Life Cycle Inventories of Cement, Concrete and Related Industries - Brazil

for the SRI project

Fernanda Belizario Silva[1], Fabiana da Rocha Cleto[1], Elisabeth Donega Diestelkamp[1], Olga Satomi Yoshida[1], Luciana Alves de Oliveira[1], Marcella Ruschi Mendes Saade[2], Vanessa Gomes da Silva[2], Gustavo Longaray Moraga[3], Ana Carolina Badalotti Passuello[3], Maristela Gomes da Silva[4], Nicholas Myers[5], Simon Gmünder[5]

São Paulo, May 2018

[1] Institute for Technological Research (IPT)

[2] University of Campinas (Unicamp)

[3] Federal University of Rio Grande do Sul (UFRGS)

[4] Federal University of Espírito Santo (UFES)

[5] Quantis

Background

The creation of reliable, consistent and transparent regionalised Life Cycle Inventories (LCI) represents a core purpose of the SRI programme. The LCI component of the SRI project provides a basis for informed decision-making on the sustainability of products and developments in other components of SRI project. The main goal is to establish and provide regional LCIs for the use in Life Cycle Assessment (LCA) studies, environmental product declarations, carbon foot-printing and similar assessment tools. The ecoinvent Association, as the leading global supplier of transparent LCI data, is in charge of developing the basis for national LCI data in South America (Brazil, Colombia, Peru), South Africa, and India.

Acknowledgments

This report was prepared as part of the Sustainable Recycling Industries programme (SRI). The SRI programme has built on the success of implementing e-waste recycling systems with various developing countries for more than ten years. SRI is funded by the Swiss State Secretariat of Economic Affairs (SECO) and is implemented by the Institute for Materials Science & Technology (Empa), the World Resources Forum (WRF) and the ecoinvent Association.

We would like to thank the Brazilian Association of Portland Cement (ABCP), the Brazilian Association of the Concrete Block Industry (BlocoBrasil) and all construction product manufacturers (not identified due to confidentiality issues) for providing primary data from the Brazilian industry. We also thank Prof. Alessandra Castro, Prof. Vanderley John, Prof. Ana Paula Kirchheim, Lidiane Oliveira and Yazmin Mack for the contributions to this work.

Data provider details

Data Provider is here defined as the association/s that created and submitted datasets to the ecoinvent Database in the context of the SRI project. The Data Provider are the authors of this report in collaboration of the ecoinvent Association.

Institute for Technological Research (IPT)

www.ipt.br/EN
Av. Prof. Almeida Prado, 532, cx. 11, Cidade Universitária
CEP: 05508-901 São Paulo, SP, Brazil

Association Team

Fernanda Belizario Silva, Project Manager for Brazil and Data Supplier, fbsilva@ipt.br

Fabiana da Rocha Cleto, Data Supplier, frcleto@ipt.br

Elisabeth Donega Diestelkamp, Data Supplier, bethdonega@ipt.br

Olga Satomi Yoshida, Advisor for uncertainty modelling, olga@ipt.br

Luciana Alves de Oliveira, Laboratory Manager, Supervisor, luciana@ipt.br

University of Campinas (Unicamp)

http://www.unicamp.br/unicamp/english
Rua Saturnino de Brito, 224, Cidade Universitária Zeferino Vaz
CEP: 13083-889 Campinas, SP, Brazil

Association Team

Marcella Ruschi Mendes Saade, Data Supplier, marcellarms@hotmail.com

Vanessa Gomes da Silva, Professor, Supervisor, vanessa.gomes@fulbrightmail.org

Federal University of Rio Grande do Sul (UFRGS)

http://www.ufrgs.br/english/home
Av. Paulo Gama, 110 – Bairro Farroupilha
CEP: 90040-060 Porto Alegre, RS, Brazil

Association Team

Gustavo Longaray Moraga, Data Supplier, g.longaray@gmail.com

Ana Carolina Badalotti Passuello, Professor, Supervisor, ana.passuello@ufrgs.br

Federal University of Espírito Santo (UFES)

http://www.ufes.br/
Av. Fernando Ferrari, 514, Goiabeiras
CEP: 29075-910 Vitória, ES, Brazil

Association Team

Maristela Gomes da Silva, Professor, Data Supplier, margomes.silva@gmail.com

Quantis

https://quantis-intl.com/
Reitergasse 11
8004, Zurich, Switzerland

Association Team

Nicholas Myers, Data Supplier for Peru and Colombia, nicholas.myers@bluewin.ch
Simon Gmünder, Project Manager and Data Supplier for Peru and Colombia, simon.gmuender@quantis-intl.com

report name:

Life Cycle Inventories of Cement, Concrete and Related Industries – Brazil

key words:

construction products, clinker, cement, concrete, concrete block, granulated blast furnace slag, sand, gravel, life cycle inventory

citation:

Silva F.B., Cleto F.R., Diestelkamp E.D., Yoshida O.S., Oliveira L.A., SaadeM. R.M., Silva V.G., Moraga G.L., Passuello A.C.B., Silva M.G., Myers N., Gmünder S., (2018). Life Cycle Inventories of Cement, Concrete and Related Industries - Brazil. ecoinvent association, Zürich, Switzerland

Introduction from the data provider

The aim of this component of the SRI Project was to collect data from the local industry in order to develop representative Unit Processes (UPRs) and Life Cycle Inventories (LCIs) for cement, concrete and related products for Latin America. The countries included in the project's scope were Brazil (BR), Peru (PE) and Colombia (CO). The project was developed by a consortium of Brazilian institutions with experience in Life Cycle Assessment (LCA) applied to construction products and Quantis, as presented in the data provider details.

The following construction products were modelled in this project: clinker, cement (according to the cement types applicable to each country) and concrete (various mix designs), for BR, PE and CO; and sand, gravel, granulated blast furnace slag, calcined clay, fibre-reinforced concrete and concrete block, only for BR. We decided to include these additional products in the Brazilian scope due to data availability and because previous research showed significant differences between Brazilian LCIs and existing ecoinvent datasets.

The first part of this report documents the development of the Brazilian datasets. The second part refers to Peru and Colombia.

Construction products manufacturing in Brazil

The construction sector represented 7,3% of the Brazilian Gross Domestic Product in 2016 and the manufacturing of construction products accounted for 11,8% of sector's value added[1], which shows the economic importance of this activity. Construction is also vital in terms of overcoming the development challenges Brazil must face, such as a big housing deficit and a general lack of infrastructure, including sanitation and transportation systems.

On the other hand, the construction industry is also responsible for many environmental impacts. Regarding the manufacturing of construction products, cement-based materials are particularly relevant, both in terms of unit impacts (per ton of product) and of consumption levels[2]. Clinker, the main constituent of cement, requires a high amount of thermal energy in its calcination process, which in turn causes atmospheric emissions related to many environmental impacts, mainly Global Warming Potential due to geogenic CO_2 release. The extraction of concrete aggregates, the grinding of raw materials in cement production (including blast furnace slag) and the energy required for concrete mixing are also main drivers of construction products' embodied impacts[3].

Modelling approach

Common issues

Deterministic value of amounts

Whenever a sample was available (of "n" factories), we calculated the weighted average of each flow to represent its amount, according to Equation 1 and Equation 2. This was the case of clinker, cement, gravel, normal concrete mixes and the concrete block.

$$\bar{x} = \sum_{i=1}^{n} x_i \, . \, w_i \quad \textbf{Equation 1}$$

$$w_i = {V_i}\Big/{\sum_{i=1}^{n} V_i} \quad \textbf{Equation 2}$$

$\bar{x}$: weighted average
x_i: value of unit flow for factory "i"

w_i: weight of factory "i"
V_i: production volume of factory "i"

The production volume of each factory was calculated in terms of mass. Histograms were drawn for each flow and outliers were excluded from the sample based on charts' analysis and expert opinion, whenever these outliers seemed to be data collection or reporting mistakes.

If no sample was available, the amount value was taken from the single value collected (sand, granulated blast furnace slag, fibre reinforced concrete).

Despite the need for converting the amounts into the parameters of the probability density functions used for uncertainty modelling, this conversion was not carried out, as explained in the next item.

Uncertainty modelling

For datasets based on samples, the weighted standard deviation was calculated using Equation 3.

$$wsd = \sqrt{\sum_{i=1}^{n} w_i . x_i^2 - \left(\sum_{i=1}^{n} w_i . x_i\right)^2}$$ **Equation 3**

wsd: weighted standard deviation

In the "ecoeditor for ecoinvent version 3" software (version 3.8.600.15190), the lognormal distribution is set by default when using mathematical relations to calculate the amounts. As most flows were expressed by mathematical relations for transparency reasons, the lognormal distribution was used. According to ecoinvent data quality guidelines[4], the parameters describing the lognormal distribution are the geometric mean (μ_g) and the variance of log-transformed data (unbiased variance of the underlying normal distribution - σ_b^2). Both parameters can be calculated using Equation 4 and Equation 5, respectively.

$$\mu_g \approx \frac{\bar{x}}{e^{(wsd^3/2)}}$$ **Equation 4**

$$\sigma_b = \sqrt{ln\left[\left(\frac{wsd}{\bar{x}}\right)^2 + 1\right]}$$ **Equation 5**

Thus, the weighted average and the weighted standard deviation should be converted into the lognormal distribution parameters. However, this was said to be an unusual procedure by the internal and ecoinvent reviewers, who requested us to use the weighted average in the amount field to keep consistency with existing ecoinvent datasets. The variance of the underlying normal distribution (σ_b) was calculated based on equation 5 still.

This implies a systematic error in the uncertainty results (when running Monte Carlo simulations for instance), as a different value is used in place of the geometric mean. It can be depicted from equation 4 that the weighted average is always higher than the geometric mean, and the difference is higher for high values of the sample's standard deviation.

When no sample was available, the variability was estimated via expert opinion with ranges of likely minimum and maximum values. In these cases, the lognormal distribution was fit either to the minimum or the maximum values of the ranges, assuming that they would correspond to the minimum/maximum values of the 95% confidence interval, as shown in Equation 6, Equation 7 and Equation 8.

$$min = \frac{\mu_g}{\sigma_g^2} \approx \frac{\bar{x}}{\sigma_g^2}$$ **Equation 6**

$$max = \mu_g.\sigma_g^2 \approx \bar{x}.\sigma_g^2$$ **Equation 7**

$$\sigma_g = e^{\sigma_b}$$ **Equation 8**

σ_g: geometric standard deviation

Pedigree scores

Additional uncertainty was rated using Pedigree scores. In addition to Table 10.4 from the Data Quality Guidelines for ecoinvent version 3[4], the following criteria were adopted to attribute scores to each flow:

- Reliability: "verification" was understood as means of checking the truth of information provided by manufacturers – for instance, comparison between electricity consumption and the corresponding electricity bill – and, as such, stricter than ecoinvent's definition of verification. Consequently, most flows based on primary data informed by manufacturers (directly to the project or to other data collection initiatives) were rated as 2 (non-verified data based on measurements);
- Completeness: the rating of completeness followed the criteria given in Table 10.4 regarding number of sites in relation to the country's total. Flows extrapolated from existing datasets had this score systematically adjusted to 5, as the representativeness of an extrapolated flow cannot be considered good;
- Temporal correlation: following the guidance of Table 10.4, the score was based on the difference of the data collection period to the period declared for the dataset (and not for the time of dataset development/submission). This score was not adjusted for flows which were extrapolated from existing datasets;
- Geographical correlation: as most data were gathered in Brazil, most flows are rated as 1. For flows extrapolated from existing datasets, the score was usually 5;
- Further technological correlation: we avoided attributing additional uncertainty in this category and for data gathered in Brazil it was rated as 1. For extrapolated datasets the existing score was maintained.

