openIMPACT Concrete Documentation

April 28, 2022

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openIMPACT
Concrete Documentation

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1 Purpose of this document

The purpose of this document is to provide transparent documentation of methodology and data sources for the development of life cycle assessment models representing North American-specific concrete products. openIMPACT data are expected to be used by downstream carbon accounting software or users that need North American-specific environmental impact results for the full life cycle (A-C modules) for key building materials. Thus, this document reports the data and assumptions used in this modeling effort. Furthermore, this analysis acknowledges that the environmental impacts of construction materials can be highly variable due to upstream supply chains, technological variability, geographic variability, and mix design variability in the market. One significant advance of this modeling effort is that it includes analysis of supply chain variability, parameter variability, and their effect on Global Warming Potential (GWP). The concrete LCA models are developed in conjunction with the openIMPACT Monte Carlo Algorithm (MCA), documented separately, in order to address this variability and uncertainty.

1.1 Intended application

The primary goal of this study is to provide cradle-to-grave environmental impact results for use in design tools used by the Architecture, Engineering, and Construction (AEC) industry. The intended use may include early building design tools, so it is critical to provide ranges of impacts across concrete products on the market. This is not a comparative study. Any comparisons made in this study are only for results validation purposes.

2 Scope

2.1 Scope of analysis

This study aims to address all cradle-to-grave (A-C) life cycle stages[1]; however, given the nature of the products covered in this study, not all stages are expected to have significant effect on the overall GWP. Life cycle stages A5 and C1 are best addressed as part of a building-level analysis. Module D is outside of the scope of this study. The study focuses on understanding the variability in the GWP impact of the studied products; therefore, the data collection and modeling focuses on elements affecting primarily GWP. The functional unit of each concrete product can differ and is reported in Section 3.

The concrete products modeled in this project include ready-mix concrete, precast concrete, concrete masonry units (CMU), and mortar. In addition, models have been developed to represent sub-types for each of these products, as is shown in Table 1. Where appropriate, further parameterizations have been added to represent design choices that a user of these datasets may want to make.

Table 1. Modeling choices available for concrete products.

Material Subcategory	Stage A1-A3 User Selections			Stage B
Ready Mix	Compressive strength *(17.2 MPa, 20.7 MPa, 27.6 MPa, 34.5 MPa, 41.4 MPa, 55.6 MPa)*	SCM replacement percentage *(0%, 10%, 20%, 30%, 40%, 50%)*	SCM type *(fly ash, slag)*	Project type *(building vs infrastructure project)*
Precast	Product type *(structural, architectural, insulated, underground)*			Project type *(building vs infrastructure project)*
CMU Block	Product weight *(normal-weight, lightweight)*			
Mortar	Mortar Type *(M, N, O, S)*			

2.2 Data sources

Ecoinvent is the default background data source for the LCA models developed herein [1]. However, background data from NETL life cycle inventory (LCI) data have been substituted for default electricity and natural gas, since these are US-specific [2]. Certain ecoinvent datasets have also been modified to be US-specific where possible and these modifications are discussed in Section 0. For instance, default transportation distances have been altered where appropriate and where more specific distance data is available.

Foreground data for the concrete models are based on a variety of data sources to represent average U.S. production. However, when North American data was not available, US- or Canadian-specific data sources were used and the proxy is noted where this is true. Figure 1 illustrates the research institutions, industry associations, and databases from which, LCI data for the concrete models were sourced. In addition, individual data sources are referenced in Section 3. Data sources include publicly available sources, data available to Building Transparency under licensing agreements, or data shared by partners under confidentiality agreements. There is no confidential information revealed in this report.

[1] Refer to ISO 21930:2017 for a full list and definitions of life cycle stages.

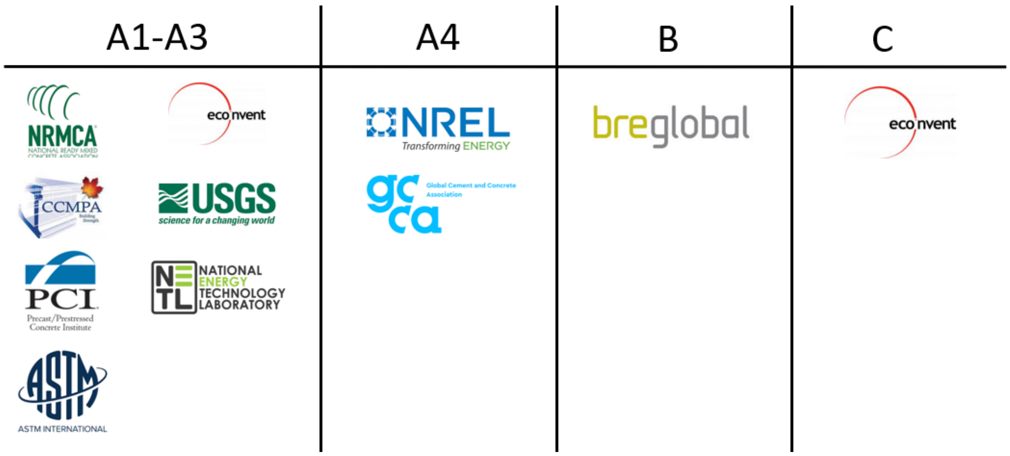

Figure 1. Summary of data sources for LCA modules

2.3 Impact assessment method

This study uses the TRACI 2.1 impact assessment method, as this is the most relevant LCIA method for North America. Future iterations of this study may include results for other LCIA methods, such as CML or EF3.0.

3 Description of material and base models

3.1 Ready-mix concrete (A1-A3)

Ready-mix concrete refers to concrete that is batched from a central plant and delivered to a construction project. It can be used for a variety of infrastructure applications including bridges, foundations, floors, road developments, footpaths, and other civil engineering projects. Ready-mix concrete accounts for approximately 75% of all concrete produced due to the flexibility and adaptability to project requirements as well as low transport and construction costs.

Typical ingredients in ready-mix concrete include cement, water, coarse aggregate, and fine aggregate. In addition, a variety of supplementary cementitious materials or other replacement materials can be used in concrete to reduce the quantity of cement used in a mix (e.g., fly ash, blast-furnace slag, silica fume). Admixtures may also be used in small doses to tailor the curing properties of the concrete mix.

The foreground data for the ready-mix A1-A3 modules are based on the National Ready Mixed Concrete Association (NRMCA) average regional mix designs [3], which also includes data on key inputs and output flows that occur at the ready-mix plant. A key performance parameter of ready-mix concrete for a project is the 28-day compressive strength; thus, models representing the six compressive strength ranges from the NRMCA have been developed for normal-weight concrete, with a declared unit of 1 m^3. Table 2 reports the national average mix designs for each strength class and Table 3 reports the electricity, fuel, water, and waste input and output flows used during concrete manufacturing. Average batch waste is reported as 0.20% (This is separate from construction waste rate). Note that admixtures are not currently included in the LCA models, but this is a part of the future work.

