement

Replacing a portion of portland cement with slag cement in concrete can substantially reduce the environmental impact of concrete. Slag cement can replace a relatively large proportion of the portland cement (as previously noted 20 to 80 percent, depending on application). The proportions examined in this paper—35 and 50 percent slag cement substitution for portland—

are typical for structural, paving and general concrete applications.

The most significant environmental factors are material use, embodied energy, and emissions. The impact of slag cement on these dimensions in a cubic yard of concrete is discussed below.

Materials. When inventorying the materials that are used to manufacture concrete, only the virgin materials have been included in the comparative calculations (and shown in Figure 5)—not recovered materials (i.e. slag cement, silica fume and fly ash)—because recovered materials already exist and would be disposed if not productively utilized. For ready mixed concrete, the virgin materials savings realized when using slag cement in the mixtures range from 117 to 253 kg/m^3 (197 to 425 lb/cu yd; mixtures R-3-35 and R-5-50, respectively). The materials savings for precast concrete range from 266 to 380 kg/m^3 (381 to 640 lb/cu yd; mixtures P-10-35 and P-7-50, respectively). For block, the savings range from 109 to 156 kg/m^3 (183 to 263 lb/cu yd; mixtures B-35 and B-50, respectively). The total percent virgin materials savings for the slag cement mixtures range from 4.3 percent (B-35) to 14.6 percent (P-7-50). Using 20 percent fly ash substitution for portland cement in the mixture saves 72 kg/m^3 (121 lb/cu yd of material), a savings of 2.9 percent versus plain portland cement concrete.

Embodied energy. Slag cement requires nearly 90 percent less energy to produce than an equivalent amount of portland cement. Figure 6 shows the embodied energy required to manufacture one cubic yard of concrete utilizing the various mixtures. The energy savings for ready-mixed concrete mixtures range from 0.355 GJ/m^3 (257,000 Btu/cy yd) for R-3-35 to 0.773 GJ/m^3 (560,000 Btu/cu yd) for R-5-50. In precast concrete, the energy savings range from 0.718 GJ/m^3 (520,000 Btu/cu yd) for mixture P-10-35 to 1.159 GJ/m^3 (840,000 Btu/cu yd) for mixture P-7-50. In concrete block, the savings range from 0.330 GJ/m^3 (239,000 Btu/cu yd) for mixture B-35, to 0.473 GJ/m^3 (343,000 Btu/cu yd) for mixture B-50. The percent energy savings among all the mixtures and product types range from a minimum 21.1 percent (R-3-35) to 36.5 percent (P-7-50). It is interesting to note that the P-10-50 mixture (slag cement and silica fume) had a 1.325 GJ/m^3 (960,000 Btu/cu yd) savings compared to the lower strength 50 MPa (7,500 psi) portland/silica fume mixture (P-7-0), a 41.7 percent savings. Clearly the combined effects of using two recovered materials—slag cement and silica fume—have a significantly positive effect on both concrete strength and embodied energy use. The substitution of fly ash for portland cement at the 20 percent level in the 20 MPa (3,000 psi) ready mixed concrete, saves 0.235 GJ/m^3 (170,000 Btu/cu yd) or 13.9 percent energy.

Emissions. Emissions are similarly reduced for mixtures with slag cement concrete, as shown in Figure 7. Although there are a number of different types of emissions (gaseous and solid waste), carbon dioxide is a significant contributor to climate change. In portland cement manufacture, one ton of finished portland cement generates about 0.9 tons of carbon dioxide (more than half the carbon dioxide generated is due to the calcination of limestone in the cement kiln), while the carbon dioxide emitted during slag cement manufacture is relatively negligible. Figure 6 indicates the amount of carbon dioxide generated in the manufacture of a cubic yard of concrete. In ready mixed concrete, the slag cement mixtures save from 69 to 147 kg/m^3 (116 to 248 lb/cu yd) of carbon dioxide (for R-3-35 and R-5-50, respectively), compared to portland cement only mixtures. Carbon dioxide emissions savings for precast concrete range from 137 to 222 kg/m^3 (231 to 374 lb/cu yd) of concrete (for P-10-35 and P-7-50, respectively). And for block, the savings range from 63 to 91 kg/m^3 (107 to 154 lb/cu yd) of concrete (for B-35 and B-50, respectively). The percent savings in carbon dioxide emissions range from 29.2 percent (B-35) to 46.1 percent (P-7-50). Again, for precast concrete, the 70 MPa (10,000 psi) mixture with both slag cement and silica fume outperformed the 50 MPa (7,500 psi mixture) from both a strength and emissions perspective, generating 249 kg/m^3 (419 lb/ cu yd) less carbon dioxide (P-10-50 compared with P-7-0). This represents a 51.6 percent decrease in emissions. The substitution of fly ash for portland cement at the 20 percent level in 20 MPa (3,000 psi) ready mixed concrete, saves 40 MPa (67 lb/cu yd) or 17.4 percent in carbon dioxide emissions.

CONCLUSIONS

The data presented, documents the LCI for ten different concrete mixtures utilizing slag cement. The mixtures include ready mixed concrete, precast concrete and concrete block. Slag cement mixtures assumed 35 percent and 50 percent slag cement substitution for portland cement, typical values for everyday concrete mixture. The data were developed using an industry average LCI for slag cement, and values previously determined by the PCA for all other materials.

The slag cement concrete LCI data was compared to equivalent ordinary portland cement concrete mixtures, and the savings was documented. A comparative mixture using 20 percent fly ash substitution—a typical everyday mixture proportion—was also used for 20 MPa (3,000 psi) ready mixed concrete. The slag cement mixtures produced an energy savings ranging from 21.1 to 36.5 percent; a reduction in carbon dioxide emissions of 29.2 to 46.1 percent; and a virgin material decline of 4.3 to 14.6 percent.

These savings quantitatively document the fact that slag cement can substantially lower the environmental impact of concrete, thereby helping to produce greener, more sustainable buildings and other structures.