Local markets

Construction products usually have a heavy weight and are thus traded mostly locally. Therefore, local Brazilian market activities were created for all products modelled within this project, to account for product transportation to consumers.

Global datasets

Due to the structure of the ecoinvent database, all activities must have a corresponding global dataset. Therefore, some global datasets have been created from Brazilian ones to allow integration of Brazilian datasets into the database. However, it does not mean that there is a global market for certain products – cement types, for instance, are country-specific.

Infrastructure

As required by ecoinvent, infrastructure was informed for all datasets. However, developing inventories for infrastructure (buildings, industrial equipment, etc.) is a complex activity and thus, infrastructure information was extrapolated from existing datasets. Hence, high uncertainty is associated to those flows.

Clinker

General introduction

The clinker manufacturing process in Brazil is similar to the one described in the "Life Cycle Inventories of Building Products" report[5] and consists of mixing the raw meal (mainly composed of limestone and clay) and heating it in the rotary kiln for calcination and sintering of clinker, at temperatures up to 1450°C. Dry kilns are used in Brazil and about 50% of the factories include preheating and precalcining steps[6], recovering heat from the rotary kiln.

Clinker production is a fuel intensive process, with a thermal energy consumption of 3734 MJ/t clinker (weighted average for Brazil based on the data collected), including the drying of fuels. The main energy source are fossil fuels (in the case of Brazil, petroleum coke), but biomass and various waste types are also used – the use of waste fuels in the cement kiln is called "coprocessing". Figure 1 shows the distribution of thermal energy consumption by fuel types in Brazil.

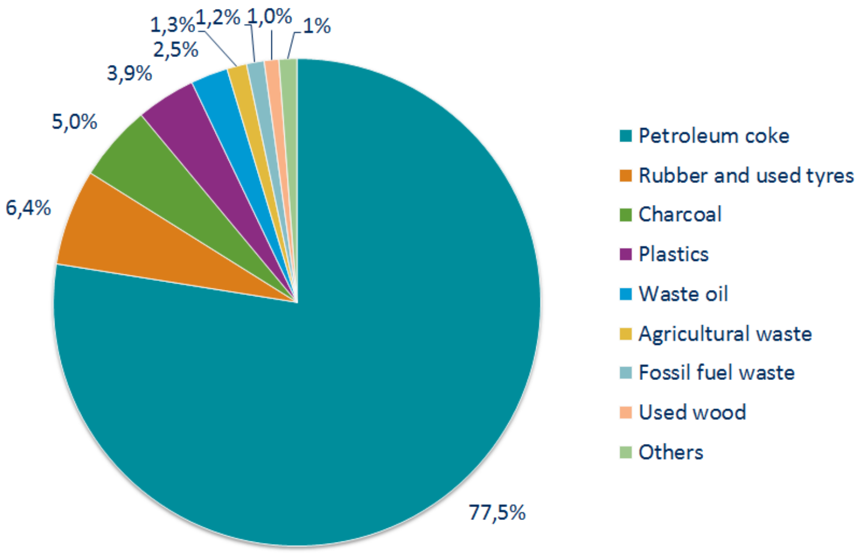

Figure 1 - Thermal energy sources for clinker production in Brazil.

Primary data were provided by six Brazilian cement manufacturers, which represent circa 70% of the total cement production volume of Brazil. They informed their total consumption of raw materials, auxiliary materials, fuels, electricity and water; as well as waste generation (which turned out to be negligible) and clinker production for the year of 2016, via a standard questionnaire. They also provided data from environmental monitoring for air emissions, namely pollutant concentrations in exhaust gas from the cement kiln and the exhaust air flow to enable converting concentrations into mass flows. Fuel lower heating values and CO_2 emissions factors were also informed to enable the calculation of unit CO2 emissions per kilogram of clinker produced.

Data submission was confidential. Questionnaires were sent by factory or manufacturer (some manufacturers preferred to inform total numbers for all factories grouped) through a submission platform developed by IPT, in a way that did not allow identification of each manufacturer. After compiling all data and calculating national weighted averages and standard deviations of the unit flows, a meeting was held with the collaborating manufacturers for data validation and elucidation of some questions. Manufacturers who deemed necessary to correct their questionnaires had the chance to submit the revised version, which was considered for the final data compilation.

System boundaries

From reception of raw materials and fuels at factory gate to the clinker cooled and stored in silos. Infrastructure and maintenance included. Some cement factories are located near limestone quarries and therefore, some manufacturers included quarry operation inputs in the reported flows; however, the contribution of these flows to total inputs for clinker manufacturing is negligible.

Description of the products

Clinker is the main raw material for cement and consists basically of calcium silicates (C2S, C3S), tricalcium aluminate (C3A) and calcium aluminoferrite (C4AF). After sintering, clinker nodules have a diameter between 5 mm and 25 mm.

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	1	-
Water in wet mass	kg	0	-
Water content	kg	0	-

Time and geographical boundaries

This dataset refers to the year of 2016, which corresponds to the date of information delivered by manufacturers. Geographical boundary is Brazil (country), as factories are distributed in all regions.

Technology level

Current technology mix, including dry kilns with preheater and precalciner (49%) and long dry kilns (51%)[6].

Calculation models

Unit flows were calculated for each manufacturer by dividing the total amount informed for the flow by the clinker mass (except for air emissions). Then, the weighted average of unit flows and the corresponding weighed standard deviation were calculated to represent each flow's amount and uncertainty, respectively, in the national inventory, using the clinker production volume as weighing factor. For some flows, such as auxiliary materials and air emissions, not all manufacturers reported all required values; in this case, they were excluded from the sample (and not considered zero). For flows admitting a zero value (e.g. a specific type of raw material that might not be used by all manufacturers), the zero value was attributed when necessary and all manufacturers were kept in the sample. The only flow extrapolated from clinker production/CH was "industrial machine, heavy, unspecified/GLO".

Fuel consumption was informed by manufacturers in mass or volume units. They were converted into energy units using their lower heating values in order to calculate CO_2 emissions from fuels, as CO_2 emission factors are given in terms of energy (Table 1).

Table 1 - Lower heating values and CO_2 emission factors of fuels used in clinker production.

	Fuel	Lower heating value		Fossil CO_2 emission (kg/GJ)	Biogenic CO_2 emission (kg/GJ)	Source
Conventional fuels	Diesel	35,6	MJ/L	74	0,0	Manufacturers
	Coal	23,6	MJ/kg	96	0	Manufacturers
	Fuel oil	40,2	MJ/kg	77	0	Energy: BEN16[7]; CO_2: CSI[8]
	Natural gas	36,8	MJ/m³	56	0	Energy: BEN16[7]; CO_2: CSI[8]
	Petroleum coke	33,2	MJ/kg	92	0	Manufacturers
	Charcoal	23,0	MJ/kg	0	84	Manufacturers
	Wood	13,0	MJ/kg	0	110	Energy: BEN16[7]; CO_2: CSI[8]
	Biodiesel	38,4	MJ/kg	69	5	Manufacturers
	Fossil fuel waste	30,0	MJ/kg	80	0	Estimated
Alternative fuels	Rubber and used tyres	22,1	MJ/kg	62	23	Manufacturers
	Waste oil	14,9	MJ/kg	74	0	Manufacturers
	Impregnated saw dust	11,6	MJ/kg	15	60	CETESB[9]
	Used wood	11,9	MJ/kg	0	110	Manufacturers
	Agricultural waste	18,0	MJ/kg	0	110	Manufacturers
	Industrial sludge	11,6	MJ/kg	110	0	CETESB[9]
	Plastics	30,8	MJ/kg	75	0	treatment of waste plastic, mixture, municipal incineration/ GLO
	Others	11,6	MJ/kg	80	0	CETESB[9]

Secondary raw materials and fuels were modelled as negative outputs (which equals a positive input) following ecoinvent guidelines[10].

Water consumption was sometimes informed by the manufacturers separately for clinker and cement production processes and sometimes in only one of these processes. As most plants are integrated, it can be difficult for manufacturers to perform this separation; therefore, the total amount of water for clinker and cement was summed for each manufacturer, and then this amount was equally divided (50%/50%) by these two production stages (this equal division is coherent with the numbers of those manufacturers who informed water consumption separately). Water is consumed mainly for cooling (of rotary kiln bearings and other equipment) and dust control and, as such, it was assumed that it evaporates. The exception is tap water, which was considered to be used for drinking and sanitary purposes and has a corresponding output of wastewater.

Parameters

No parameters were used.

Production volumes

The cement production volume for Brazil in 2016 was 57.556.901 t, according to the National Union of the Cement Industry[11]. The clinker factor calculated from the primary data gathered was 0,744. Hence, the clinker production volume for 2016 (time period of the dataset) is 4,28E+10 kg.

Market activities

The “market for clinker, BR” dataset was developed to represent the transportation of clinker to non-integrated cement plants. 24 of 88 plants in Brazil were assumed to be non-integrated, based on data from SNIC[12] and consultation of manufacturers’ websites (Figure 2).

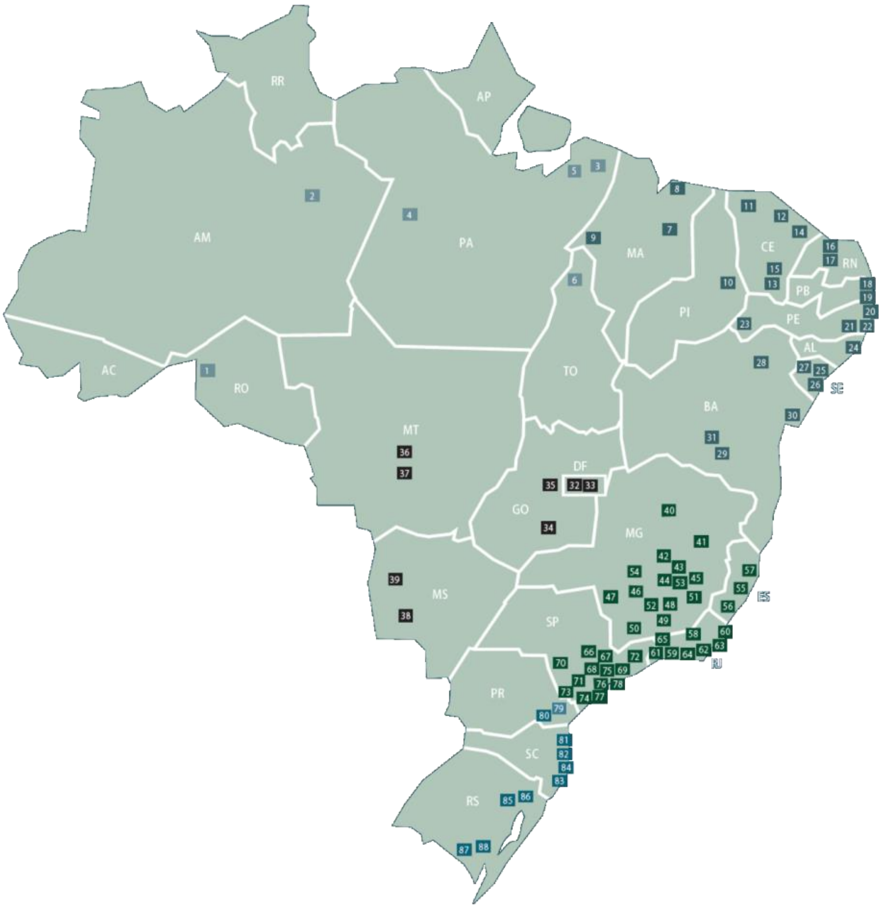

Figure 2 – Distribution of cement plants in Brazil[12].

The average transportation distance (500 km) was calculated considering equal weight for each plant, and that clinker will be transported from the closest clinker factory, preferably from the same manufacturing group. For integrated plants, transportation distance is set to zero. Routes were calculated using Google Maps and thus, high uncertainty is associated to this estimate.