Table 2. Quantity of ingredients used in national average mixture designs.

Material	Unit	17.2 MPa (2500 psi)	20.7 MPa (3000 psi)	27.6 MPa (4000 psi)	34.5 MPa (5000 psi)	41.4 MPa (6000 psi)	55.6 MPa (8000 psi)
Portland cement	kg	210.0	233.8	281.8	341.7	361.9	426.6
Fly ash	kg	36.8	40.9	49.2	59.9	63.5	74.8
slag	kg	10.1	11.3	13.7	16.6	17.8	20.8
water	kg	181.0	181.0	181.0	186.9	202.3	202.3
crushed coarse aggregate	kg	668.0	661.5	642.5	610.5	629.5	604.0
natural coarse aggregate	kg	328.1	324.5	315.0	299.6	309.1	296.0
crushed fine aggregate	kg	100.3	99.1	96.1	91.4	94.3	90.2
natural fine aggregate	kg	760.6	753.5	731.5	694.7	716.7	687.6
plasticizer and SP	kg	0.1	0.1	0.1	0.3	0.1	0.1
set accelerator	kg	0.9	0.7	0.6	0.4	0.9	0.7

Table 3. National average energy, water, and waste inputs/outputs at the batching plant.

Input	Units	Quantity
electricity	kWh	4.21
natural gas	m3	0.44
fuel oil	L	0.04
diesel	L	1.59
gasoline	L	0.00
LPG	L	0.04
water	L	114.02
hazardous solid waste	kg	0.01
non-hazardous solid waste	kg	4.12
material losses	%	3

3.2 Precast Concrete (A1-A3)

Precast concrete refers to concrete that is produced off-site and then transported to the construction location. It is produced by casting concrete in a reusable form in a controlled environment. Precast concrete has greater costs related to materials and transportation; however, particular project constraints may make precast concrete the preferred or cheaper option. For instance, constraints on the speed of building erection or assurance of concrete performance may make precast concrete the most feasible option.

Mix designs for precast concrete and energy inputs can be significantly different compared to ready-mix concrete. This is primarily due to the need for quick turnover of forms, and therefore accelerated curing times. Strategies such as using accelerating admixtures, Type III Portland cement, and elevated curing temperatures may all be used to more rapidly produce precast concrete. In addition, it is critical to note that the declared unit for precast concrete is assumed to include the steel needed for rebar, welded wire reinforcement, steel anchors, and steel stressing strand. Contrastingly, the declared unit for ready-mix concrete does not include reinforcing steel, which is an important distinction.

The foreground data for the precast concrete A1-A3 modules are based on the Precast/Prestressed Concrete Institute (PCI) industry-average LCA of precast concrete products and has a declared unit of one metric ton [4]. The mix designs and production methods for precast concrete can be significantly different when comparing different applications of precast concrete; therefore, this study shows models representing structural, architectural, insulated, and underground concrete. Table 4 reports the raw material inputs for the four precast material subtypes, and Table 5 reports the other manufacturing inputs and outputs including fuel, electricity, water, and wastes. The plant wastage rate is assumed to be the same as for ready-mix concrete manufacturing (0.2%).

Table 4. Precast raw material inputs.

	Unit	Structural precast	Architectural precast	Insulated precast	underground precast
Portland cement	kg	152.2	143.5	160.9	135.2
PLC	kg	7.0	13.9	3.9	3.1
Fine aggregate, natural	kg	298.3	302.7	278.2	341.3
Fine aggregate, manufactured	kg	59.4	40.6	58.6	48.8
coarse aggregate, natural	kg	156.6	185.5	121.3	88.8
coarse aggregate, crushed	kg	233.3	209.6	258.3	292.7
Manufactured lightweight aggregate	kg	2.6	1.2	1.0	0.0
Natural lightweight aggregate	kg	3.0	0.1	4.3	0.3
Fly ash	kg	14.5	6.0	6.7	17.8
Silica fume	kg	1.8	-	-	-
Slag cement	kg	2.7	-	-	13.6
Total admixture	kg	2.9	2.5	2.1	2.5
Rebar	kg	18.7	17.9	11.4	14.3
Welded wire reinforcement	kg	5.7	9.0	8.0	11.5
Steel anchors	kg	4.7	7.9	5.2	0.5
Steel stressing strand	kg	13.8	8.9	12.5	0.8
Polypropylene fibers	kg	-	-	-	2.8
expanded polystyrene	kg	0.3	0.0	5.1	0.1
extruded polystyrene	kg	0.1	0.3	8.8	-
brick	kg	0.4	4.0	2.6	-
natural stone	kg	-	0.8	-	-
pigments	kg	0.1	1.6	0.7	-
net consumables	L	0.1	0.1	0.1	0.1
total batch water	L	59.4	57.9	65.1	57.3

Table 5. Other input and output flows during precast concrete manufacturing.

Manufacturing inputs (A3)	Unit	Amount
Electricity	kWh	20.3
Onsite electricity generation from solar	kWh	0.4
Gasoline	liter	0.7
Natural gas	m3	3.5
Diesel	liter	1.8
Heavy fuel oil	liter	0.1
LPG	liter	0.2
Total plant water use	liter	438.4
Hazardous waste to landfill	kg	2.8
Hazardous waste to recycling facility	kg	1.9
Hazardous waste to incineration facility	kg	-
Non-hazardous waste to landfill	kg	11.3
Non-hazardous waste to recycling facility	kg	15.3
Non-hazardous waste to incineration facility	kg	0.9

3.3 Concrete Masonry Units (A1-A3)

Concrete masonry units (CMU) are rectangular concrete blocks used in a variety of building and infrastructure applications such as load-bearing walls and retaining walls. They are modular, with the most common size being nominally 8x8x16 inches. Units are cast with voids in the center, where reinforcement can be placed as needed and then filled with grout. When constructed, units are then held together with mortar.

CMU are typically composed of Portland cement, water, fine aggregate, and fine gravel, but they may incorporate a variety of industrial wastes or recycled materials (e.g., recycled aggregate, post-consumer glass, blast furnace slag). In addition, lightweight CMU may employ lightweight aggregate in order to achieve low densities, which can be cost-effective in certain design situations. It should be noted that for this subcategory, the declared unit is per metric ton of CMU, which does not include reinforcement, grout, or mortar.

The foreground data for the CMU A1-A3 modules are based on the Canadian Concrete Masonry Producers Association (CCMPA), which contains average mix designs for normal-weight and lightweight CMU blocks [5]. Since there are no North American- or US-specific industry-wide EPDs, the Canadian industry-wide EPD is used as the best approximation of North American CMU mix designs. Table 6 reports the average mix designs for normal and lightweight CMU, and Table 7 reports other inputs and outputs at the plant during manufacturing including electricity, fuels, water, and wastes. The plant wastage rate is assumed to be the same as for ready-mix concrete manufacturing (0.2%).