REFERENCES

1. American Concrete Institute, "Slag Cement in Concrete and Mortar," *ACI 233R-03*, Farmington Hills, MI, 2003.
2. U. S. Green Building Council, "LEED Fact Sheet," Washington, D.C., 2003
3. U. S. Green Building Council, "LEED project list," www.usgbc.org/LEED/Project/project_list.asp, Washington, D.C., 2003
4. Nisbet, Michael A., Marceau, Medgar L. and VanGeem, Martha G., "Environmental Life Cycle Inventory of Portland Cement Concrete," *SN2137a*, Portland Cement Association, Skokie, IL, July 2002.
5. Environmental Council of Concrete Organizations, "Environmental Life Cycle Assessment," EV17, Skokie, IL, 1997.
6. Marceau, Medgar L. and VanGeem, Martha G., "Life Cycle Inventory of Slag Cement Manufacturing Process" *CTL Project Number 312012*, Construction Technology Laboratories, Skokie, IL, August 11, 2003.
7. Marceau, Medgar L. and VanGeem, Martha G., "Life Cycle Inventory of Slag Cement Concrete" *CTL Project Number 312012,* Construction Technology Laboratories, Skokie, IL, August 11, 2003.
8. U.S. Environmental Protection Agency, "Compilation of Air Pollution Emission Factors," *AP-42, Fifth Edition*, EPA Office of Air Quality Planning and Standards, Research Triangle Park, NC, 1995.
9. U. S. Green Building Council, "LEED Innovation & Design Process CIR: Innovation in Design, Specific Title (IDc11)," https://www.usgbc.org/Members/Credit/credit_question_details.asp?QuestionID=446, Washington, D.C., 2003

TABLES AND FIGURES

List of Tables

List of Figures

Table 1 – Concrete Mixtures – Cementitious Materials Percentages

Description	Mixture #	Percentage of Cementitious Material			
		Portland Cement	Slag Cement	Fly Ash	Silica Fume
Ready Mixed Concrete 20 MPa (3000 psi)	R-3-0	100			
	R-3-35	65	35		
	R-3-50	50	50		
	R-3-20F	80		20	
Ready Mixed Concrete 35 MPa (5000 psi)	R-5-0	100			
	R-5-35	65	35		
	R-5-50	50	50		
Precast Concrete 50 MPa (7500 psi)	P-7-0	100			
	P-7-35	65	35		
	P-7-50	50	50		
Precast Concrete 70 MPa (10000 psi)	P-10-0	89			11
	P-10-35	58	31[a]		11
	P-10-50	45	44[b]		11
Concrete Block	B-0	100			
	B-35	65	35		
	B-50	50	50		

a. Slag cement is a 35% replacement for portland cement and 31% of the total cementitious materials.
b. Slag cement is a 50% replacement for portland cement and 44% of the total cementitious materials.

Table 2 – LCI Mixture Proportions (kg/m^3 and lb/yd^3 concrete)[a]

Mixture #	Units	Portland Cement	Slag Cement	Fly Ash	Silica Fume	Water	Coarse Aggregate	Fine[b] Aggregate
R-3-0	kg/m^3	223	0	0	0	141	1127	831
	lb/yd^3	376	0	0	0	237	1900	1400
R-3-35	kg/m^3	145	78	0	0	141	1127	831
	lb/yd^3	244	132	0	0	237	1900	1400
R-3-50	kg/m^3	112	112	0	0	141	1127	831
	lb/yd^3	188	188	0	0	237	1900	1400
R-3-20F	kg/m^3	179	0	44	0	141	1127	831
	lb/yd^3	301	0	75	0	237	1900	1400
R-5-0	kg/m^3	335	0	0	0	141	1187	712
	lb/yd^3	564	0	0	0	237	2000	1200
R-5-35	kg/m^3	218	117	0	0	141	1187	712
	lb/yd^3	367	197	0	0	237	2000	1200
R-5-50	kg/m^3	167	167	0	0	141	1187	712
	lb/yd^3	282	282	0	0	237	2000	1200
P-7-0	kg/m^3	504	0	0	0	178	1050	555
	lb/yd^3	850	0	0	0	300	1770	935
P-7-35	kg/m^3	328	177	0	0	178	1050	555
	lb/yd^3	552	298	0	0	300	1770	935
P-7-50	kg/m^3	252	252	0	0	178	1050	555
	lb/yd^3	425	425	0	0	300	1770	935
P-10-0	kg/m^3	445	0	0	56	136	1112	611
	lb/yd^3	750	0	0	95	230	1875	1030
P-10-35	kg/m^3	290	155	0	56	136	1112	611
	lb/yd^3	488	262	0	95	230	1875	1030
P-10-50	kg/m^3	222	222	0	56	136	1112	611
	lb/yd^3	375	375	0	95	230	1875	1030
B-0	kg/m^3	208	0	0	0	142	0	2017
	lb/yd^3	350	0	0	0	240	0	3400
B-35	kg/m^3	135	72	0	0	142	0	2033
	lb/yd^3	228	122	0	0	240	0	3427
B-50	kg/m^3	104	104	0	0	142	0	2033
	lb/yd^3	175	175	0	0	240	0	3427

a. For the mixtures designed for this study and the PCA study (excluding the block mixture), differences in specific gravities of portland and slag cements and fly ash are assumed to be accounted for by air contents, which vary from approximately 3% to 5%.
b. Fine aggregate is assumed to be 30% crushed stone and 70% sand and gravel. Differences in aggregate take into account the difference in specific gravity of portland and slag cements.