Transportation modes were assumed equal to the cement transportation means (see cement item).

Cement

General introduction

Portland cement consists of a heterogeneous mixture of different compounds. Cement is chemically composed of (but not limited to) calcium silicates, calcium aluminate and ferroaluminate, calcium and magnesium oxides, alkalis (sodium and potassium), and calcium sulphates. Cement hydration process with water consists of simultaneous reactions of the compounds, yet not at same hydration rate (Mehta; Monteiro, 2006, p. 210-214)[13]. The highly reactive form of calcium silicates ($3CaO.SiO_2$ or "C3S") tends to quick-set the cement hydration, whereas the primary purpose of calcium sulphate is to retard this process. Industries add calcium sulphate to cement in the form of gypsum ($CaSO_4 \cdot 2H_2O$), hemihydrate ($CaSO_4 \cdot 1/2H_2O$), and anhydrite ($CaSO_4$) (Mehta; Monteiro, 2006, p. 212)[13].

Cement production starts after the main constituent, Portland clinker, is cooled from the rotary kiln. The clinker is ground in ball or roller mills to particles under 75 µm size. Then it goes to silos where cement is mixed with calcium sulphate (gypsum) and filler materials, such as milled limestone. It may also have supplementary cementitious materials (SCM's), such as slags and pozzolans. The mixed cement goes to a finishing mill and then it is stored in cement silos to be shipped, in bulk or packaged.

For blast furnace slag-blended cements: blast furnace slag is a byproduct of iron production (see specific item) and, when finely ground, it is also a cementing material with hydraulic properties. Slag hydration alone is too slow to give structural properties to cement, but when the slag is combined with Portland cement, the hydration is accelerated due to the extra amount of calcium hydroxide and gypsum (Mehta; Monteiro, 2006, p. 232)[13]. In Brazil, the blast furnace slag is granulated in the iron industry, but ground in the cement plant. This extra energy for grinding may be important; however, it is not evaluated due to the lack of specific data of energy consumption per type of cement (electricity consumption in cement plants are informed as a whole).

For pozzolan-blended cements: pozzolan materials are siliceous materials with no (or low) cementing property; however, when finely ground and in the presence of water, they react with the calcium hydroxide produced by clinker's hydration to form a cementing material[13]. Pozzolans can be natural materials, such as volcanic stones with natural pozzolanic activity, or artificial, including manufactured products (e.g. calcined clay) or byproducts from other industries (e.g. fly ash from coal thermal power plants).

Since the speed of hydration reaction for cements with additions of blast furnace slag or pozzolanic materials is lower than for Ordinary Portland cement, strength development is slower in cementitious products with this cement type, although final strength may reach similar levels of that of OPC. The addition of slags and pozzolans also lead to other changes in cement properties: lower hydration heat, better workability, reduced permeability, reduced porosity and increased durability[14].

Data collection

Data for the life cycle inventory of cements were collected from the same six cement manufacturers mentioned in the previous item (clinker), representing 70% of the national cement production volume (see details of data collection procedure in the clinker section). They informed the average composition of each cement type they produce, the consumption of electricity, water, auxiliary materials and fuels (for cement grinding and drying of raw materials); and cement production. Waste generation is negligible in this process.

Data refer to the year of 2016.

System boundaries

The activity starts with the reception of raw materials in the cement plant. In plants which are integrated with clinker production, clinker is stored in the silo after cooling in the upstream process.

The activity includes the drying of raw materials, the grinding and mixing of raw materials for cement production in the cement mill (with grinding aids) and ends with cement stored in silos, ready to be shipped or packaged. No particulate emission is considered due to lack of data – part of it is considered in the clinker dataset, as environmental monitoring measures are taken for the whole integrated plant. The dataset does not include packaging and administration.

Description of the products

These datasets describe the production of seven types of Portland cement production in Brazil, as presented in Table 2. The composition of each cement type set by the corresponding Brazilian standards is presented in Table 3. Table 4 shows the composition of the Brazilian cement datasets submitted to ecoinvent (weighted averages of primary data) – variations are represented by each flows' basic uncertainty.

Table 2 - Cement types for Brazil and corresponding technical standards.

Cement type	Name	Standard	Description
High early strength Portland cement	CP-V-ARI	ABNT NBR 5733[15]	Hydraulic binder that meets the requirements for high early-strength (34 MPa after 7 days), produced by the grinding of Portland clinker, constituted mainly of hydraulic calcium silicates, to which one or more forms of calcium sulphate is added. During grinding, it is possible to add to this mixture carbonaceous materials, in the proportions indicated in the Brazilian standard ABNT NBR 5733
Blast furnace slag Portland cement	CP-III	ABNT NBR 5735[16]	Hydraulic binder made by the homogeneous mixture of Portland clinker and granulated blast furnace slag, ground together or separated. During grinding, it is allowed to add one or more forms of calcium sulphate and carbonaceous materials in the proportions indicated in the Brazilian standard ABNT NBR 5735. The content of granulated blast furnace slag must be between 35% and 70% of the total binder mass.
Pozzolanic Portland cement	CP-IV	ABNT NBR 5736[17]	Hydraulic binder made by the homogeneous mixture of Portland clinker and pozzolanic materials, ground together or separated. During grinding, it is allowed to add one or more forms of calcium sulphate and carbonaceous materials in the proportions indicated in Brazilian standard ABNT NBR 5736. The content of pozzolanic materials must be between 15% and 50% of the total binder mass. Pozzolanic materials include natural pozzolans (from sedimentary or volcanic origin) and artificial pozzolans such as calcined clay, fly ash or other materials (acid steel slags, micro-silica, ashes from mineral coal residues, ashes from vegetable residues, etc.).
Portland composite cement	CP-II-F CP-II-E CP-II-Z	ABNT NBR 11578[18]	Hydraulic binder composed of Portland clinker, one or more forms of calcium sulphate and pozzolanic materials, granulated blast furnace slag and/or carbonaceous materials, added during grinding in the proportions indicated in the Brazilian standard ABNT NBR 11578.
Sulphate resistant cement	CP-V-RS	ABNT NBR 5737[19]	Hydraulic binder that meets the condition of resistance to sulphate, made by the grinding of Portland clinker together with one or more forms of calcium sulphate. During grinding it is allowed to add granulated blast furnace slag or pozzolanic materials and/or carbonaceous materials. Cements are considered sulphate resistant if the C3A content of clinker is equal to or lower than 8% and the content of carbonaceous additions is equal to or lower than 5% in relation to the total binder mass*. In the case of high early resistance cements (see NBR 5733), it is allowed to add blast furnace slag or pozzolanic materials. * CP-III with granulated blast furnace slag content higher than 60% and CP-IV with pozzolanic materials' content between 25% and 40% are also considered to be sulphate resistant.

Table 3 - Brazilian cement types and corresponding composition.

<table>
<tr><th></th><th>CP II-F</th><th>CP II-E</th><th>CP II-Z</th><th>CP III</th><th>CP IV</th><th>CP V ARI</th><th>CP V RS</th></tr>
<tr><td>Clinker + Sulphate (%)</td><td>90 - 94</td><td>56 - 94</td><td>76 - 94</td><td>25 - 65</td><td>25 - 65</td><td>95 - 100</td><td rowspan="4">Varies</td></tr>
<tr><td>Limestone (%)</td><td>6 - 10</td><td>0 - 10</td><td>0 - 10</td><td>0 - 5</td><td>0 - 5</td><td>0 - 5</td></tr>
<tr><td>Pozzolanic materials (%)</td><td>-</td><td>-</td><td>6 - 14</td><td>-</td><td>15 - 50</td><td>-</td></tr>
<tr><td>Granulated blast furnace slag (%)</td><td>-</td><td>6 - 34</td><td>-</td><td>35 - 70</td><td>-</td><td>-</td></tr>
</table>

Table 4 - Composition (average values) of Brazilian cement datasets submitted to ecoinvent.

	CP II-F	CP II-E	CP II-Z	CP III	CP IV	CP V ARI	CP V RS
Clinker (%)	86,0	65,8	74,0	39,7	58,7	88,9	75,0
Sulphate (gypsum) (%)	3,0	2,7	3,0	2,8	2,2	6,2	6,3
Phosphogypsum (%)[a]	2,1	2,0	1,4	-	1,4	0,3	-
Limestone (%)	8,9	7,6	9,9	3,3	5,0	4,6	4,4
Natural pozzolan (%)[b]	-	-	2,3	-	6,0	-	-
Fly ash (%)	-	-	2,3	-	16,1	-	1,9
Slags with pozzolanic activity (%)[c]	-	-	4,0	-	6,7	-	12,4
Calcined clay (%)	-	-	3,1	-	3,8	-	-
Granulated blast furnace slag (%)	-	21,9	-	54,2	-	-	-

Composition variability between manufacturers is represented in the datasets via the basic uncertainty factor.

[a] Phosphogypsum is a by-product of phosphoric acid production; however, the activity "phosphoric acid production, dihydrate process/GLO" includes the treatment of phosphogypsum and thus, there is no representative dataset for this secondary raw material. Therefore, it was modelled as normal gypsum with a proper remark in the flow's comment field.

[b] "Silica sand/GLO" was used as a proxy for natural pozzolans

[c] Manufacturers reported the use of slags from the production of nickel, copper and manganese. "nickel smelter slag/GLO" was used to represent this type of raw material used in pozzolanic cements

Cement compressive strength classes can be 25 MPa, 32 MPa or 40 MPa, depending on the cement type, its composition and the characteristics of its raw materials.

Properties

Cement type	Property	Unit	Value
cement, Portland (CP-V-ARI)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0
cement, limestone 6-10% (CP-II-F)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1

Cement type	Property	Unit	Value
	Water in wet mass	kg	0
	Water content	kg	0
cement, blast furnace slag 6-34% (CP-II-E)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0
cement, blast furnace slag 35-70% (CP-III)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0
cement, pozzolana and fly ash 6-14% (CP-II-Z)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0
cement, pozzolana and fly ash 15-50% (CP-IV)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0
cement, sulphate resistant (CP-V-RS)	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	1
	Dry mass	kg	1
	Water in wet mass	kg	0
	Water content	kg	0

Time and geographical boundaries

This dataset refers to the year of 2016, which corresponds to the date of information delivered by manufacturers. Geographical boundary is Brazil (country), as factories are distributed in all regions.

Technology level

The datasets represent typical current technology for average Brazilian cement production.

Calculation models

The composition of each cement type is based on the weighted average of the cement compositions informed by manufacturers. The basic uncertainty, modelled through the variance of the log-transformed data, represents the existing variations in cement composition between manufacturers. Not all manufacturers/factories produce all cement types, so the sample size was adjusted accordingly. The consumption of grinding aids was also based on the weighted average of the unit consumption for each cement type informed by manufacturers.

Consumption of materials for factory and equipment maintenance (lubricating oil, steel and rubber for replacement of wearing parts) and corresponding basic uncertainty were also calculated as a weighted average of the manufacturers who informed these numbers (not all manufacturers reported all required values; in this case, they were excluded from the sample). The only flow extrapolated from “cement production, Portland/CH” was the input of “cement factory/GLO”.

The datasets consider the industry aggregated average electricity used for the grinding of the clinker and additions (weighted average of electricity consumption informed by each manufacturer). Thus, no distinction of electricity consumption between different cement types is made, although different materials may require different energy consumption for grinding, such as SCM, gypsum, and limestone.

Some manufacturers reported the use of fuels for drying of raw materials. To calculate the weighted average of thermal energy consumption, a zero value was attributed to those manufacturers who did not report fuel consumption. To simplify the dataset, fuel consumption was converted into energy units to enable the use of the datasets “heat, district or industrial, natural gas/GLO” and “heat, district or industrial, other than natural gas/GLO”. It also allows accounting for the corresponding air emissions from fuel combustion.