Table 6. Average mixture designs for normal and lightweight CMU.

Material	Mass of ingredients (kg) normal weight	Mass of ingredients (kg) lightweight
Portland Cement	171.2	190.2
Blended Cement	34.8	53.2
Slag	10.0	7.0
Fly ash	0.9	0.0
Crushed coarse aggregate	777.0	190.0
natural coarse aggregate	107.0	8.6
crushed fine aggregate	161.0	0.0
natural fine aggregate	1003.0	143.0
expanded slag (use sand LCI)	0.0	1242.0
silica flour	18.0	20.9
Water reducer	0.1	0.1
Water repellant/efflorESENCE control admixture	0.10	0.0
Air entraining admixture	0.0	0.0
Batch water	58.9	68.9

Table 7. Manufacturing inputs and outputs for CMU.

Manufacturing Inputs	Normal weight	Lightweight
Grid electricity (kWh)	37.7	37.7
Natural gas (m3)	16.6	16.6
Diesel (kg)	1.4	1.4
Gasoline (kg)	0.0	0.0
LPG (kg)	0.0	0.0
process and wash water (kg)	104.4	104.4
oil and lubricants (kg)	0.1	0.1
grease (kg)	0.0	0.0
plastic wrap (kg)	0.9	0.9
plastic bags and top sheets (kg)	0.2	0.2
Non-hazardous solid waste to landfill (kg)	6.1	6.1
Non-hazardous solid waste to recycling/reuse - concrete (kg)	52.1	52.1
Non-hazardous solid waste to recycling/reuse - wood (kg)	2.0	2.0
Non-hazardous solid waste to recycling/reuse - steel (kg)	0.3	0.3
Hazardous liquid waste, to incinerator (kg)	0.1	0.1

3.4 Mortar (A1-A3)

Mortar is a workable paste, which hardens to bind and seal building blocks including CMU, bricks, and stones. This category refers specifically to cement mortar, which is specified under ASTM C270 and designates four types of premixed dry mortar products [6]; the volumetric ratio of dry mixture ingredients in these mortar types are reported in Table 8. Notably, mortar is produced as a dry powder; it is not until construction (A5), that water is added and a paste is formed. Thus, water usage is accounted for in the A5 module. The declared unit for mortar is one metric ton of prepared (wet) mortar. Since the mortar mix proportions are reported volumetrically, the densities of these ingredients (reported in Table 9) are used to calculate the mass of each ingredient used as foreground quantities.

Table 8. Volumetric ratio of mixture ingredients for four types of mortar mix.

Mortar Type	Compressive Strength (MPa)	Portland Cement	Lime	Sand
M	17.2	1	0.25	3.5
S	12.4	1	0.5	4.5
N	5.2	1	1	6
O	2.4	1	2	9

Table 9. Densities of mortar mix ingredients.

Ingredient	Density (kg/m^3)
Portland Cement	1440
Lime	2210
Sand	1600
Water	997

Finally, no industry-wide EPD exists for dry mortar mix; thus, the manufacturing inputs and outputs have been estimated as the same as for ready mix concrete on a per metric ton basis. The wastage during manufacturing is also assumed to be the same as that for ready-mix concrete. Since mortar mix is often sold in the US in 50 pound bags, foreground quantities for packaging are sourced from the North American EPD for mortar mix [7]. The plant wastage rate is assumed to be the same as for ready-mix concrete manufacturing (0.2%)

3.5 Transport (A2, A4, and C2)

The A2 module refers to transportation impacts that occur due to transporting raw materials to the manufacturing plant. The A4 module refers to transportation impacts that occur from transporting a product to the construction site. The C2 module represents transportation impacts that occur from transporting flows at end-of-life. For this project, default transportation distances from ecoinvent have been replaced with North American-specific distances when available. These transportation distances for A2, A4, and C2 modules are sourced from the Global Cement and Concrete Association (GCCA) Life Cycle Inventory and reported in Table 10 [8].

Table 10. Default transportation distances for key concrete materials.

Material	Truck Distance (km)	Truck Type	Train Distance (km)	Ship Distance (km)
Cement	123.9	16-32 t	77.2	170.6
Other primary raw materials (e.g., aggregate)	33.8	16-32 t	-	-
Admixtures	172.2	7.5-16 t	-	-
Other additives	172.2	7.5-16 t	-	-
Reinforcement	172.2	16-32 t	-	-
Packaging	212.4	7.5-16 t	-	-
Insulation	172.2	7.5-16 t	-	-
Concrete products (A4)	56.3	16-32 t	-	-
EoL transport (C2)	32.2	16-32 t	17.7	-

3.6 Construction (A5)

The construction module (A5) encompasses emissions occurring at the construction site. Each of the concrete categories requires different methods of construction and therefore generate different environmental impacts. For instance, for ready mix concrete, pumps, vibrators, and spreaders, may all be used to appropriately place the concrete, depending on the application. For precast concrete, cranes and lifts may be used during installation. Contrastingly, CMU and mortar are generally placed without heavy machinery.

However, overall, environmental impacts of construction are most accurately captured at the building level rather than the individual material level. Thus, these impacts are not currently covered in this study.

3.7 Carbonation during use phase and end-of-life (B and C)

Concrete carbonation is the reaction by which carbon dioxide from the atmosphere reacts with compounds in cement paste, which permanently sequesters the carbon dioxide. This is a diffusion-based process that generally happens on the time scale of years, but the rate and extent of concrete carbonation during the use phase is dependent on many in-situ factors (e.g., surface area exposed to air, environmental exposure type, quantity of cement used, building lifetime, etc.) Similarly, end-of-life (EOL) carbonation is dependent on additional EOL parameters such as the surface area of waste concrete (e.g., if it is crushed or ground), and the EOL scenario (e.g., if it is landfilled or reused).

Methodologies for quantifying the extent of concrete carbonation have been developed and adopted into at least one PCR. For instance, the BRE Global PCR, based on previous carbonation research [9,10] has adopted a method for quantifying concrete carbonation if certain use phase and EOL parameters are known. The methodology provides distinct equations for "Group 1" concrete products (CMU blocks and mortar) and "Group 2" concrete products (ready-mix and precast concrete). This is due to the fact that Group 1 products are expected to fully carbonate over the building lifetime, while Group 2 products only carbonate to a certain depth in the use phase.