Table 3 – Raw Material Inputs for One Cubic Meter (Yard) of Concrete Production

Concrete mix description	Ready Mixed Concrete							Precast Concrete						Concrete Block		
28 day comp. strength	3,000 psi				5,000 psi			7,500 psi			10,000 psi			Unspecified		
Slag cement percent	0%	35%	50%	0%	0%	35%	50%	0%	35%	50%	0%	35%	50%	0%	35%	50%
Fly ash percent	0%	0%	0%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mixture	R-3-0	R-3-35	R-3-50	R-3-20F	R-5-0	R-5-35	R-5-50	P-7-0	P-7-35	P-7-50	P-10-0	P-10-35	P-10-50	B-0	B-35	B-50
SI UNITS (kg/m³):																
Portland cement	360	234	180	288	541	352	270	815	529	408	718	468	359	335	219	168
Slag cement	0	87	124	0	0	130	186	0	196	280	0	173	247	0	80	115
Fly ash	0	0	0	44	0	0	0	0	0	0	0	56	56	0	0	0
Silica fume	0	0	0	0	0	0	0	0	0	0	56	0	0	0	0	0
Water	141	141	141	141	141	141	141	178	178	178	136	136	136	142	142	142
Coarse aggregate	1,127	1,127	1,127	1,127	1,187	1,187	1,187	1,050	1,050	1,050	1,112	1,112	1,112	0	0	0
Fine aggregate	831	831	831	831	712	712	712	555	555	555	611	611	611	2,033	2,033	2,033
Total	2,458	2,420	2,403	2,431	2,580	2,521	2,495	2,598	2,509	2,471	2,634	2,557	2,522	2,511	2,475	2,459
US CUST. UNITS (lb/yd³):																
Portland cement	606	394	304	485	911	593	455	1,374	892	687	1,210	788	605	565	369	283
Slag cement	0	147	209	0	0	219	313	0	331	472	0	291	416	0	135	194
Fly ash	0	0	0	75	0	0	0	0	0	0	0	95	95	0	0	0
Silica fume	0	0	0	0	0	0	0	0	0	0	95	0	0	0	0	0
Water	237	237	237	237	237	237	237	300	300	300	230	230	230	240	240	240
Coarse aggregate	1,900	1,900	1,900	1,900	2,000	2,000	2,000	1,770	1,770	1,770	1,875	1,875	1,875	0	0	0
Fine aggregate	1,400	1,400	1,400	1,400	1,200	1,200	1,200	935	935	935	1,030	1,030	1,030	3,427	3,427	3,427
Total	4,143	4,078	4,050	4,097	4,348	4,249	4,205	4,379	4,228	4,164	4,440	4,309	4,251	4,232	4,171	4,144

Table 4 - Energy Inputs for One Cubic Meter (Yard) of Concrete Production

Concrete mix description	Ready Mixed Concrete							Precast Concrete						Concrete Block		
28 day comp. strength	3,000 psi				5,000 psi			7,500 psi			10,000 psi			Unspecified		
Slag cement percent	0%	35%	50%	0%	0%	35%	50%	0%	35%	50%	0%	35%	50%	0%	35%	50%
Fly ash percent	0%	0%	0%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mixture	R-3-0	R-3-35	R-3-50	R-3-20F	R-5-0	R-5-35	R-5-50	P-7-0	P-7-35	P-7-50	P-10-0	P-10-35	P-10-50	B-0	B-35	B-50
SI UNITS (GJ/m³):																
Portland cement manufacturing	1.173	0.769	0.592	1.780	0.948	1.156	0.889	2.677	1.740	1.340	2.360	1.537	1.181	1.103	0.719	0.552
Slag cement manufacturing	0.000	0.057	0.080	0.000	0.000	0.084	0.121	0.000	0.128	0.182	0.000	0.112	0.160	0.000	0.052	0.075
Aggregate production	0.132	0.132	0.132	0.132	0.132	0.128	0.128	0.109	0.109	0.109	0.117	0.117	0.117	0.116	0.116	0.116
Transporting materials to plant	0.123	0.123	0.123	0.123	0.123	0.131	0.131	0.134	0.134	0.134	0.139	0.139	0.139	0.126	0.126	0.126
Concrete plant operations	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247	0.247
Concrete block curing	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.065	0.068	0.068
Total	1.684	1.329	1.176	1.518	2.291	1.753	1.518	3.174	2.360	2.015	2.870	2.153	1.849	1.656	1.326	1.183
US CUST. UNITS (MBtu/yd³):																
Portland cement manufacturing	0.850	0.557	0.429	1.290	0.687	0.838	0.644	1.940	1.261	0.971	1.710	1.114	0.856	0.799	0.521	0.400
Slag cement manufacturing	0.000	0.041	0.058	0.000	0.000	0.061	0.088	0.000	0.093	0.132	0.000	0.081	0.116	0.000	0.038	0.054
Aggregate production	0.096	0.096	0.096	0.096	0.096	0.093	0.093	0.079	0.079	0.079	0.085	0.085	0.085	0.084	0.084	0.084
Transporting materials to plant	0.089	0.089	0.089	0.089	0.089	0.095	0.095	0.097	0.097	0.097	0.101	0.101	0.101	0.091	0.091	0.091
Concrete plant operations	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179	0.179
Concrete block curing	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.047	0.049	0.049
Total	1.22	0.96	0.85	1.10	1.66	1.27	1.10	2.30	1.71	1.46	2.08	1.56	1.34	1.20	0.96	0.86

Table 5 – Selected Emissions Outputs for One Cubic Meter (Yard) of Concrete Production