Water inputs and outputs were modelled as described in the clinker section: 50% of the total water volume was assumed to be consumed in the cement production step, mainly for cooling and dust control, with 100% evaporation, except for tap water.

Parameters

No parameters were used in the different cement types datasets.

Production volumes

The share of each cement type in the market was applied to the total cement production in 2016 (57.556.901 t) according to Table 5. Data provided by SNIC[20] for 2013 – it was assumed that the distribution of production between cement types does not change significantly for different years and could thus be extrapolated for 2016. Public data had to be used for calculation of production volumes, because some manufacturers opted not to inform the exact amount of each cement type produced for confidentiality reasons.

Table 5 - Distribution of production volume in Brazilian cement types.

Cement type	Share	Remarks
CPI	0,4%	Portland Cement – not considered in this study
CPII	62,1%	Blended cements, three types included (20,7% per type): ‘cement, limestone 6-10%’; ‘cement, blast furnace slag 6-34%’; ‘cement, pozzolana and fly ash 6-14%’
CPIII	14,2%	‘cement, blast furnace slag 35-70%’
CPIV	14,8%	‘cement, pozzolana and fly ash 15-50%’
CPV	8,5%	High early strength cement, two types included (4,26% per type): ‘cement, Portland’ and ‘cement, sulphate resistant’.

Market activities

The market represents each cement type delivered at the consumption point in Brazil. The National Union of the Cement Industry estimated the average transport distances for cement as 400 km in Southeastern and Southern regions of Brazil, but high uncertainty is associated with it, as transportation distances can reach 1000 km in the Northern region (SNIC, 2013a, p.11[12]); thus, the basic uncertainty is adjusted for log-normal distribution considering the estimation of minimum and maximum distances (160 - 1000 km).

The data are considered representative for cement commercialization to construction activities in Brazil. The major part of cement is distributed by road, but there is also a share of train and barge transportation (SNIC, 2013b, p.23[12]), according to the table below:

Table 6 - Modal distribution of cement transportation in Brazil.

Transport type	Share
road	96,3%
train	2,9%
barge	0,8%

Granulated blast furnace slag

General introduction

The granulated blast furnace slag (GBFS) resembles a natural sand grain, with a more angular form. It has a glass content of over 95% and presents excellent hydraulic properties. GBFS usually goes through a subsequent grinding process, generating a supplementary cementitious material called ground granulated blast furnace slag (GGBFS). In Brazil, around 70% of the blast furnace slag used in cement making is grinded jointly with clinker. Therefore, this dataset focuses exclusively in the blast furnace slag granulation process, which happens in the steelmaking company.

Data collection

Blast furnace slag granulation was mainly based on primary data provided by one Brazilian steelmaking plant, representing an average condition of granulated blast furnace slag (GBFS) production in Brazil. Water and electricity consumption come from internal company reports, and granulated blast furnace slag daily production is measured by scales within the plant. Emissions data were extrapolated by Marceau and VanGeem (2003)[21], for the granulation and dewatering process. According to the company which provided primary granulation data, there is no mass loss within the granulation process.

System boundaries

The included modelled activities start from the generation of blast furnace slag from pig iron production and end with the granulation process itself. They include the water and electricity consumed for the granulation process, and emissions that arise from it. Infrastructure, machinery and administration activities are not included.

Description of the product

This dataset represents the intermediate treatment of 1 kg of raw blast furnace slag, producing an output of 1 kg of granulated blast furnace slag. Granulation happens in the steelmaking process, prior to transportation to cement making companies, for further joint grinding with clinker.

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	1	-
Water in wet mass	kg	0	-
Water content	kg	0	-

Time and geographical boundaries

The LCI was based on primary company data from January to June of 2017. The dataset’s start of period date was set to 2015 since the granulation process's technology as modeled has been available for some time already.

Technology level

Granulation is performed using pressurized cold water jets, which is a current technology.

Calculation models

Since the granulation was based on one company's data, calculation was quite straightforward. The steelmaking company states there is no mass loss during their granulation process. Blast furnace slag is listed as a negative reference product (output), which is equal to say that it is a positive input. Since blast furnace slag is a byproduct of the pig iron production, the inverted sign merely allows the different calculation algorithms involved in each available system model (regarding multifunctionality modelling) to take place.

Particulate matter (PM) emission was taken from Marceau and VanGeem (2003)[21]. PM (dust) is generated during the "breaking" of slag through contact with pressurized cold water.

The water consumption documented value is actually 21,38% of the total water used for granulation. The 78,62% that was not included in the dataset modelling is recirculated within the company. For mass balance purposes, evaporated water was also included in the dataset as an emission to air.

Parameters

No parameters were used in the granulation dataset.

Production volumes

The blast furnace slag production volume documented in the dataset is related to 2014, listed in a chapter within the book entitled "Materiais de construção civil e Princípios de Ciência e Engenharia dos Materiais", published by the Brazilian Concrete Institute in 2017[22]. The total blast furnace slag production in Brazil is actually 7,38E+9 kg. However, only 7,24E+9 kg are granulated - the rest is reused within the steel industry for sintering purposes, or directed to other potential uses. The granulated blast furnace slag production volume was published in the 2016 Cement Industry Energy and CO2 performance - Getting the numbers right (GNR) for Brazil[23]. Data referred to the year of 2014.

Market activity

GBFS production is characterized as a constrained market. It is not fully elastic, which means that in a case when demand is higher than supply one of the uses of GBFS will be affected by this shortage.

The GBFS is used in the cement production as a substitute for Portland cement. In case of shortage of GBFS on the market it is the cement production which will be affected and will start using another product.

The market activity represents the transportation of GBFS from the steelmaking plant (granulation) to the cement plant (consumption point). Average distance was calculated based on the distances from all the Brazilian steelmaking companies associated to the Brazilian Steel Institute to their closest cement plants. The average distance calculated is 159 km. Transportation is done by lorries 16-32 t.

Calcined clay

General introduction

Calcined clay is a pozzolanic material used as a supplementary cementitious material in cement production. It is produced by grinding and heating natural clay (with proper mineral composition) between 500°C and 900°C. The addition of calcined clay to cement results in higher sulphate resistance of the hydrated paste and in low permeability of the cementitious matrix, thus increasing the durability of cementitious products[24].

Data collection

This dataset is based on key process parameters informed by one cement manufacturer in Brazil, namely electricity consumption and fuel (petroleum coke) consumption for grinding and calcination operations (part of the data is published in Vieira and Machado, 2015[25]). Corresponding air emissions from petroleum coke combustion are modelled based on emission factors from IPCC. The exact representativeness of this dataset on a national scale is unknown, since the manufacturer did not inform its annual production volume.

System boundaries

The activity starts with the reception of the raw material (clay) and fuels in the calcining plant. Quarrying operations are not included.

The activity includes the grinding and calcination of clay and ends with the calcined clay ready to be shipped (production of 1kg calcined clay). No particulate emission is considered due to lack of data. The dataset does not include packaging, administration and infrastructure.

Description of the product

Calcined clay is produced by grinding and heating natural clay between 500°C and 900°C. This thermal treatment, also called “activation”, converts crystalline clay materials to amorphous alumino silicates. When added to cement, amorphous silica reacts with calcium hydroxide formed during calcium silicate hydration from cement, forming C-S-H (hydrated calcium silicate). Secondary reactions may occur due to the reactive alumina content of calcined clay, forming also C-A-H (hydrated calcium aluminate)[26].

Calcined clay is one of the types of pozzolanic materials that can be used for cement production. These materials are standardized by the Brazilian technical standard ABNT NBR 12653[27].

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	1	-
Water in wet mass	kg	0	-
Water content	kg	0	-

Time and geographical boundaries

The LCI was based on primary company data from 2015. Geographical boundary is Brazil.

Technology level

Clay is ground in mills and calcined in rotary kilns, which is considered current technology.

Calculation models

Both electricity and thermal energy consumption were informed as unit flows (kWh/ton and MJ/ton). Thermal energy was converted to fuel consumption using the lower heating value of petroleum coke informed by IPCC[28]. Air emissions from petroleum coke combustion were calculated using greenhouse gas emission factors of IPCC[28]. These information are presented in Table 7.

Table 7 – Lower heating value and greenhouse gas emission factors of petroleum coke given by IPCC.

Factor	Value
Lower heating value (MJ/kg)	32,5
CO_2 emission factor (kg/GJ)	97,5
CH_4 emission factor (kg/GJ)	0,003
N2O emission factor (kg/GJ)	0,0006

Parameters

No parameters were used in this dataset.

Production volumes

The annual calcined clay production volume was estimated using the calcined clay proportion in cement composition and the estimated production volumes of the corresponding pozzolanic cement types (for 2016) (see Table 8).

Table 8 - Calcined clay production volume calculation.

Cement type	Calcined clay content (kg/kg)	Cement production volume (kg)	Total calcined clay production volume (kg)
CP-II-Z	0,031	1,2E+10	7,0E+08
CP-IV	0,038	8,5E+09	

Market activity

The market activity of calcined clay represents its transportation until the consumption point (cement plants). It was assumed that the average distance is equal to the transportation distance of granulated blast furnace slag (159 km) and that transportation is done by heavy lorries (>32t).

Sand

General introduction

Sand is a material widely used in construction, in the composition of various types of mortars, concrete and concrete artifacts. There are mainly two types of sand in Brazil: natural quartz sand, which can be extracted from alluvial deposits (open pits) or riverbeds; and artificial sand, produced from rock crushing[29]. The sand datasets developed in this project refer to natural sand for the construction industry (circa 90% of sand consumption[29]) and should not be extrapolated to represent sand production for other purposes (industry, water treatment, etc.).

In Brazil, circa 70% of natural sand are extracted from riverbeds and 30% from open pits[30]. The production process consists in general of extraction, transportation, classification into grain sizes, drying and loading of trucks for sand delivery:

- **Open pit:** the dataset describes the wet mining process. The topsoil is removed by conventional excavation equipment and then pit slopes are excavated with high pressure water jets sprayed against them. The force of water disintegrates the slope and the sand-water pulp accumulates at the bottom of the pit. This pulp is then pumped to the cyclone for classification. The classification is done in the “cyclone”, an equipment with integrated sieves which separates water from the sand fines. Solids accumulate at the bottom of the cyclone and the water is released in the overflow pipe at the top of the cyclone. After decantation of the extremely fine particles in a decantation tank, water is returned to the process. Sand is released from the cyclone with a high water content and dries naturally.

- **Riverbed:** pumps dredge the slurry, which consists of sand, water, clay, silt, and gravel, from the river bed. Suction Hopper Dredger (autonomous vessels that perform all stages of sand mining, i.e., extraction, loading, transport, and unloading) is considered. Extraction and loading stages are executed by centrifugal pumps powered by diesel engines. The pulp is pumped through the pipeline up to the vessel top where it is poured into steel sieves. Coarse materials (gravel, leaves, and sticks) are retained by the sieves and are returned to the river. The rest of the slurry (sand, water, and mud) falls into big chambers inside the vessel. Sand decants faster from the slurry, due its density and size, and deposits at the chamber's bottom. Most of the water overflows from the vessel to the river, carrying a great amount of the mud (silt and clay). Auxiliary suction pumps drain water surplus from the sand to lower the cargo weight. After completing the extraction and loading stages, the same vessel transports the dredged sand until loading ports. The pulp is then pumped to the loading port by pipelines to semi-closed chambers at the loading port. Sand deposits at the bottom of the port's chambers, water returns to the river carrying part of the fines. Some companies may sort the sand by grain size in this stage. In the end, sand is washed to clean the fines and is transported by heavy equipment to storage piles.

Beware that sand used for industrial mortar production must be totally dried and therefore, this dataset is not representative of dry sand.