For CMU blocks and mortar, the quantity of carbon dioxide reabsorbed through carbonation is modeled in Equation 1:

$$carbonation\left(\frac{kg}{m^3}\right) = 0.75 * M_{CaO} * \frac{mm_{CO_2}}{mm_{CaO}} \qquad \text{Equation 1}$$

Where:

0.75 = the percent of CaO that will carbonate
mm_{CO2} = molecular mass of CO_2
mm_{CaO} = molecular mass of CaO
M_{CaO} = mass of CaO within the concrete product (kg/m^3), obtained as shown in Equation 2

$$M_{CaO} = Q_{Cem} * \%C_{Cem} * \%CaO_C \qquad \text{Equation 2}$$

Where:

Q_{Cem} = amount of cement in the concrete (kg/m^3)
$\%C_{Cem}$ = percentage of clinker in cement
$\%CaO_C$ = percentage of CaO within Portland cement clinker

Table 11. Parameters for use phase carbonation for CMU and mortar.

Variable name	Description	Lightweight	Normal weight	Unit	Source of default parameter value
q_{Cem}	mass cement per m3 concrete	190	171.2	kg/m3	CCMPA industry average EPD [5]
$\%C_{Cem}$	mass clinker per mass cement	0.914	0.914	kg/kg	NRMCA Member National and Regional Benchmark LCA Report [3]
mm_{CaO}	molar mass of CaO	56	56	g/mol	BRE Global Product Category Rules [11]
mm_{CO2}	molar mass of CO2	44	44	g/mol	BRE Global Product Category Rules [11]
$\%CaO_C$	kg CaO per kg clinker	0.65	0.65	kg/kg	BRE Global Product Category Rules [11]

Group 2 products are generally stronger, less permeable, and have greater thicknesses than Group 1 products; thus, to calculate the quantity of carbon dioxide sequestered over the use phase, the depth of carbonation must be taken into account. Carbonation for Group 2 products can be calculated via Equation 3.

$$carbonation = \left(K * S * \sqrt{SP}\right) * (0.75 * \ M_{CaO} * \frac{mm_{CO_2}}{mm_{CaO}} * Q_{Cem} * \%C_{Cem}) \qquad \text{Equation 3}$$

Where:

K = depth of carbonation (m)
S = surface area (m^2)
SP = study period (years)

The values for the depth of carbonation (K) can be determined via Equation 4:

$$K = k * D_c \qquad \text{Equation 4}$$

Where:

k = correction factor for calculating depth of carbonation for different strength classes and exposure conditions, which can be found in Table 12

D_C = degree of carbonation possible (as a percentage) for different exposure conditions, which can be found in Table 12.

Table 12. Values for k-factor and degree of carbonation for range of strengths and exposure scenarios.

Strength Range		< 15 MPa	15-25 MPa	25-35 MPa	> 35 MPa	
Type of Infrastructure	**Exposure Condition**	**Value of k-factor, in mm/year$^{0.5}$**				**Degree of carbonation (D_C) (%)**
Civil Engineering Structures	Exposed to rain	-	2.7	1.6	1.1	85
	Sheltered from rain	-	6.6	4.4	2.7	75
	In ground	-	1.1	0.8	0.5	85
Buildings	Exposed to rain	5.5	2.7	1.6	1.1	85
	Sheltered from rain (outside)	11.0	6.6	4.4	2.7	75
	Indoor with cover	11.6	6.9	4.6	2.7	40
	Indoor without cover	16.5	9.9	6.6	3.8	40
	In ground	-	1.1	0.8	0.5	85

Table 13 reports the default parameters for carbonation modeling of ready-mix and precast concrete. For these two material types, the only parameter that the user must select is whether the project is for a building or infrastructure, the remaining parameters are pre-specified, as shown below.

Table 13. Parameters for use phase carbon dioxide sequestration for ready-mix and precast concrete.

Parameter	Description	Default value (building)	Default value (infrastructure)	Unit	Source of default parameter value
Exposure condition	Exposure condition	Exposed to rain	Exposed to rain	n/a	Conservative value
k	correction factor, surface exposure conditions	See Table 12 , depends on the strength of the mix design	See Table 12, depends on the strength of the mix design	mm	GCCA Inventory conservative value [8]
D_C	degree of carbonation	85	85	%	BRE Global Product Category Rules conservative value [9]
S	surface area per volume	6	2	m2/m3	GCCA Inventory conservative value [8]
SP	study period	60	100	years	GCCA Inventory conservative value [8]
q_{cem}	mass cement per m3 concrete	value taken from mix design	value taken from mix design	kg/m3	NRMCA Industry average EPD [3]
c_{cem}	mass clinker per mass cement	0.9	0.9	kg/kg	GCCA Inventory [8]
amt_carb_{CaO}	Percent of CaO that will carbonate (experimentally determined)	0.63	0.63	kg/kg	BRE Global Product Category Rules [9]
mm_{CaO}	molar mass of CaO	56	56	g/mol	BRE Global Product Category Rules [9]
mm_{CO2}	molar mass of CO2	44	44	g/mol	BRE Global Product Category Rules [9]
$\%CaO_C$	kg CaO per kg clinker	0.65	0.65	kg/kg	BRE Global Product Category Rules [9]

3.8 End-of-Life (EOL) (C)

Emissions for concrete result from a variety of EOL activities including demolition, transport, waste processing, and landfilling. Since it is not possible to know the actual EOL scenario for concrete when it is being procured, the LCA models account for the average EOL scenario. According to the US EPA Advancing Sustainable Materials Management: 2018 Fact Sheet, approximately, 82% of concrete demolition waste is recycled and 18% is landfilled [11]. Thus, the LCA model assumes 85% of the material is attributed the environmental impacts of landfilling via the ecoinvent process "market for municipal solid waste - CA-QC". In addition, The GCCA Industry EPD Tool for Cement and Concrete assumes an average waste transportation distance of 57.9 km [8]. Table 14 summarizes these EOL assumptions.

Table 14. Parameters for EOL processes.

EOL Process	Description	Value	Unit	Reference
Transportation	Distance transported via truck	57.9	km	[8]
Disposal	Fraction landfilled	18%	-	[11]

4 Sources of variability in parameters contributing to GWP for concrete materials

In this section, the variability in parameters contributing to GWP for concrete products is discussed and documented. Not all sources of variability have been implemented in the code thus far; this is a working document. Therefore, the results shown in Section 2 are a proof of concept at the current time. In the following sections it is noted whether the source of variability has been captured in the Monte Carlo simulation (MCS) code and results yet.

4.1 Raw Material Production

4.1.1 Cement

There is a large amount of variability in GWP due to the cement used in concrete products. This is primarily due to two parameters: kiln efficiency and fuel types, as is explained below.

There are a variety of cement kiln technologies with a range of energy use per mass of clinker produced, but there are two main technology categories: wet and dry cement kilns. Wet kilns have low efficiencies and require approximately 6,000 MJ to produce one metric ton of clinker [12]. Dry kilns have a wider range of efficiencies with energy consumption ranging from 2,900 to 4,500 MJ per metric ton clinker [12]. According to the USGS 2017 Minerals Yearbook for cement, 98.1% of US cement production utilized dry kiln technology (only 1.9% wet kiln) because most wet kilns have been phased out in the U.S [13].