28 day comp. strength	3,000 psi				5,000 psi			7,500 psi			10,000 psi			Unspecified		
Slag cement percent	0%	35%	50%	0%	0%	35%	50%	0%	35%	50%	0%	35%	50%	0%	35%	50%
Fly ash percent	0%	0%	0%	20%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Mixture	R-3-0	R-3-35	R-3-50	R-3-20F	R-5-0	R-5-35	R-5-50	P-7-0	P-7-35	P-7-50	P-10-0	P-10-35	P-10-50	B-0	B-35	B-50
SI UNITS (kg/m³):																
CO_2	228	160	131	189	329	227	182	482	326	260	429	292	233	218	154	126
SO_2	0.545	0.408	0.351	0.457	0.765	0.562	0.474	1.098	0.789	0.659	0.985	0.712	0.593	0.528	0.402	0.347
NOX	0.713	0.513	0.429	0.598	1.004	0.706	0.578	1.436	0.985	0.795	1.288	0.896	0.724	0.670	0.488	0.408
VOC	0.031	0.029	0.027	0.030	0.037	0.032	0.030	0.043	0.036	0.033	0.042	0.036	0.033	0.030	0.027	0.026
CO	0.322	0.259	0.232	0.283	0.424	0.329	0.289	0.568	0.425	0.364	0.522	0.396	0.342	0.306	0.246	0.221
CH_4	0.011	0.009	0.008	0.010	0.015	0.012	0.010	0.022	0.016	0.013	0.020	0.014	0.012	0.011	0.008	0.007
Particulate matter	1.09	0.90	0.82	0.98	0.98	1.08	0.96	1.71	1.30	1.12	1.60	1.23	1.07	1.01	0.84	0.77
Port. cement kiln dust	11.6	7.5	4.6	9.3	9.3	11.3	8.7	26.2	17.0	13.1	23.1	15.1	11.6	10.8	7.1	5.4
Slag reject**	0.000	0.133	0.103	0.000	0.000	0.201	0.154	0.000	0.301	0.232	0.000	0.266	0.205	0.000	0.125	0.096
US CUST. UNITS (lb/yd³):																
CO_2	385	269	220	318	555	382	307	812	550	438	723	492	393	367	260	213
SO_2	0.918	0.688	0.591	0.770	1.289	0.947	0.799	1.850	1.330	1.110	1.660	1.200	1.000	0.890	0.678	0.585
NOX	1.201	0.865	0.723	1.008	1.693	1.190	0.975	2.420	1.660	1.340	2.170	1.510	1.220	1.130	0.823	0.688
VOC	0.053	0.048	0.046	0.050	0.062	0.055	0.051	0.073	0.061	0.056	0.071	0.060	0.056	0.051	0.046	0.044
CO	0.543	0.436	0.391	0.477	0.714	0.555	0.487	0.957	0.716	0.614	0.880	0.668	0.577	0.515	0.415	0.373
CH_4	0.019	0.015	0.013	0.017	0.026	0.020	0.017	0.037	0.027	0.022	0.033	0.024	0.021	0.018	0.014	0.013
Particulate matter	1.83	1.52	1.39	1.64	1.64	1.82	1.62	2.89	2.19	1.89	2.69	2.07	1.81	1.71	1.42	1.30
Port. cement kiln dust	19.6	12.7	7.8	15.7	15.7	19.1	14.7	44.2	28.7	22.1	39.0	25.4	19.5	18.2	11.9	9.1
Slag reject	0.000	0.224	0.173	0.000	0.000	0.338	0.259	0.000	0.508	0.391	0.000	0.449	0.345	0.000	0.210	0.161