Data collection

- **Open pit:** data were collected in one quarry located in São Paulo, which produces mainly medium sand.
- **Riverbed:** Data collection is mainly based on literature review. Estimate of diesel consumption was based on the annual production of sand from river bed deposits in the state of Rio Grande do Sul and on fuel consumption data gathered from dredge specifications. Complementary primary data were collected from one company's loading port, located in the state of Rio Grande do Sul (Brazil), thus with limited representativeness on a national scale. Data regarding building infrastructure and maintenance of rubber and steel parts were approximated from data for sand extraction from open pits in Brazil.

Although electricity and fuel consumption include the size classification step, sand output is not presented in terms of particle sizes due to lack of data.

System boundaries

From reception of fuels at quarry gate and extraction of sand to the sand air-dried and loaded in trucks for delivery (open pit) or stored in piles (riverbed). Dataset includes machinery and infrastructure based on rough estimates. Removal of top soil layer (for the open pit dataset) and the quarries' end of life were not considered due to lack of data.

Description of the products

According to the Brazilian standard ABNT NBR 7211[31], fine aggregates (which include sand) have a particle size of less than 4,75mm. Commercial sand grain size classification adopted in Brazil is: fine sand (0,15mm -1,2mm), medium sand (0,3mm - 2,4mm) and coarse sand (2,4mm – 4,75mm), based on the superseded version of ABNT NBR 7211.

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	0,95	-
Water in wet mass	kg	0,05	Sand is not totally dry at the end of the process.
Water content	kg	0,0526	-

Time and geographical boundaries

- **Open pit:** dataset refers to the year of 2016, corresponding to the data collection period. Geographical boundary is Brazil (country), despite the low representativeness (additional uncertainty adjusted accordingly).
- **Riverbed:** The period is set to the year 2015 as the data were collected in the year 2015. Geographical boundary is Brazil (country), despite the low representativeness (additional uncertainty adjusted accordingly).

Technology level

- **Open pit:** current technology for hydraulic mining, most common process for open pit sand mining in Brazil.
- **Riverbed:** typical technology for sand dredging in Brazil, though the data has low representativeness in the national scale.

Calculation models

- **Open pit:** unit flows for diesel, electricity, steel and rubber (replacement of wearing parts) were calculated by dividing the amounts of inputs/outputs by the total sand production in mass. Land use was modelled based on information of 2016 provided by the quarry manager, and unit flows were calculated by dividing the areas by the respective accumulated production until then, which was calculated by multiplying the yearly production of 2016 with the total operation years until 2016 (41 years) – production records for the past not available. Building hall area was calculated from aerial images of the quarry. Basic uncertainty was extrapolated from the variations between quarries observed for gravel extraction in Brazil (assumed to have a similar behavior) and additional uncertainty was estimated using Pedigree scores.
- **Riverbed:** the total diesel consumption is calculated by Equation 9:

$$Diesel\ consumption = \mathrm{dredging} + \mathrm{transport} + \mathrm{port} \qquad \textbf{Equation 9}$$

dredging: diesel consumption during dredging operation;
transport: diesel consumption during transport operation;
port: diesel consumption for the port operations.

Calculation for the dredging operation: during the dredging process, the pulp has a share of water and sediments, including the sand. An estimation of 20% sediments: 80% water is used for the pulp constitution with 10m depth dredging (ALMEIDA, 2003, p.71[32]). The sediments' constitution is based on literature in the Patos Lagoon with 10 m of depth (CALLIARI; TAGLINI, 1997 apud TORRES, 2000[33]), according to Table 9.

Table 9 - Sediment composition for riverbed sand extraction in Patos Lagoon (Brazil).

Sediment	Share
Gravel	0,42%
Sand	53,32%
Silt	27,36%

Clay	18,79%

For this amount of sediments and water the pulp's composition was calculated for the dataset reference unit (1 kg of sand), according to Table 10.

Table 10 - Pulp composition - riverbed sand extraction.

Composition	Amount	Unit	Density	Unit
Sand	1,00E+00	kg	2650	kg/m³
Gravel	7,88E-03	kg	2680	kg/m³
Silt	5,13E-01	kg	2680	kg/m³
Clay	3,52E-01	kg	2650	kg/m³
Water	7,49E+00	kg	1000	kg/m³
Total	9,37E+00	kg	-	-

The volume of the pulp was estimated with Equation 10:

$$V = \sum_{i=1}^{n} \frac{m_i}{\rho_i} \quad \textbf{Equation 10}$$

V: volume; m_i: mass of pulp component “i”; ρ_i: density of pulp component “i”.

This gives a pulp density of 1143 kg/m³. There is 122 kg sand per m³ of pulp.

The theoretical data of one industry in Brazil is considered for the dredging pumps with 10 m of head height. Then the diesel consumption is pondered by the production of the reference product. The result is multiplied by two considering the pulp needs to be dredged in and out of the vessels (Table 11).

Table 11 - Diesel consumption for sand dredging.

Dredge type (m³/h)	Diesel consumption (l/h)	l/m³ pulp	kg sand/m³ pulp	Diesel consumption (l/kg sand)
700	9	0,013	122	2,11E-04
700	12	0,017		2,81E-04
900	15	0,017		2,73E-04
2100	30	0,014		2,34E-04

The average value of the different types of dredges is used for the amount of diesel during dredge operations.

The amount of diesel during the vessel transport (port-mine-port) was estimated from ecoinvent process "transport, freight, inland waterways, barge tanker/GLO". The mentioned dataset was not considered a representative proxy for transport in the sand production, given differences in the infrastructure (vessel, canal, etc.). Thus, only its diesel consumption is present in the sand dataset.

The amount of diesel during the port operations is taken from unverified measures of one producer in the state of Rio Grande do Sul.

Parameters

- **Open pit:** no parameters were used.
- **Riverbed:** see next table.

Parameter	Meaning
diesel consumption for pump operations	Calculated value for diesel used in the mining process with pumps for dredging. Theoretical data for pump's flows and consumptions obtained from one pump industry in Brazil. Flows rates can vary from 700 up to 2100 m3/h (head height of 10 m). Diesel consumption for the pumps is in average 16,7 liter/h. (Itubombas, Commercial specification for the pumps http://itubombas.com.br/arquivos/especificacoes-tecnicas.pdf)
diesel consumption for transport operation	Calculated value, liters of diesel used in the internal transport within the industrial process. Sand is mined with "Suction Hopper dredgers", that is, barges that transport the sand from the river to the port, diesel consumption was estimated from the ecoinvent process "transport, freight, inland waterways, barge tanker/GLO". The transport considers 1kg for 55km of distance (measured distance mine-port of one industry).
diesel consumption for port operation	Measured value, a non-verified measurement from one company. Diesel used for port operations with excavators, liter per kg of produced sand.

Production volumes

The total production volume of sand reported for 2014 is 391.765.746t[29]. The production volume was extrapolated to 2016 based on data of cement consumption for those years[20] and assuming that sand consumption would behave proportionally, resulting in an annual sand volume for 2016 of 266.023.033t, 30% of it being extracted from open pits (79.806.909t) and 70% of riverbeds (186.216.123t).

Based on the production volumes informed by the quarries that delivered the data for this project, representativeness is estimated as 0,12% for the open-pit dataset (in relation to total open-pit sand production) and 0,14% for the riverbed dataset (in relation to total riverbed sand production).

Market activities

The most part of the sand commercialization cost is its transportation cost[30] and, as sand is an abundant resource, it is usually extracted near its potential consumers, except for some regions where this resource is becoming scarce due to high consumption (e.g. São Paulo)[29].

Transport distance was based on information provided by 33 concrete block manufacturers, who estimated the distance to the gravel deposits of their suppliers. The average distance is 60.35 km, but high uncertainty is associated with it. Estimation of lorry's size is based on the cargo fleet from 5 sand companies in the south of Brazil (0.54% with 3.5-7.5 t; 12.64% with 7.5-16 t; 58.67% with 16-32 t; 28.16% with >32t).

Gravel

General introduction

Crushed stone (gravel) is a material widely used in construction, mainly in concrete, concrete artifacts and as a base layer for pavements and floors. In Brazil, the main rock types used for crushed stone production are granite and basalt.

Natural stone is quarried by drilling and explosion in open pits. The large stone blocks extracted from the pit are loaded into large trucks by shovels and transported to the crushing equipment by trucks, which run on diesel. The first crushing step takes place in a large jaw crusher, followed by subsequent screens (vibrating screens) and crushers (gyratory or impact crushers) connected by conveyor belts. Crushing equipment is powered by electricity. The process produces gravel of different sizes. Water sprays are used for dust control in the crushing process, using harvested rainwater. Gravel is not washed.

Data collection

Data were collected in 3 quarries located in the State of São Paulo, Brazil. Data refer to a 12 month period. Although finer stones require more crushing energy than coarse ones, no distinction between gravel sizes was done, due to lack of detailed information.

Information was provided by quarry managers. Land use was modelled based on aerial pictures of the quarries. Infrastructure was estimated based on specification of industrial equipment and on manufacturer catalogues.

System boundaries

From the mining of stone (granite or basalt) in open pits by blasting and drilling to the crushed stone loaded into trucks for delivery. Removal of the top soil layer (overburden) is not considered. Land use for mine operation included but the quarry's end-of-life not, due to lack of data and specific legislation (some quarries remain open for leisure; others may be transformed into waste landfills, etc.). Infrastructure included.

Description of the product

Crushed gravel used as aggregate for construction, usually applied for concrete production or as a raw material in pavement subbase. According to the Brazilian standard NBR 7211[34], coarse aggregates have a particle size between 4,75 mm and 75 mm. Commercial gravel sizes adopted in Brazil are the following: #0 (2,4–12,5mm), #1 (4,8-25mm); #2 (9,5-32mm), #3 (19-50mm) and #4 (32-76mm), based on the superseded version of NBR 7211.

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	1	-
Water in wet mass	kg	0	-
Water content	kg	0	-

Time and geographical boundaries

Data represent one year of quarry operation in 2015 or 2016 according to the quarry. Data from a small sample and a specific state (São Paulo) is extrapolated to represent the whole country, with the associated additional uncertainty.

Technology levels

Current technology for crushed gravel production in Brazil.

Calculation models

Unit flows were calculated for each quarry, by dividing the amounts of inputs and outputs by the total gravel production in mass, regardless of gravel size. The unit flows of the dataset are the simple average of each quarries' unit flows – as the sample is small, a weighted average could lead to a wrong estimate.

Lifetime of the quarry was considered 80 years.

Particulate emission was modelled using emission factors for crushed stone processing developed by US-EPA[35], for total particulate matter (TPM), PM-10 and PM-2.5. Particulate matter fractions were calculated as following.

$$PM_{2.5\ to\ 10mm} = PM10 - PM2.5$$ **Equation 11**

$$PM > 10 = TPM - PM10$$ **Equation 12**

The US-EPA does not provide emission factors for the quarrying process (blasting) due to poor quality test data. As the blasting process used in the dataset only includes the emissions from the explosive (and not from the disaggregated stone), particulate emission is significantly underestimated for this process. Modelling of particulate emissions in open systems remains a challenge.

Parameters

No parameters were used in this dataset.

Production volumes

The total production volume of gravel reported for 2014 is 308.828.808t[29]. The production volume was extrapolated to 2016 based on data of cement consumption for those years[20] and assuming that gravel consumption would behave proportionally, resulting in an annual gravel volume for 2016 of 2,097E+11 kg.

Based on the production volumes informed by the quarries that delivered the data for this project, representativeness is estimated as 2,1%.

Market activities

Transport distance was based on information provided by 33 concrete block manufacturers, who estimated the distance to the gravel deposits of their suppliers. The average distance is 23,8 km, but high uncertainty is associated with it. Estimation of lorry's size was assumed to be the same of sand market dataset.