To develop a distribution representing the variability in kiln energy use per metric ton of clinker, mean and standard deviation for clinkering energy is taken from the “Getting the Numbers Right” project from the GCCA. The mean of

The other major source of variability in GWP associated with cement production is due to fuel types used in cement kilns. The graph below illustrates the fraction of clinkering energy coming from each fuel source in the U.S., which is based on quantities reported in the USGS 2017 Minerals Yearbook for cement [13] and higher heating values for each fuel reported in the GCCA LCI dataset [9]. These fuel sources lead to a range of effective GWP impact per metric ton of cement. This variability has not yet been included in the MCS code and results.

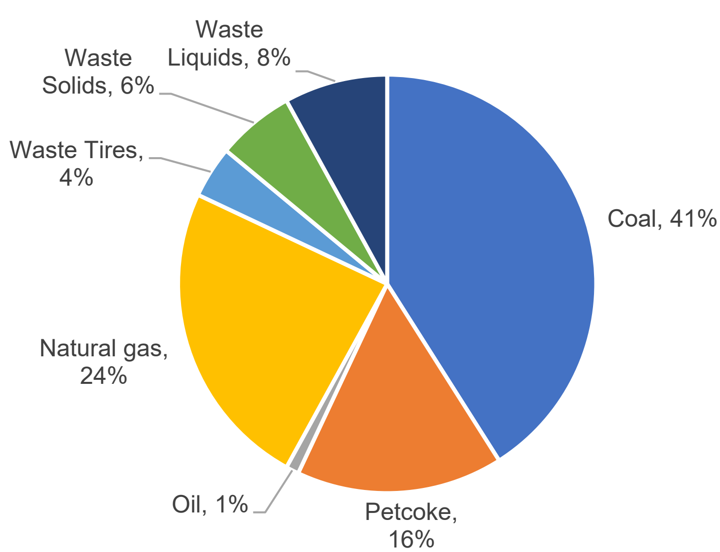

Figure 2. Fraction of energy supplied by each fuel type.

4.1.2 Aggregate

Normal-weight aggregate production has relatively low GWP per metric ton, and supply chain variability is not expected to be highly significant. However, lightweight aggregate production involves the expansion of raw materials such as shale, slate, or clay, in a kiln similar to the cement clinkering process. Therefore, much like cement production, lightweight aggregate production is likely to have high variability in GWP. There is currently a lack of data on lightweight aggregate production input and output flows. This section will be expanded as more data becomes available.

4.2 Mixture Design

The proportion of ingredients used in a concrete mix is known as its mixture design. Different concrete mixes are used to tailor the fresh- and hardened-state concrete for a particular application. A significant source of variability in emissions from concrete products that have the same performance and function is the mixture design of the concrete.

Variability in mixture design comes from many factors including:

- Supply chain availability and cost of supplementary cementitious materials (SCMs)
- Cultural willingness replace cement with SCMs (and local standards)
- Variability in quantity of cement required due to local aggregate properties
- Requirements on additional concrete properties such as fresh-state properties and exposure to corrosive or degrading environments

The NRMCA Member National and Regional LCA Benchmark study [3] reports regional differences in mix designs for concrete that achieve the same benchmark compressive strength level. There is significant variation regionally in the quantity of cement, fly ash, and blast furnace slag as shown in Table 15. The table illustrates that the GWP of ready-mix concrete mixtures of the same compressive strength vary significantly. The mean and standard deviation of ingredients for mixes is also reported.

Table 15. Regional mixture design variability for 17.2 MPa strength concrete.

Mix ingredient per m3	Eastern	Midwest	North Central	Pacific Northwest	Pacific Southwest	Rocky Mountains	South Central	South Eastern	Mean	Std Dev
Portland cement (kg)	204.7	202.3	208.8	214.8	224.9	214.8	194.6	210.0	209.4	9.2
Fly ash (kg)	20.8	23.1	38.6	55.2	32.6	40.9	36.2	50.4	37.2	12.0
Slag cement (kg)	35.6	14.2	2.4	6.5	0.0	0.0	0.6	13.1	9.0	12.2

4.3 Plant activities

There is some variability in the quantity of input and output flows that occur during manufacturing of concrete products due to regional and technological differences. In the NRMCA Member National and Regional LCA Benchmark report [3], the NRMCA collected fuel, electricity, water, and waste statistics including mean and standard deviation for the manufacturing of ready-mix concrete. These values are confidential and cannot be reported in this document, but the variability is propagated in the model.

In addition to the variability in input and output flow quantities, there is regional variability in the emissions associated with electricity and natural gas flows. For instance, electricity grids across the U.S. vary in their carbon intensity due to the range of generating resources used. Thus, this variability in carbon intensity is propagated through to the concrete product. We utilize the method described in the Monte Carlo code overview to propagate emissions intensity variability for electricity and natural gas.

Varying providers of electricity, natural gas are substituted in the concrete manufacturing process using the Monte Carlo Algorithm (MCA). Electricity and natural gas providers represent regional options available in the NETL database and are sampled according to their consumption statistics (see the electricity and natural gas provider sheets).

4.4 Transportation

Currently, variability in transportation distances is not considered in the models since the contribution to GWP from transportation modules is relatively small. Future iterations of the models will consider variability in emissions due to transport.

4.5 Carbonation

Currently, variability in carbonation is not considered in the concrete models. However, it is a significant (negative) contribution to GWP of concrete products. Currently a conservative carbonation scenario as a default in the models, but a way to consider variability in carbonation would be to vary parameters such as the exposure scenario or surface area assumptions and see how the carbon dioxide uptake changes. A future iteration of the models will consider uncertainty in carbonation

4.6 End-of-life (EOL)

Currently, EOL emissions variability is not considered in the models since the contribution to GWP is quite small. A future iteration of the model will consider the EOL scenario (recycling vs landfilling) as a probabilistic parameter using the data provided in Table 14, thus propagating EOL uncertainty.

5 Initial Results

5.1 Cradle-to-grave (A-C) results

The following graphs illustrate the total GWP for each concrete model developed in openLCA. In addition, the relative importance of each life cycle stage is illustrated. Note that these bar charts do not consider uncertain variables; instead, they show GWP when average life cycle parameters are utilized.

For ready-mix concrete, mixes with higher compressive strength tend to use more cement and therefore tend to have higher GWP impacts (see Figure 3). For CMU blocks (Figure 4), it is clear that lightweight CMU tend to have greater GWP than normal-weight CMU since they generally use manufactured lightweight aggregate, which has much greater CO_2 emissions than normal-weight aggregate. For mortar (Figure 5), the GWP trends align with the strength (and cement content) of each mortar type. For instance, Type O mortar is the strongest and therefore has the greatest GWP. A precast contribution graph will be added when the openLCA modeling is complete.