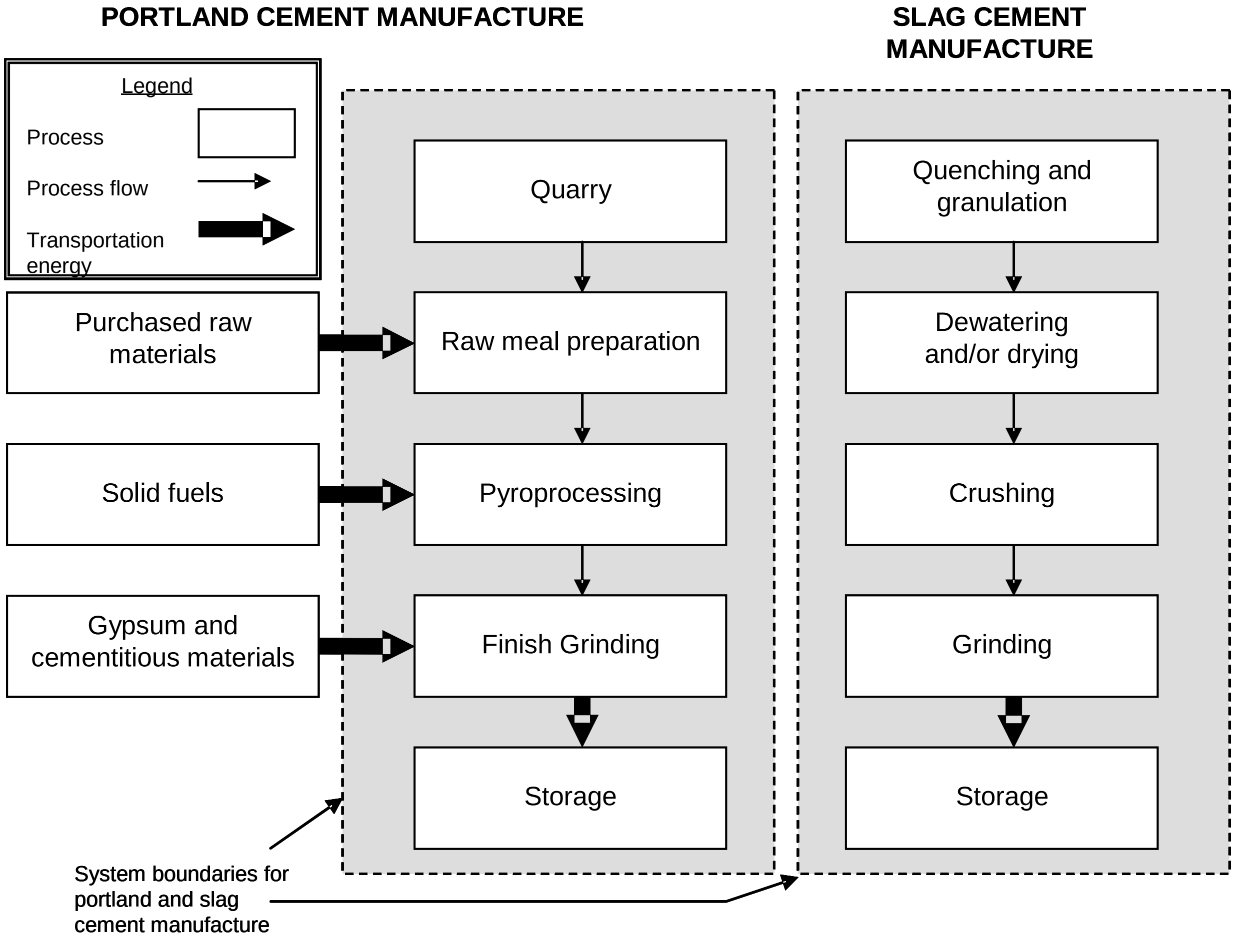
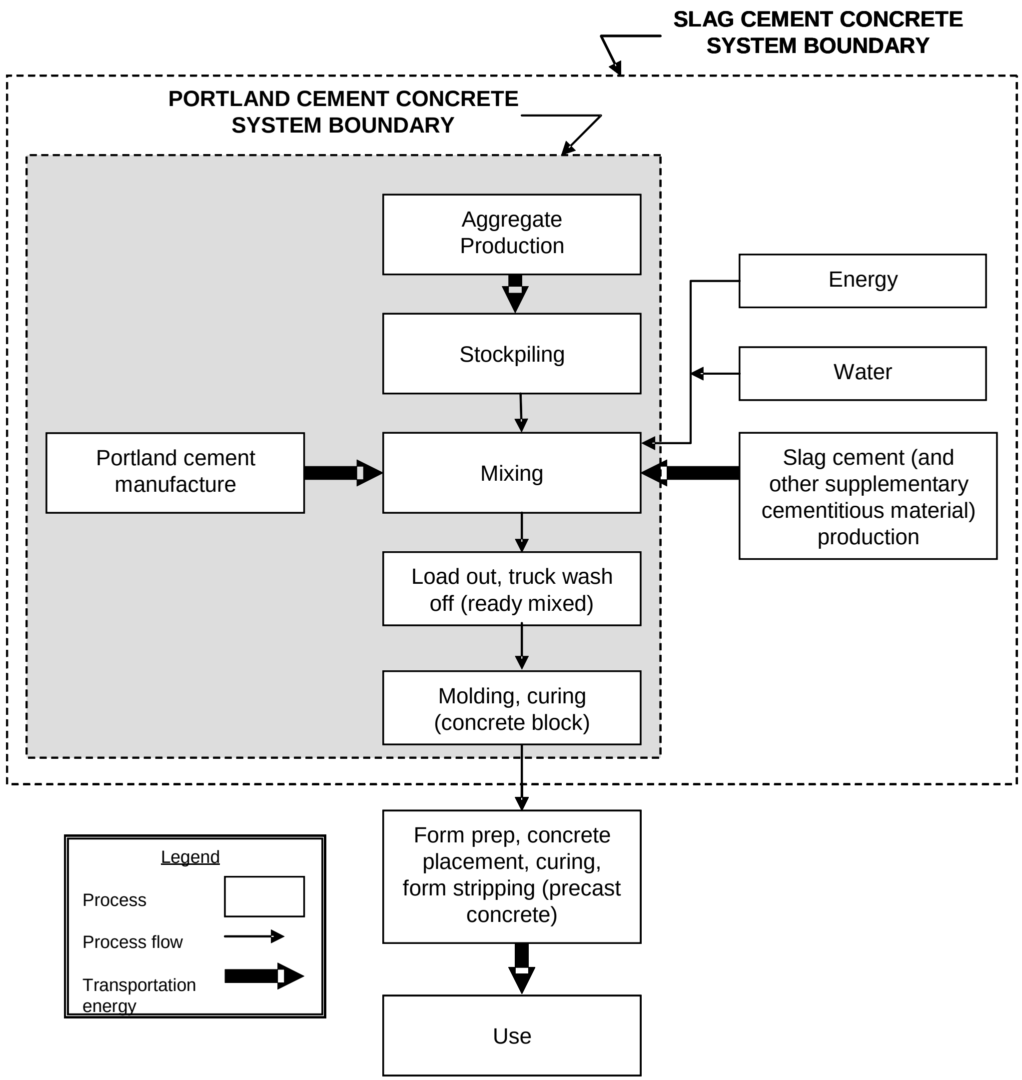


Figure 1 – System boundaries for portland and slag cement manufacturing


SLAG CEMENT CONCRETE SYSTEM BOUNDARY
PORTLAND CEMENT CONCRETE SYSTEM BOUNDARY
Aggregate Production
Stockpiling
Energy
Water
Portland cement manufacture
Mixing
Slag cement (and other supplementary cementitious material) production
Load out, truck wash off (ready mixed)
Molding, curing (concrete block)
Form prep, concrete placement, curing, form stripping (precast concrete)
Use
Legend
Process
Process flow
Transportation energy

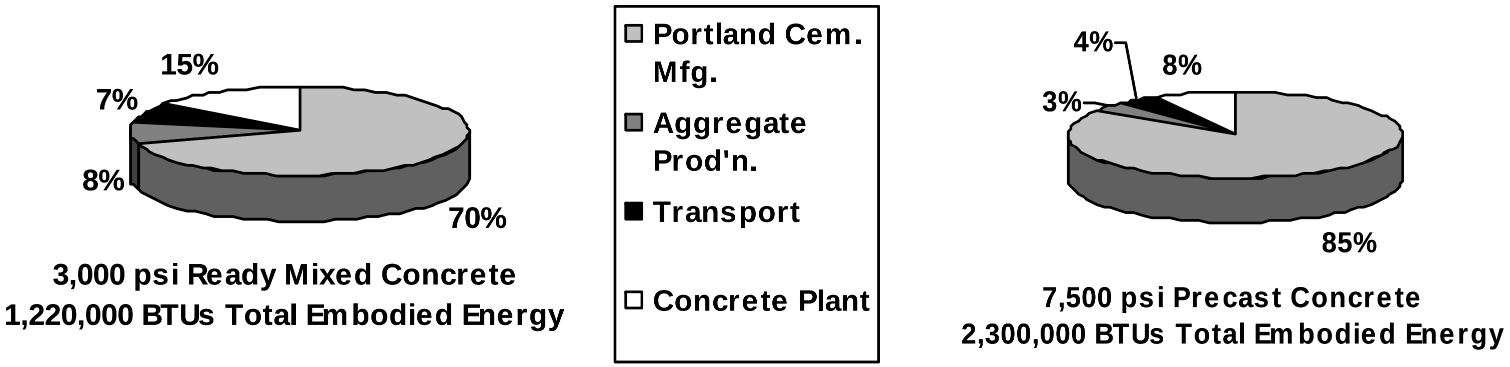


Figure 3 – Embodied energy by process step in a cubic yard of concrete for mixtures with the lowest (20 MPa [3,000 psi] ready mixed concrete) and highest (50 MPa [7,500 psi] precast concrete) levels of embodied energy.