Ready-mix concrete

General introduction

Ready mix concrete production consists on mixing cement, aggregates, admixtures and water in a predefined proportion, using an automatic dosing central. The proportioned mix is discharged in the concrete delivery truck. Part of the water is stored in a reservoir within the truck and may be added in the construction site, for consistency adjustment, within the limits of the water/cement ratio. The concrete mix designs are used for building structures in general, including residential, commercial and industrial uses.

Data collection

Seven different concrete companies provided data on their concrete mix designs (basically cement (amount and type), aggregates, water and admixtures consumption per m^3 of concrete). One of these seven companies provided quantities for other flows related to infrastructure maintenance (water, rubber, lubricating oil and electricity) from 34 different factories. The concrete making plants were spread out around the Southeast, South, Northeast and Center-west regions of Brazil.

There are, in total, 60 ready-mix concrete production companies in Brazil[36]. The representativeness of the datasets ranges from 3,3% to 10%, depending on concrete's strength class and cement type used – some concrete types' mixes were provided by almost all seven companies, while others were provided only by two or three companies (please refer to the table on "calculation models").

System boundaries

The included modelled activities start from reception of raw materials at the ready-mix plant gate and end before the delivery of concrete at the construction site. The dataset includes the whole manufacturing processes to produce ready-mixed concrete, internal processes (material handling and mixing) and infrastructure.

Description of the product

The 24 modeled datasets describe concrete with compressive strength varying from 25 to 40MPa, with three cement types: cement with blast furnace slag addition (6-34% or 35-70%), and cement with limestone addition (6-10%) (Table 12).

Table 12 - Concrete mix designs of the submitted datasets.

25 MPa						
Cement type	**CP-II-E**		**CP-II-F**		**CP-III**	
Materials	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**
Cement	234	3%	258	10%	305	8%
Natural sand	472	29%	482	35%	719	36%
Artificial sand + gravel	1509	12%	1421	13%	1185	18%
Water	174	3%	186	5%	184	17%
Superplasticizer admixture	-	-	0,109	302%	0,654	188%
Polyfunctional admixture	1,815	5%	1,996	35%	1,140	118%
30 MPa						
Cement type	**CP-II-E**		**CP-II-F**		**CP-III**	
Materials	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**
Cement	283	11%	295	10%	330	9%
Natural sand	468	28%	483	34%	639	56%
Artificial sand + gravel	1477	11%	1389	12%	1311	24%
Water	176	2%	185	5%	178	20%
Superplasticizer admixture	0,362	240%	0,283	261%	1,382	114%
Polyfunctional admixture	1,744	43%	2,018	52%	0,774	200%
35 MPa						
Cement type	**CP-II-E**		**CP-II-F**		**CP-III**	
Materials	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**	**Weighted average**	**Coef. of variation**
Cement	315	8%	329	9%	370	10%
Natural sand	423	27%	462	33%	588	51%
Artificial sand + gravel	1477	10%	1406	10%	1277	22%
Water	179	5%	187	5%	179	14%
Superplasticizer admixture	0,126	412%	0,144	300%	0,929	151%
Polyfunctional admixture	2,282	28%	2,544	33%	1,598	111%

40 MPa						
Cement type	CP-II-E		CP-II-F		CP-III	
Materials	Weighted average	Coef. of variation	Weighted average	Coef. of variation	Weighted average	Coef. of variation
Cement	358	6%	385	8%	416	18%
Natural sand	403	22%	389	30%	474	64%
Artificial sand + gravel	1460	9%	1340	12%	1110	10%
Water	178	2%	183	5%	180	17%
Superplasticizer admixture	0,193	346%	0,334	236%	0,697	188%
Polyfunctional admixture	2,566	32%	2,826	39%	1,975	116%

Properties

For specific remarks please refer to "Calculation models".

Concrete type	Property	Unit	Value
concrete production, 25 MPa, with cement blast furnace slag 6-34%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2390
	Dry mass	kg	2271
	Water in wet mass	kg	119
	Water content	kg	0,0524
concrete production, 25 MPa, with cement blast furnace slag 35-70%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2367
	Dry mass	kg	2254
	Water in wet mass	kg	113
	Water content	kg	0,050133
concrete production, 25 MPa, with cement limestone 6-10%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2349
	Dry mass	kg	2223
	Water in wet mass	kg	126
	Water content	kg	0,05668
concrete production, 30 MPa, with cement blast furnace slag 6-34%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2406
	Dry mass	kg	2295
	Water in wet mass	kg	111
	Water content	kg	0,0483
concrete production, 30 MPa, with cement blast furnace slag 35-70%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2348
	Dry mass	kg	2247
	Water in wet mass	kg	101
	Water content	kg	0,0449
concrete production, 30 MPa, with cement limestone 6-10%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2354
	Dry mass	kg	2237
	Water in wet mass	kg	117

Concrete type	Property	Unit	Value
	Water content	kg	0,0523
concrete production, 35 MPa, with cement blast furnace slag 6-34%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2395
	Dry mass	kg	2288
	Water in wet mass	kg	107
	Water content	kg	0,0468
concrete production, 35 MPa, with cement blast furnace slag 35-70%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2385
	Dry mass	kg	2290
	Water in wet mass	kg	95
	Water content	kg	0,0415
concrete production, 35 MPa, with cement limestone 6-10%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2386
	Dry mass	kg	2275
	Water in wet mass	kg	111
	Water content	kg	0,0488
concrete production, 40 MPa, with cement blast furnace slag 6-34%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2401
	Dry mass	kg	2305
	Water in wet mass	kg	96
	Water content	kg	0,0416
concrete production, 40 MPa, with cement blast furnace slag 35-70%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2182
	Dry mass	kg	2098
	Water in wet mass	kg	84
	Water content	kg	0,0400
concrete production, 40 MPa, with cement limestone 6-10%	Carbon content, fossil	dimensionless	0
	Carbon content, non-fossil	dimensionless	0
	Wet mass	kg	2299
	Dry mass	kg	2205
	Water in wet mass	kg	94
	Water content	kg	0,0426

Time and geographical boundaries

The LCI was based partly on Brazilian literature data from 2015 and mostly from mix designs provided by Brazilian companies in 2017.

Technology levels

The datasets represent typical current technology for average Brazilian concrete production.

Calculation models

The data on concrete mixes are a weighted average of a number of mix designs provided by the seven concrete making companies consulted in this project. For some concrete types, such as "concrete production, 35 MPa, with cement blast furnace slag 6-34%", the averages were based on up to 20 different mix designs. For other, such as "concrete production, 25 MPa, with cement blast furnace slag 35-70%", only 4 mix designs fed the weighted average calculation. Table 13 shows specific information for each concrete type modeled.

Table 13 - Number of data providers for each concrete mix design and corresponding representativeness.

Concrete type	Number of mix designs for average calculation	Representativeness
concrete production, 25 MPa, with cement blast furnace slag 6-34%	17 mix designs, from 2 different companies	3,33%
concrete production, 25 MPa, with cement blast furnace slag 35-70%	4 mix designs, from 4 different companies	6,67%
concrete production, 25 MPa, with cement limestone 6-10%	19 mix designs, from 5 different companies	8,33%
concrete production, 30 MPa, with cement blast furnace slag 6-34%	20 mix designs, from 6 different companies	10%
concrete production, 30 MPa, with cement blast furnace slag 35-70%	4 mix designs, from 4 different companies	6,67%
concrete production, 30 MPa, with cement limestone 6-10%	19 mix designs, from 6 different companies	10%
concrete production, 35 MPa, with cement blast furnace slag 6-34%	18 mix designs, from 6 different companies	10%
concrete production, 35 MPa, with cement blast furnace slag 35-70%	6 mix designs, from 5 different companies	8,33%
concrete production, 35 MPa, with cement limestone 6-10%	18 mix designs, from 5 different companies	8,33%
concrete production, 40 MPa, with cement blast furnace slag 6-34%	13 mix designs, from 5 different companies	8,33%
concrete production, 40 MPa, with cement blast furnace slag 35-70%	4 mix designs, from 4 different companies	6,67%
concrete production, 40 MPa, with cement limestone 6-10%	18 mix designs, from 4 different companies	6,67%

For other flows, the weighted average was calculated from several different concrete plants (26 for process water, 34 for rubber parts and lubricating oil, 29 for electricity), belonging to one of the 7 concrete making companies that provided data. Basic uncertainty was calculated from the coefficient of variation of the sample.

Diesel consumption and waste generation values were taken from a national published paper[37]. For other materials used for maintenance (steel parts) and infrastructure, data were extrapolated from the dataset "concrete production 25 MPa, RNA only/GLO".

“Gravel, crushed” was used as a proxy for artificial sand in all concrete datasets. This input then refers to the amount of gravel + artificial sand in each mix modeled.

The input “chemical, organic/GLO” refers to the consumption of polyfunctional admixture, superplasticizers and plasticizers. Companies sometimes provided this information in a volume unit. In those cases, we used density values published in the admixture’s manufacturer’s website to convert their unit.

The dry mass value of each concrete mix was calculated considering the combined water. Water consumed for total cement hydration = 23% of cement mass according to Neville & Brooks (2013)[38]. Thus: dry mass = wet mass - mix water + 0,23*cement.

The water in wet mass values refers to water contained in fresh concrete, that evaporates during curing. It does not include combined water (cement hydration). As a consequence, the datasets are not water balanced according to ecoinvent guidelines.

Parameters

The following parameter was applied to all flows that are directly embedded into concrete (namely cement, sand, gravel, water and admixtures):

Parameter	Meaning
losses	losses due to returned concrete from construction sites.

Production volumes

Estimated value, based on the following information:

- Cement production in Brazil in 2016[11]: 57.475.901 t;
- Amount of cement used by ready-mix concrete companies[36]: 21%;
- General average consumption of cement for ready-mix concrete[36]: 280 kg/m³;
- Amount of concrete produced for 2016 (calculated from previous numbers): 43.106.926 m³.

The production volume of each combination of strength class and cement type was calculated by multiplying the numbers presented in Table 14 and Table 15.

Table 14 - Brazilian concrete production per strength class[36].

Company size	Share of national production volume (installed capacity)	Share of ready-mix concrete strength class		
		20 MPa	25/30 MPa	35/40 MPa
Small	7%	30%	58%	6%
Medium	16%	11%	78%	11%
Large	76%	0%	89%	11%
	Average share of strength class	4%	84%	11%
	Production volume	1.663.927	36.287.410 *	4.543.470 *
* Value can be equally divided into the 2 strength classes				

Table 15 - Cement consumption for ready-mix concrete production divided by cement type.

Company size	Share of cement type used for ready-mix concrete production					
	CP-II-E*	CP-II-F	CP-II-Z	CP-III	CP-IV	CP-V
Small	21%	19%	19%	14%	18%	9%
Medium	35%	3%	18%	30%	13%	1%
Large	17%	11%	6%	30%	19%	17%
Average	21%	10%	9%	29%	18%	14%
* inferred						

Market activity

Markets were defined only by the compressive strength class, regardless of cement type, as ready-mix concrete is usually specified only by the strength class and the cement type depends mainly on local availability (except for special concrete mixes, which are not the case of these datasets). Hence, markets combine different cement types, based on their respective share in terms of production volume in the specific strength class.

Transportation until the construction site with mixer trucks is considered. Distances are based on sector-specific information declared by ready-mix concrete manufacturers. Average distance is said to be 24,45 km and the maximum distance 64,25 km. The basic uncertainty coefficient of the lognormal distribution was adjusted to these parameters.

Fibre-reinforced concrete

General introduction

The dataset represents the production of fibre-reinforced concrete used for the production of industrial floor in Brazil. This concrete contains discrete long steel fibres acting as the reinforcement material for structural strength.