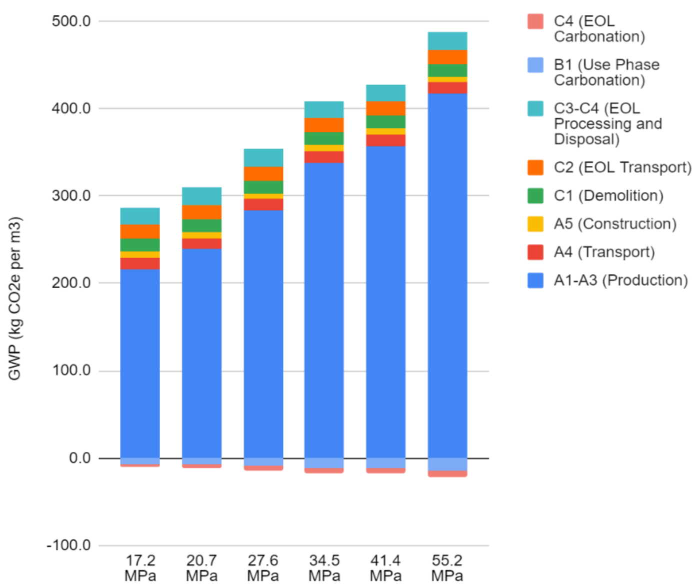

Figure 3. GWP per m3 for ready-mix concrete of six strength classes.

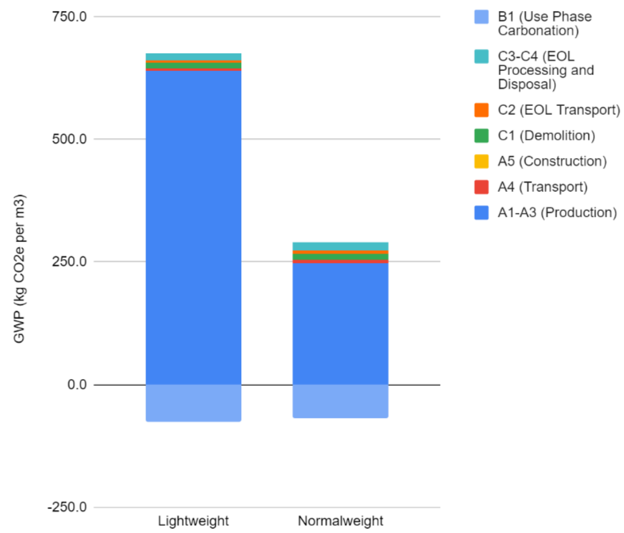

Figure 4. GWP per metric ton for normal-weight and lightweight CMU.

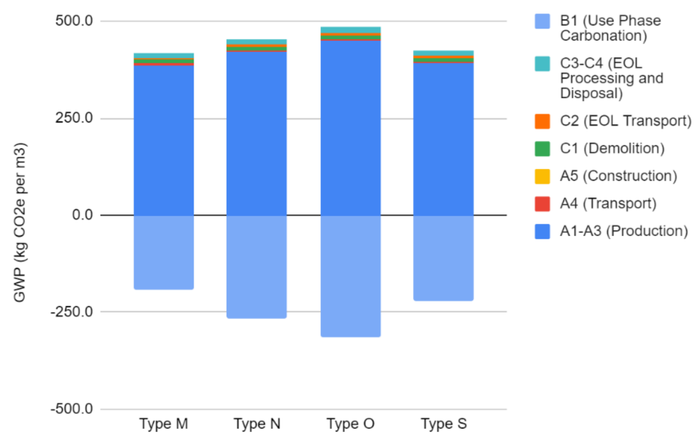

Figure 5. GWP per metric ton for four mortar types.

5.2 Cradle-to-gate (A1-A3) Results

The results reported below are a first draft comparing the openIMPACT results to product and industry EPDs in the EC3 database for A1-A3 impacts only. It is clear that for each of the different compressive strength values, the openIMPACT results tend to have lower GWP than the product EPD range and slightly lower than the industry EPD range. We suspect that the high values for product EPDs are due to the existence of lightweight concrete EPDs in the data, which tend to have relatively high GWP. We are in the process of improving the filtering of lightweight EPDs in the EC3 tool so that the openIMPACT project can be compared to only normal weight ready mix EPDs.

In addition, the range of GWP values sampled via the Monte Carlo analysis is somewhat narrow. This is due to the fact that not all sources of variability have been modeled and captured so far, as was discussed in Section 4. We are currently in the process of adding variability from cement production, and mix design variability to the model; these two sources are expected to significantly widen the range of resultant GWP.

Lastly, note the increase in GWP from Figure 3 to Figure 7 for all boxplots. This trend is due to the increase in cement content as compressive strength increases.

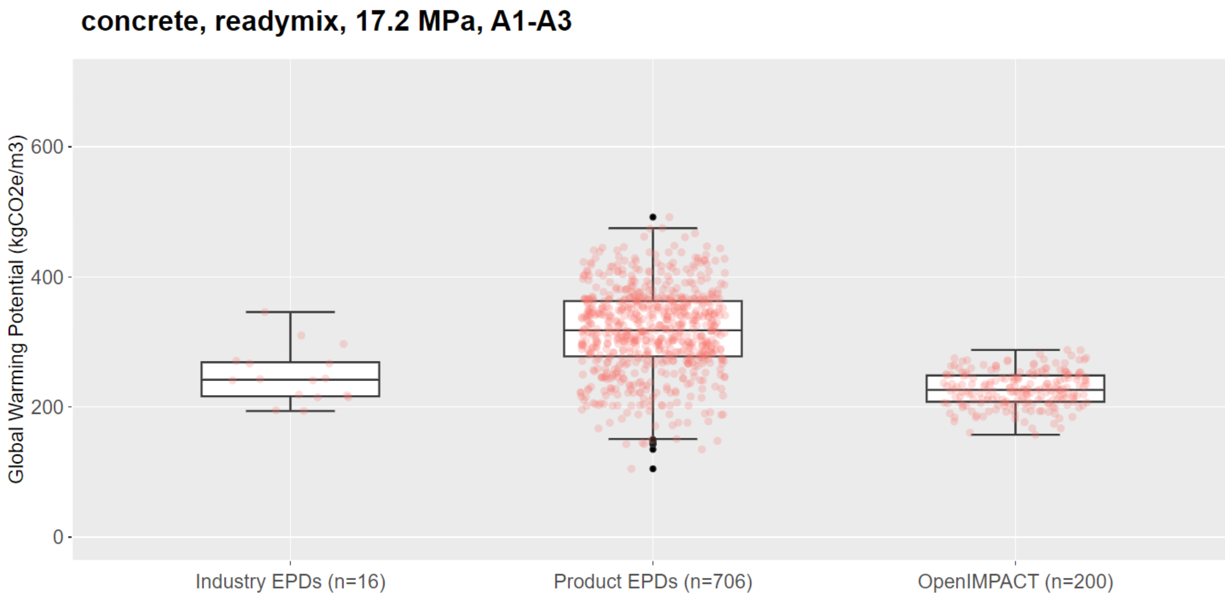

Figure 6. Comparison of openIMPACT results to product and industry EPDs for 17.2 MPa (2500 psi) strength