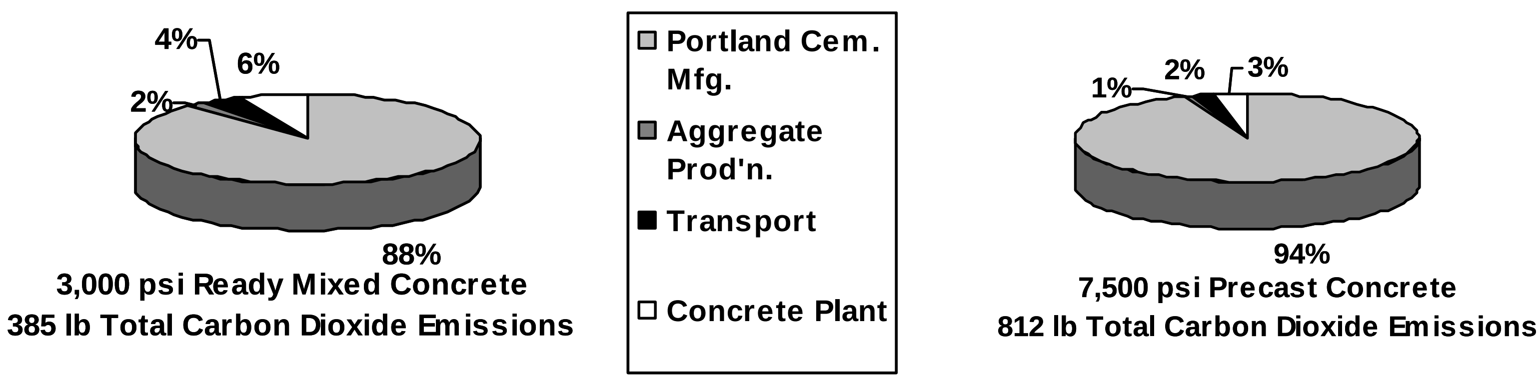


Figure 4 – Carbon dioxide emissions by process step in a cubic yard of concrete for mixtures with the lowest (20 MPa [3,000 psi] ready mixed concrete) and highest (50 MPa [7,500 psi] precast concrete) levels of embodied energy

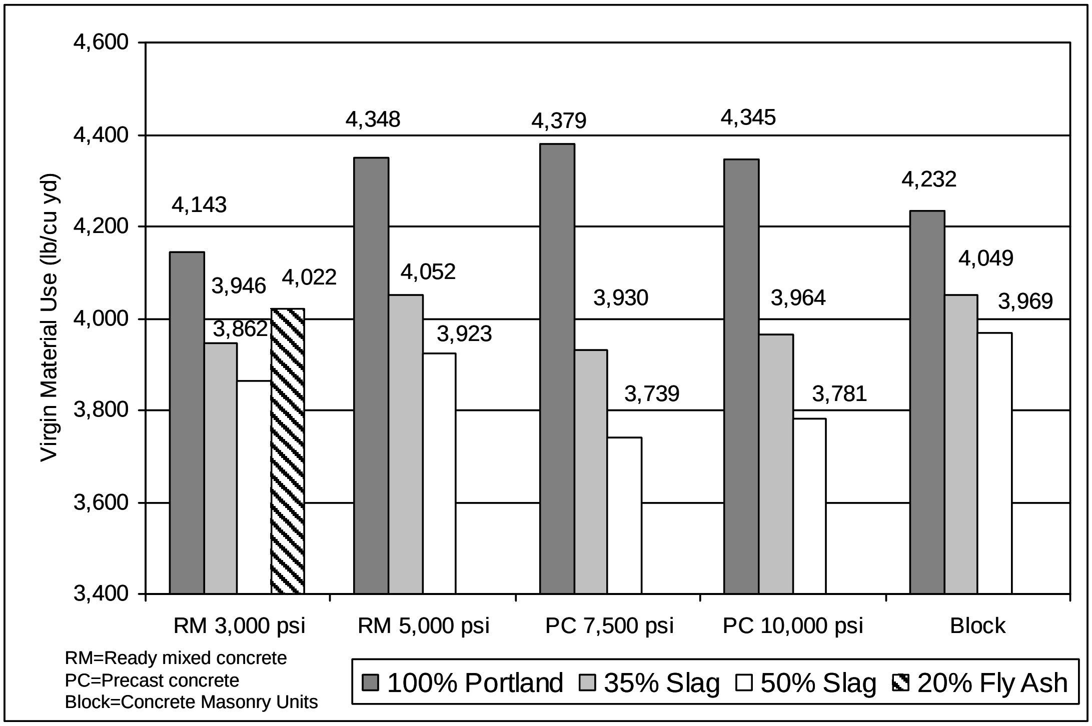


Figure 5a – Virgin material use in one cubic yard of concrete of various mixtures (includes water) (SI Units)