Fibre reinforcement is employed replacing totally or partially the conventional structural reinforcement in concrete industrial floors, road pavements, and tunnel linings. Fibre serves as bridge transferring the stress in the concrete cracks, acting as structural reinforcement[39]. Fibres also reduce water bleeding, reducing concrete permeability. Even improving concretes properties, the market for fibre-reinforced concrete is small compared to ordinary concrete. The world consumption of fibres in concrete was estimated to be 300,000 tons in 2006[40].

"Reinforcing steel/GLO" is used as a proxy for steel fibre reinforcement.

The dataset represents the production of fresh concrete and includes the water to be added at the construction site for consistency adjustment. Exchange properties are declared for the fresh concrete. Concrete dry mass considers the amount of water that reacts with cement to form hydrates. Consequently, this dataset is not water balanced according to ecoinvent guidelines.

Data collection

Data for the concrete ingredients, except for fibre content, were taken from one company with low representativeness in Brazil for industrial floor applications. The fibre incorporation is made by the client at the construction site in different proportions; since small fibre content does not affect the dosage of other concretes ingredients[41].

Data on concrete are based on the design mix for 35 MPa fibre-reinforced concrete used for industrial floor, from one ready-mix concrete company. For fibre content, an estimated value from different sources is set considering literature values. For a fibre content lower than 50 kg/m^3, concrete compressive strength is not affected and concrete workability is minimally influenced[42].

For other flows, the weighted average was calculated from several different concrete plants (26 for process water, 34 for rubber parts and lubricating oil, 29 for electricity), belonging to one of the 7 concrete making companies that provided data for normal ready-mix concrete for Brazil.

Other data for the life cycle inventory (materials used for maintenance and infrastructure) were extrapolated from ecoinvent activities: concrete production, 25MPa, with cement blast furnace slag 6-34%/BR (accessed 20.11.2017) and concrete production, 25 MPa, RNA only/GLO (accessed 10.10.2017).

System boundaries

From reception of raw materials at the ready-mix plant gate. This activity ends before the delivery of concrete at the construction site. The dataset includes the whole manufacturing processes to produce ready-mixed fibre-reinforced concrete, internal processes (material handling and mixing) and infrastructure. It includes fibre addition, although it happens in the construction site.

Description of the product

This concrete has a compressive strength (fck) of 35 MPa. The production considers ready-mix concrete with blended cement (cement, limestone 6-10%). Ingredients for 1 m^3: cement 357 kg, water 200 kg, gravel 913 kg, sand 724 kg, polyfunctional admixture 3,57 kg, steel long fibre 25 kg.

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	2307	-
Dry mass	kg	2189	-
Water in wet mass	kg	118	-
Water content	kg	0.0539	Automatic calculation

Time and geographical boundaries

The mix designs are from 2017; literature data are estimated from different years. Time period is set to 2016. Geographical boundary is Brazil.

Technology level

Technology existent for fibre-reinforced concrete production in Brazil, for industrial floors only.

Calculation models

The data on concrete mix was given by one industry in the Brazil for industrial floors.

Concrete ingredients' basic uncertainty for the lognormal distribution was calculated considering a coefficient of variation of 10%, based on the coefficients of variation calculated for the ready-mix concrete datasets for BR, so that data represent the variation expected for the whole country.

The dry mass value of each concrete mix was calculated considering the combined water. Water consumed for total cement hydration = 23% of cement mass according to Neville & Brooks (2013)[38]. Thus: dry mass = wet mass - mix water + 0,23*cement.

The water in wet mass values refers to water contained in fresh concrete, that evaporates during curing. It does not include combined water (cement hydration). As a consequence, the datasets are not water balanced according to ecoinvent guidelines.

Parameters

The following parameters were used:

Parameter	Meaning
losses	Literature value. Losses due to returned concrete from construction sites.

Production volumes

Production volume and proportion per strength class derived from a report published by the Brazilian Association for Portland cement in 2013. Production volumes adjusted to 2016 based on more recent data for cement consumption from ABCP. Proportion of steel fibre reinforced concrete in relation to total ready-mix concrete from three experts' opinion.

Market activity

This dataset represents 1m³ of fibre-reinforced ready-mix concrete delivered at the construction site. Average transportation distance was taken from literature.

Concrete block

General introduction

Concrete blocks are used for structural and non-structural walls. In Brazil, they are standardized by ABNT NBR 6136:2014 (Hollow concrete blocks for concrete masonry – Requirements). Concrete blocks may have various compressive strength classes, being the minimum 3 MPa for non-structural blocks and typically ranging from 4 to 20 MPa for the structural blocks. They may also have various nominal dimensions: width (6,5 cm, 9 cm, 11,5 cm, 14 cm and 19 cm), height (fixed in 19 cm) and length (29 cm or 39 cm), which consider a mortar joint between blocks of 1 cm thickness. Concrete blocks are modular and as such, masonry is built using multiple components from the same dimension family, like the "half-block", the "one-and-a-half block", etc.

The manufacturing process begins by dosing and mixing the cement, aggregates and water to make concrete. Unlike the "concrete block/GLO" dataset, which uses "concrete, normal/GLO" (ordinary ready-mix concrete) as input, the concrete used here has a dry consistency.

The mixed concrete is transported to the block machine by conveyor belts. In the block machine, the steel cast is filled with concrete and the block is shaped and compacted by vibration. There are various types of block machines with different degrees of automation; this dataset does not make any distinction among them.

The fresh concrete block is then transported to the curing chambers. Curing promotes cement hydration and strength gain and can be done in the following ways: 1) in closed chambers with no water addition; 2) wet cure, spraying water over the blocks; 3) with steam, for faster strength gain and lower shrinkage levels.

After curing the blocks are packed in pallets and stored. It is common to produce various types and shapes of concrete blocks in a single factory, as well as concrete pavers.

Data collection

Data collection was done by a previous project, carried out by the Polytechnic School of the University of São Paulo (EPUSP), the Brazilian Council for Sustainable Construction (CBCS), the Brazilian Association of the Concrete Block Industry (BlocoBrasil) and the Brazilian Association of Portland Cement (ABCP), covering a 12 month period between 2012 and 2013. The dataset contains data from 25 factories located in 6 different states in the Southern and Southeastern regions of Brazil and is considered representative of the current Brazilian technology mix for concrete block production. Representativeness is estimated by association experts as 50% of the national production volume.

System boundaries

From reception of raw materials at factory gate to the concrete block packed and stored in the factory. Infrastructure and maintenance are not included due to lack of data.

Description of the products

This dataset describes a concrete block with 4 MPa characteristic compressive strength and dimensions (14 x 19 x 39 cm). The concrete mix is 0,057 kg cement Portland : 0,38 kg sand : 0,62 crushed gravel (for 1 kg concrete block).

Properties

Property	Unit	Value	Remark
Carbon content, fossil	dimensionless	0	-
Carbon content, non-fossil	dimensionless	0	-
Wet mass	kg	1	-
Dry mass	kg	0,95	-
Water in wet mass	kg	0,05	We assumed 5% humidity (expert guess)
Water content	kg	0,052632	-

Time and geographical boundaries

The dataset refers to the years of 2012 and 2013. Geographical boundary is Brazil (country).

Technology level

Current technology mix, including various types of block machines and curing procedures. Splitting data into different technologies was not possible, as production processes and manufacturer names were kept confidential during data collection.

Calculation models

Factory production volumes considered their total production (all types of blocks and pavers) in mass.

The concrete mix was calculated as following: only the cement content was declared by manufacturers. Concrete block mass is composed by cement, aggregates, water that reacts with cement and humidity. Water for hydration was assumed to be 23% of cement mass[38] and humidity was assumed to be 5% of concrete block mass; thus, aggregate consumption was calculated by subtracting other components from the block mass (1 kg) (Equation 13). The total consumption of sand and gravel in each factory was taken to divide the amount of aggregates into the specific products (Equation 14 and Equation 15); however, this is an approximation due to lack of more specific data. As the mix is theoretical, its flows were multiplied by the loss factor informed.

$$agr = 1 - cem - 0{,}23.cem - 0{,}05$$ **Equation 13**

$$sand = \left(\frac{total\ sand}{total\ sand + total\ gravel}\right).agr$$ **Equation 14**

$$gravel = \left(\frac{total\ gravel}{total\ sand + total\ gravel}\right).agr$$ **Equation 15**

agr: aggregate share in concrete block mass
sand: sand share in concrete block mass
gravel: gravel share in concrete block mass

total sand: total sand consumption in the factory
total gravel: total gravel consumption in the factory

For the electricity, fuels and water input flows, as well for waste output flows, their amount was calculated by dividing the total consumption in the period by the total mass of products manufactured in the same period, which means an implicit mass allocation for these items. However, declaring all multiple outputs of different concrete blocks and pavers was not possible due to lack of data.

Five fuel types were reported by manufacturers, used for internal transportation and/or for steam curing: diesel, liquefied petroleum gas, natural gas, heavy fuel oil and firewood. Not all manufacturers use all fuel types and thus, an “energy mix” was calculated, considering a zero value for those manufacturers who did not report using a specific fuel. As a consequence, there is a high variability of these flows among manufacturers.

Fuel consumption was converted into thermal energy using lower heating values presented in Table 16 to enable the use of heat production datasets, which also allows considering the corresponding air emissions. The following heat production datasets were used: “propane, burned in building machine/GLO” (proxy for combustion of liquefied petroleum gas); “heat production, natural gas, at boiler modulating > 100 kWh/GLO”; “heat production, heavy fuel oil, at industrial furnace 1 MW/GLO” and “heat production, mixed logs, at furnace 100 kW/GLO”.

Table 16 - Heating values for fuels used in concrete block production.

Fuel	Parameter	Value	Unit	Source
Diesel	Net heating value	42,8	MJ/kg	Ecoinvent[43]
	Density	0,84	kg/L	Ecoinvent[43]
Heavy fuel oil	Net heating value	40,2	MJ/kg	IPCC[44]
Natural gas	Net heating value	48	MJ/kg	IPCC[48]
	Density	0,00074	kg/L	Brazil National Energy Balance[45]
Liquefied petroleum gas	Net heating value	47,3	MJ/kg	IPCC[48]
	Density	0,552	kg/L	Brazil National Energy Balance[45]
Firewood	Net heating value	15,6	MJ/kg	IPCC[48]

Water input was calculated based on factory data, divided by source: tap water, river or well. Harvested rainwater was not considered due to high uncertainty in measurement of its quantity. Water output was calculated considering a 50% evaporation rate (and 50% effluent), based on previous work, and using Equation 16 and Equation 17.

$$water\ input = water\ added + 0{,}05 * sand + 0{,}05 * gravel$$ **Equation 16**

$$water\ output = water\ input - 0{,}23.\,cem.\,(1 + losses) - 0{,}05.\,(1 + losses)$$ **Equation 17**

Parameters

The following parameters were used.

Parameter	Meaning
cement content	concrete mix, informed by manufacturers, without losses
share of fraction A	sand content, calculated, without losses
share of fraction B	gravel content, calculated, without losses
share of fraction C	block humidity (5%)
losses	calculated from primary data
reaction water	23% of cement mass, from literature, for total cement hydration
water input_added water	water added by manufacturers
water input_aggregates	water contained as humidity in sand and gravel (5%, assumed)
water_output	total water output, subtracting hydration and humidity
fraction, water, to water	50%, measured in one factory
fraction, water, to air	50%, measured in one factory

Production volumes

The yearly production informed by the Association (BlocoBrasil) is of 1,2 billion blocks. Considering the average unit mass of 12,45kg/block, it corresponds to 1,49E10 kg.

Market activity

The market activity considers the transportation of the block to the consumer, which can be a construction site or a retailer. The transportation distance informed by the association (BlocoBrasil) is between 1 km and 70 km, which were used as the minimum and maximum values of the uniform distribution. No losses during transportation were considered. Transport means assumed for this market activity is a transportation lorry 16-32 metric ton, EURO 3 emission standard.