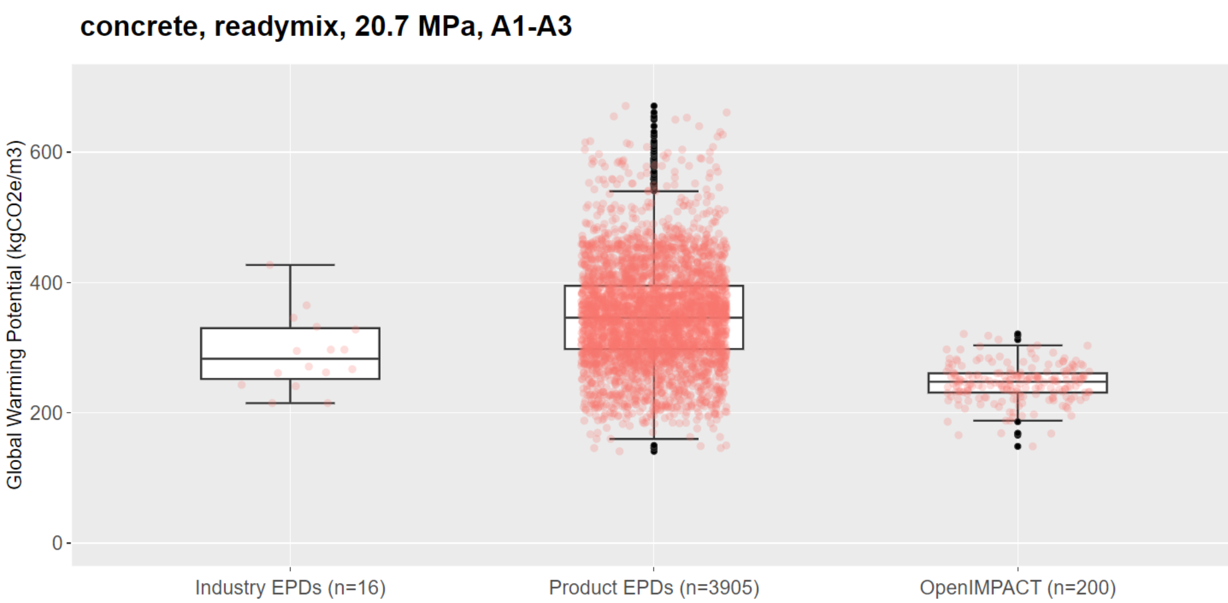

Figure 7. Comparison of openIMPACT results to product and industry EPDs for 20.7 MPa (3000 psi) strength

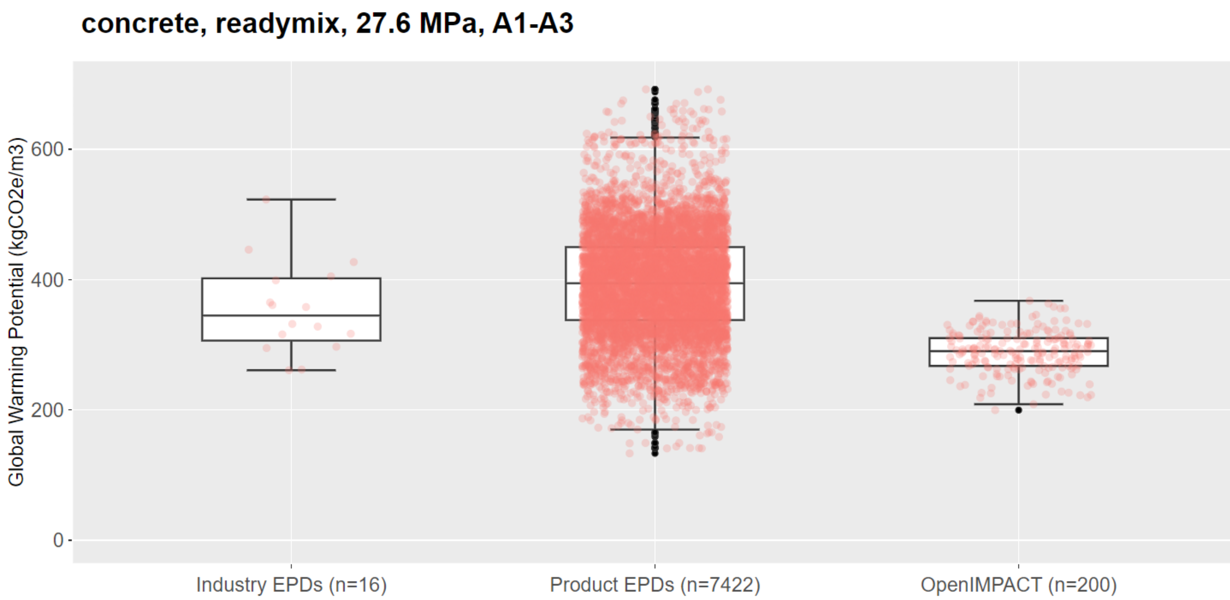

Figure 8. Comparison of openIMPACT results to product and industry EPDs for 27.6 MPa (4000 psi) strength