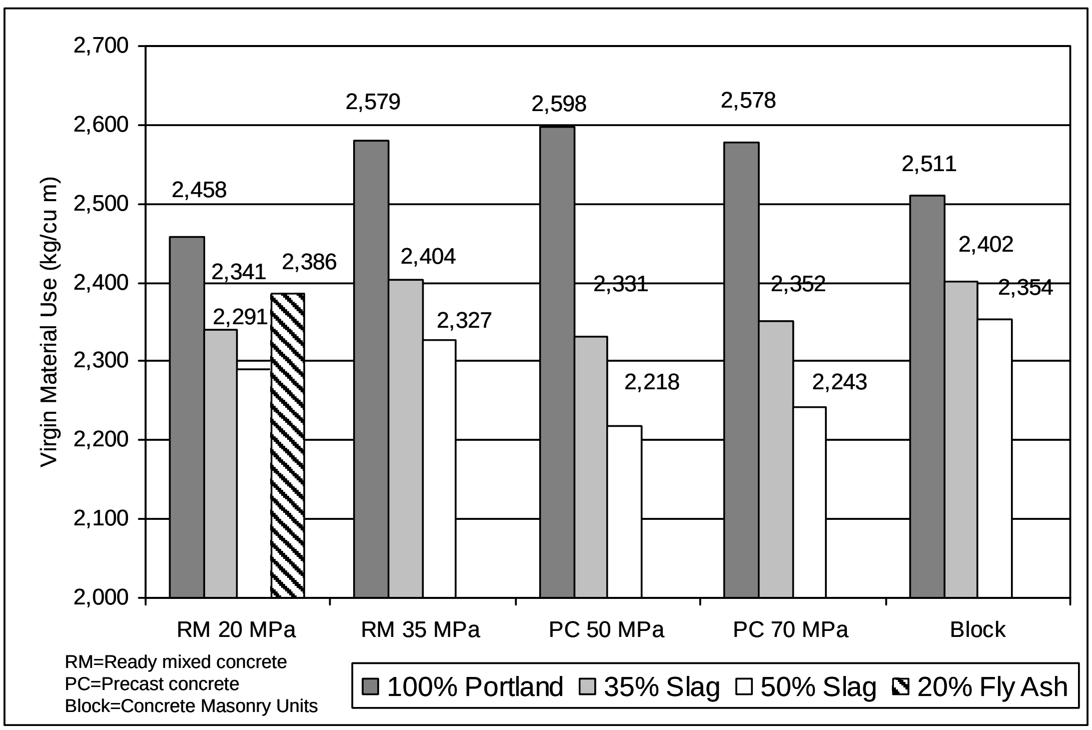


Figure 5b – Virgin material use in one cubic yard of concrete of various mixtures (includes water) (US Customary Units)

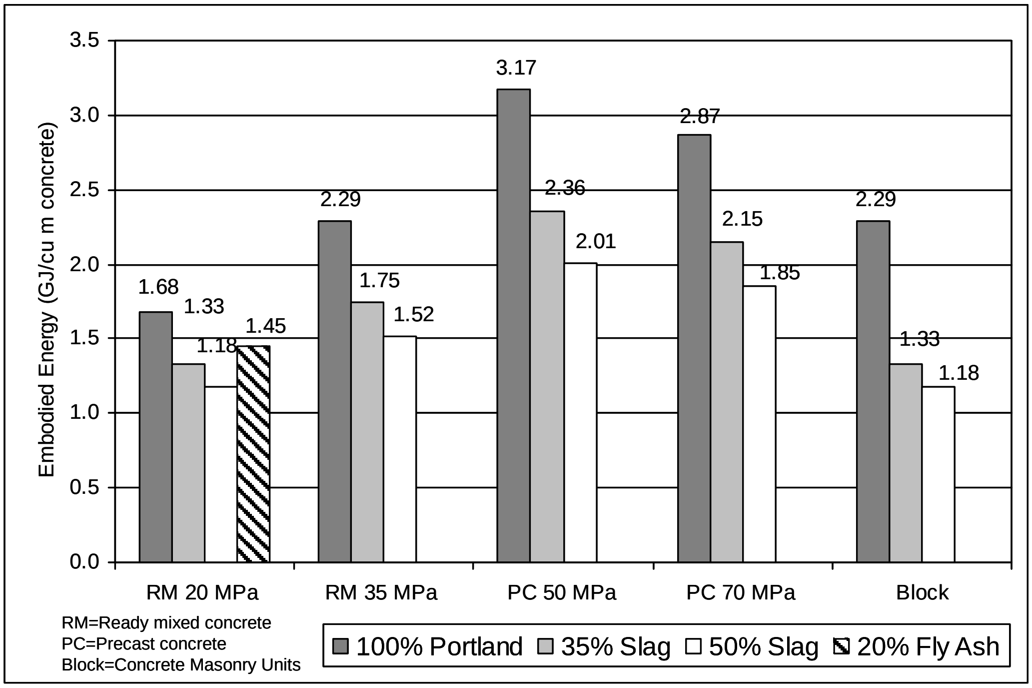


Figure 6a – Embodied energy required to produce one cubic yard of concrete in various mixtures (SI Units)

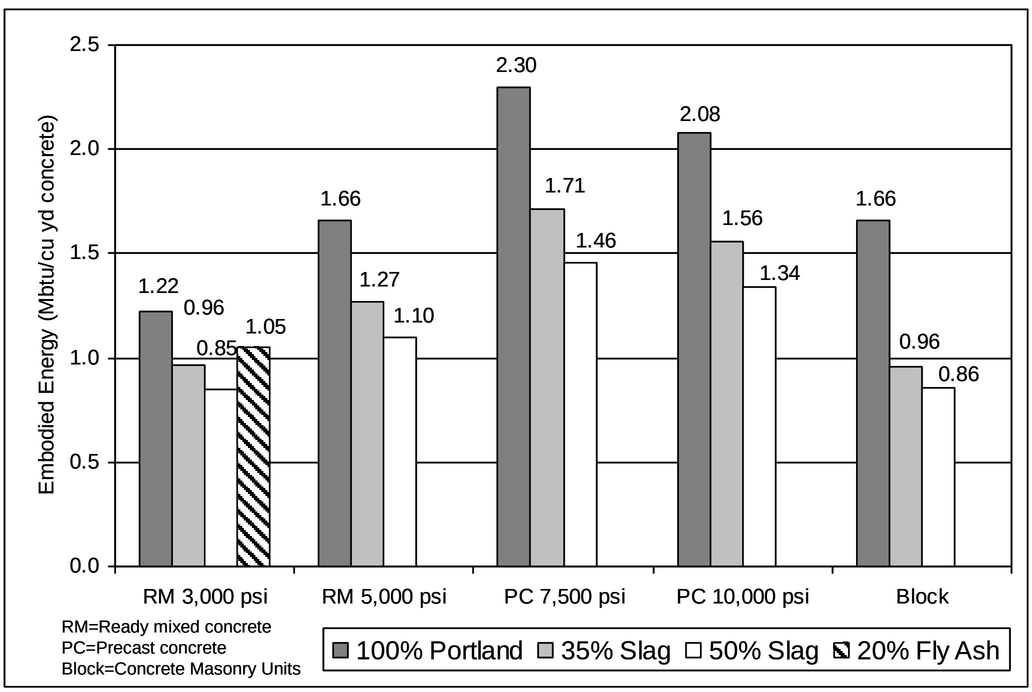


Figure 6b - Embodied energy required to produce one cubic yard of concrete in various mixtures (US Customary Units)

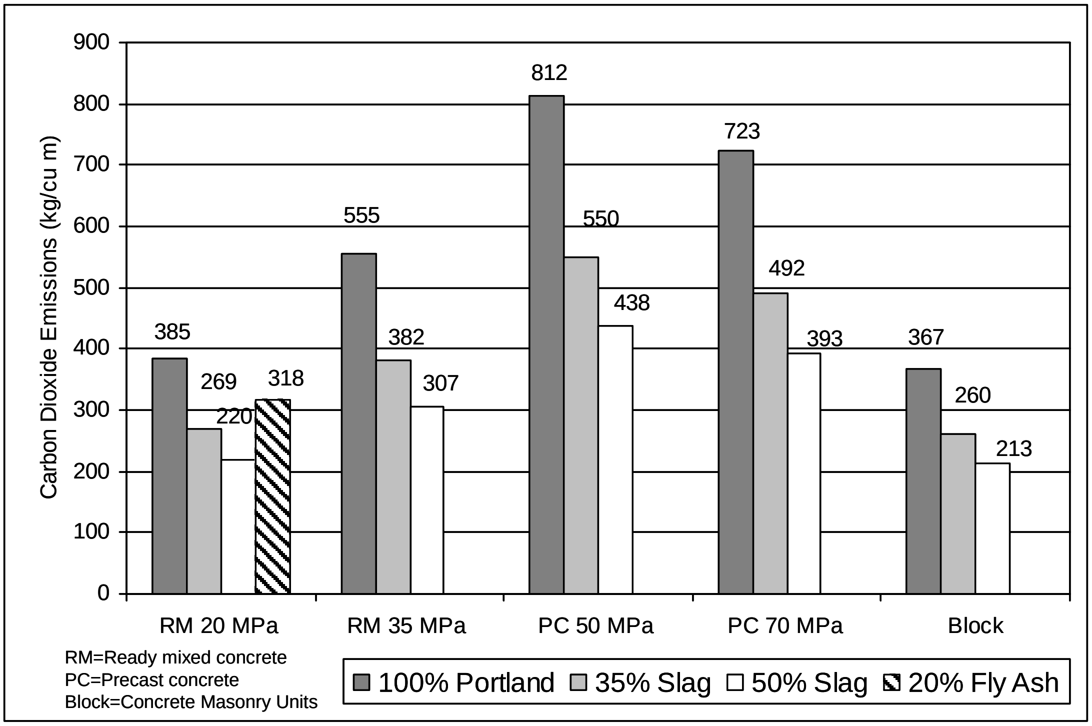


Figure 7a - Carbon dioxide emissions in one cubic yard of concrete of various mixtures (SI Units)

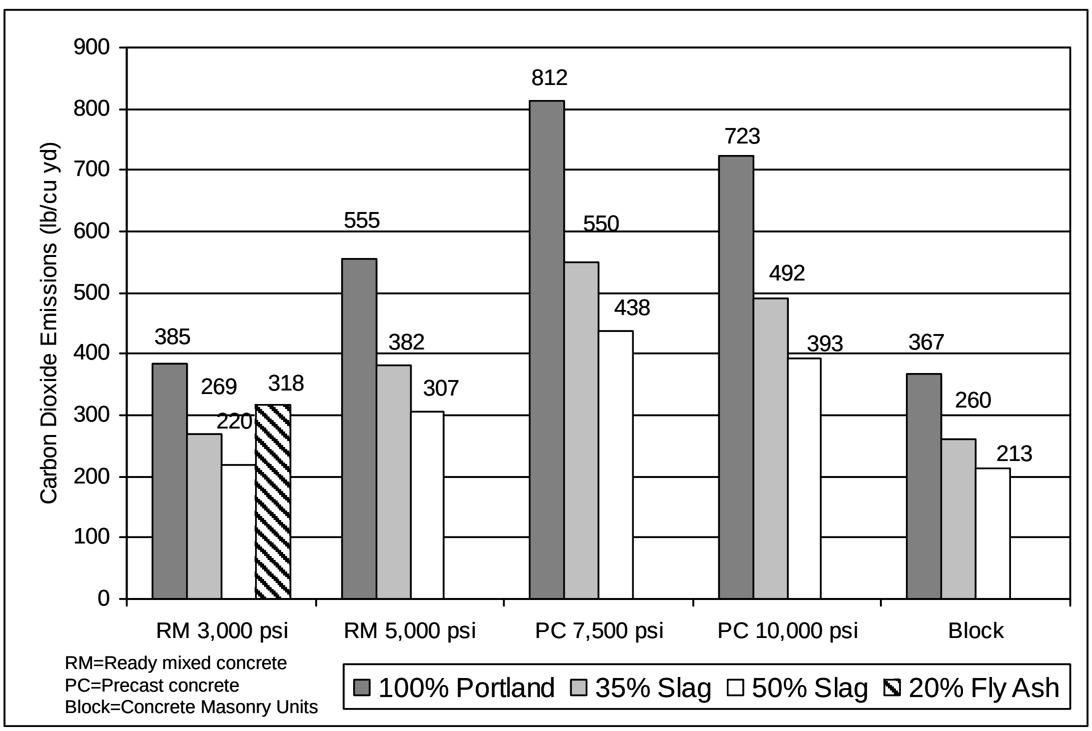


Figure 7b – Carbon dioxide emissions in one cubic yard of concrete of various mixtures (US Customary Units)