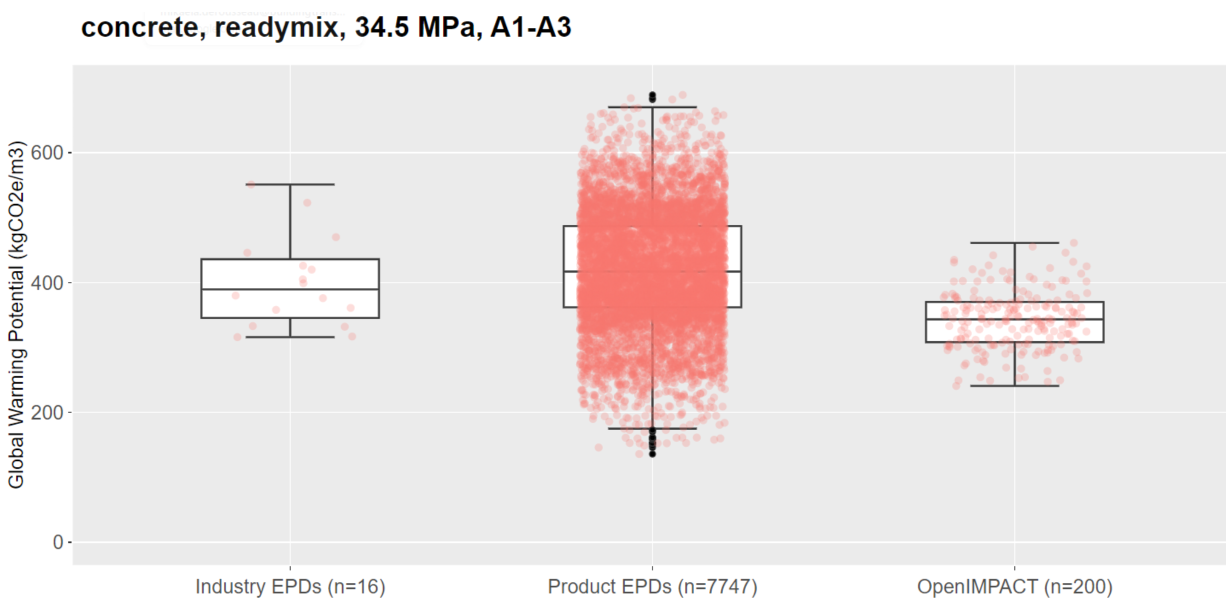

Figure 9. Comparison of openIMPACT results to product and industry EPDs for 34.5 MPa (5000 psi) strength

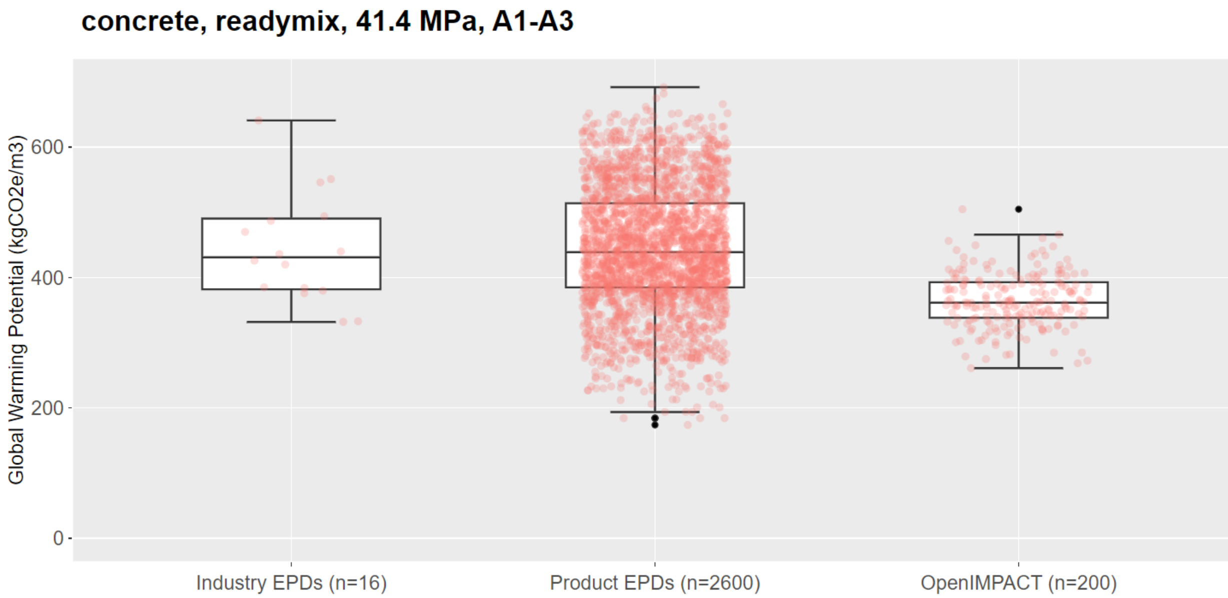

Figure 10. Comparison of openIMPACT results to product and industry EPDs for 41.4 MPa (6000 psi) strength

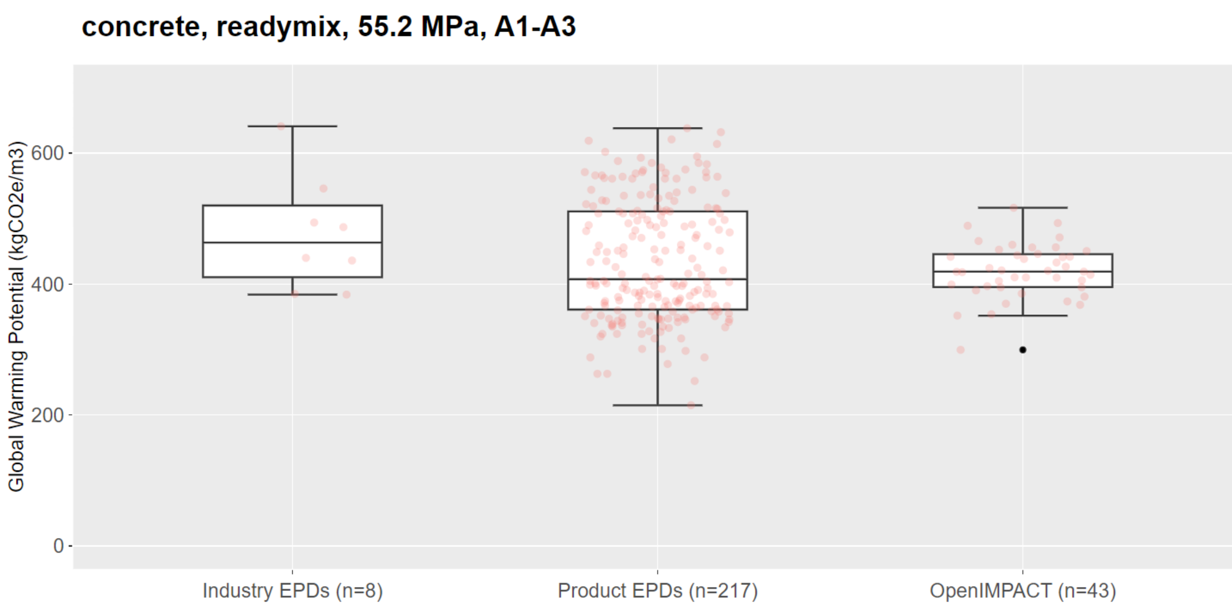

Figure 11. Comparison of openIMPACT results to product and industry EPDs for 55.2 MPa (8000 psi) strength.

6 Future Work

6.1 Impact results for precast concrete

Modeling results for precast concrete are forthcoming due to life cycle inventory data gaps associated with raw material inputs from Table 4. Proxy data to will be used when necessary LCI data are missing.

6.2 Modeling of admixtures

Similarly, LCI data for admixtures currently does not exist in most LCI databases. Environmental impact contributions from admixtures will be modeled by importing impact data from existing environmental product declarations (EPDs).

6.3 Added variabilities in models

As discussed in the model descriptions, not all major sources of variability have been included in the models thus far. Currently, the variability associated with cement production, mix design, carbonation, and lightweight aggregate manufacturing have not been included in the results. Data used to support this modeling effort is discussed in Section 4, and will be included in the next draft of models and documentation.

7 References

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