Results

Discussion and hotspots

During life cycle inventory development, life cycle impact assessment (LCIA) results[1] were calculated as an additional means of verifying data quality (e.g. possible mistakes in orders of magnitude). LCIA results of Brazilian datasets were compared to "Rest of the World" (RoW) datasets. Significant relative differences (often higher than 50%) were observed between LCIA results from BR and RoW datasets, especially in impact categories/methods that have wide amplitude for characterization factors of different substances, such as toxicity-related impact categories. This shows the importance of having primary representative data of local conditions in international databases.

Alone the difference between BR and RoW results was not sufficient for data verification; therefore, a hotspot analysis was carried out for all products, to see if intuitive expectations for hotspots would agree with the results. The main environmental hotspots for the inventories developed in this project are presented in Table 17.

Table 17 - Main environmental hotspots.

Product	Hotspot
Clinker	The process itself is the main hotspot for most impact categories related to air emissions. Electricity is the hotspot for some categories, including ozone depletion, land use and water consumption (due to hydropower share in the Brazilian energy matrix). Fuel production processes appear as hotspot for eutrophication and some toxicity-related categories.
Cements	The main hotspot for cements is clinker, followed by electricity.
Granulated blast furnace slag	The upstream process that generates blast furnace slag is the hotspot for most impact categories. The process itself is a hotspot for water consumption
Calcined clay	The main hotspot is clay quarrying. The calcination is the hotspot for global warming, while electricity is the hotspot for water consumption.
Sand	Diesel consumption and corresponding air emissions from its combustion. The process itself is a hotspot for land use and water consumption.
Gravel	Surprisingly, the "blasting" process appears as a hotspot for most impact categories – as we used an existing dataset to represent the use of a generic explosive, this shows a need for data quality improvement. As this result was unexpected, we checked again the amount of explosives informed by the data providers (3,7E-04 kg/kg gravel) and compared it with literature values, concluding that the adopted value is plausible and in the same order of magnitude of literature (around 2,7E-04 kg/kg gravel[49]). The process itself is a hotspot for land use, while electricity is a hotspot for water consumption and diesel combustion a hotspot for GWP.

[1] Using ReCiPe Midpoint H, CED and Selected LCI results.

Product	Hotspot
Ready-mix concrete and concrete block	The main hotspot is cement, for all strength classes and cement types. Gravel also shows a relevant contribution to ozone depletion, ozone formation, acidification and toxicity. Sand appears as a hotspot for land use.
Fibre-reinforced concrete	The main hotspots are cement and the “reinforcing steel” used as proxy for the steel fibres. Sand also appears as hotspot for land use.

In terms of mineral resource scarcity, infrastructure is often the hotspot, as most impact assessment methods have high characterization factors for metals, which are not part of the construction products modelled in this project (except for fibre-reinforced concrete). Minerals used as raw materials for construction products, such as limestone, sand, basalt, etc. are considered abundant and have therefore a low or no characterization factor in LCIA methods. Infrastructure also appears as a hotspot for toxicity in some products, due to toxic emissions arising from metallic products' manufacturing processes.

At the end of the project, LCIA results were provided by ecoinvent, calculated using the ILCD LCIA method for the cut-off system[2]. These results were analyzed and hotspots only show minor changes. However, two missing flows were identified during this analysis — water harvested from rainwater and lignite — and the lack of these flows caused significant differences from some impact categories of ILCD. This problem was reported to the ecoinvent Centre[3], who committed to fix these inconsistencies before releasing the next version of the database.

Recommended improvements

During this project, some improvement needs were identified, presented below in separate categories: improvements required for the own datasets (Brazilian data) and improvements recommended for ecoinvent.

Brazilian datasets

The main improvement required for Brazilian datasets is increasing their representativeness. This is the case of sand, gravel, calcined clay and granulated blast furnace slag datasets, which are based on one or few data providers. This is required especially for aggregates, as there are many small sites spread in the country and process flows depend on aggregate characteristics that vary according to their location. Ready-mix concrete dataset representativeness can also be increased.

ecoinvent

Some datasets required for inventory development were not available and proxies had to be used; hence, one recommended improvement would be developing specific datasets for those products, as indicated in Table 18. Proxies that were deemed to be appropriate were not included in this list.

[2] Results sent on 27.04.2018.
[3] On 04.05.2018.

Table 18 – Proxy datasets and recommendation for new datasets' development.

Product / process	Proxy	Activity that uses it	Remarks
Use of explosive for quarrying operations	Blasting/GLO	gravel production, crushed	Besides being a proper proxy, it is a hotspot for gravel production, so its uncertainty should be minimized
Biodiesel	Vegetable oil methyl ester/GLO	clinker production	-
Industrial sludge	Sewage sludge, dried/GLO	clinker production	-
Impregnated saw dust	Waste wood/GLO Waste paint/GLO	clinker production	-
Mill scale	Iron scrap/GLO	clinker production	-
Phosphogypsum	Gypsum, mineral/GLO	cement production	The dataset "phosphoric acid production, dehydrate process/GLO" models the treatment of phosphogypsum inside that process, separating the processes would allow to use that output.
Natural pozzolan	Silica sand/GLO	pozzolan-blended cement production	-
Fly ash	hard coal ash/GLO	pozzolan-blended cement production	-
Metallurgical slags (Ni, Cu, Mn)	nickel smelter slag/GLO	pozzolan-blended cement production	-
Steel fibres	reinforcing steel/GLO	fibre-reinforced concrete	-
Burning of liquefied petroleum gas	propane, burned in building machine/GLO	concrete block	-

Another important improvement is the development of a standardized procedure for calculating particulate emission in open systems, like quarries. Unlike chimneys whose air flow can be measured and used for converting particulate concentration (measured by companies for legal environmental reports) into particulate mass flow (e.g. clinker dataset), in open systems the amount of air cannot be determined, which hinders this conversion – we had access to primary particulate concentration data though. Existing reports and datasets that inform particulate emission in open systems are not clear about the calculations involved, and many existing datasets extrapolate particulate emissions from others (e.g. the "gravel production, crushed/GLO" dataset extrapolates it from "limestone quarry operation/GLO", which in turn extrapolates it from "bauxite mine operation/GLO").

There are also some improvements indicated regarding the ecoquery submission interface:

- Detach the automatic use of the lognormal distribution to model uncertainties from the use of mathematical formulas to express the amounts. This would enable the

- use of simpler probability distributions (e.g. uniform) to model flows' variabilities and avoid so many mathematical conversions (to the variance of log-transformed data). It could also avoid the inconsistency between the amount and the actual weighted average that should be used as the central parameter of the lognormal distribution (as discussed in the "common issues" section);
- Enable the modelling of uncertainties for "negative reference products" (secondary fuels or raw materials). We had to inform it in the specific comment fields.

Regarding uncertainty, we recommend to improve the guidance for its modelling and calculation of main parameters from well-known ones (e.g. coefficient of variation) to increase the use of primary data for variability modelling. Data gathered in this project show that actual variability is significantly higher than the basic uncertainty factors suggested by ecoinvent, which should also be revised – in our understanding, these estimates should be conservative and hence, higher than measured variability.

Final remarks

This project developed 26 transformation datasets for several cementitious construction products and their main raw materials: clinker, 7 Brazilian cement types, 12 concrete mixes, fibre-reinforced concrete, concrete block, granulated blast furnace slag, calcined clay, sand and gravel. In addition to that, 18 market datasets representing materials' transportation were delivered. These materials are widely used in building and infrastructure construction in Brazil and compose a big share of the mass of constructed assets, as they are part of heavy construction elements such as foundations, building structure (walls, beams, columns, slabs) and cementitious coverings and mortars. Therefore, the development of these datasets directly contributes with the increase of data quality and representativeness for LCA studies developed for Brazil and may encourage the use of this method for environmental performance assessment in the construction sector.

The availability of local, good quality and representative life cycle inventories also helps raising awareness about the environmental impacts of construction products and about the importance of taking environmental aspects into consideration in decision making processes. As datasets include information about flows variability between different manufacturers, it also helps setting a national benchmark of environmental performance, to which manufacturers can compare their scores and assess improvement alternatives. It would be valuable to carry out similar data collection initiatives for other construction products as well.

References

1. Gonçalves, R. *Perfil da Indústria de Materiais de Construção.* (FGV Projetos, ABRAMAT, 2017).

2. Scrivener, K. L., John, V. M. & Gartner, E. M. *Eco efficient cements.* (2016).

3. John, V. M. in *Materiais de Construção Civil e Princípios de Ciência e Engenharia dos Materiais* (ed. Isaia, G. C.) 97–121 (IBRACON, 2017).

4. Weidema, B. P. *et al. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Swiss Center For Life Cycle Inventories* **3,** (2013).

5. Kellenberger, D. *et al. Life Cycle Inventories of Building Products. ecoinvent report No. 7* (2007).

6. Cement Sustainability Initiative. Global Cement Database on CO2 and Energy Information - "Getting the Numbers Right" (GNR). (2014). Available at: http://www.wbcsdcement.org/index.php/key-issues/climate-protection/gnr-

database. (Accessed: 12th December 2017)

7. Brazilian Energy Research Company (EPE). *Brazilian Energy Balance 2016: Year 2015*. (2016).

8. Cement Sustainability Initiative. *CO2 and energy accounting and reporting standard for the cement industry - version 3.0*. (2011).

9. CETESB. *Procedimento para utilização de resíduos em fornos de produção de clínquer - P4.263*. (2003).

10. Moreno Ruiz, E., Lévová, T. & Valsasina, L. *Guidelines for data providers to the ecoinvent database*. *Ecoinvent* (2017).

11. SNIC. Produção nacional de cimento por regiões e estados 2016. (2016). Available at: http://snic.org.br/assets/pdf/numeros/1513362481.pdf. (Accessed: 15th November 2017)

12. SNIC. *Sindicato Nacional da Indústria do Cimento - Relatório Anual 2013*. (2013).

13. Mehta, P. & Monteiro, P. *Concrete: microstructure, properties, and materials*. *Concrete* (McGraw-Hill, 2006). doi:10.1036/0071462899

14. ABCP. Guia básico de utilização do cimento Portland - BT-106. 28 (2002).

15. ABNT. *NBR 5733 - Cimento Portland de alta resistência inicial*. (ABNT, 1991).

16. TÉCNICAS, A.-A. B. D. E. N. *NBR 5735 - Cimento Portland de alto-forno*. 4–8 (ABNT, 1991).

17. TÉCNICAS, A.-A. B. D. E. N. *NBR 5736 Cimento Portland pozolânico*. (ABNT, 1991).

18. TÉCNICAS, A.-A. B. D. E. N. *NBR 11578: Cimento Portland composto*. 5 (ABNT, 1991).

19. ABNT. *NBR 5737 - Cimentos Portland resistentes a sulfatos*. 4 (ABNT, 1992).

20. SNIC. Produção nacional de cimento por regiões e estados 2014. (2014).

21. Marceau, M. & VanGeem, M. G. *Life Cycle Inventory of Slag Manufacuring Process*. (2003).

22. *Materiais de construção civil e Princípios de Ciência e Engenharia dos Materiais*. (IBRACON, 2017).

23. CSI. Global Cement Database on CO2 and Energy Information - "Getting the Numbers Right" (GNR). (2014).

24. Barger, G. S. *et al.* Production and Use of Calcined Natural Pozzolans in Concrete. *Cem. Concr. Aggregates* **23,** 73 (2001).

25. Vieira, S. R. S. S. & Machado, J. E. in *Cement Plant Environmental Handbook* (2015).

26. Silva, M. G. in *Materiais de Construção Civil e Princípios de Ciência e Engenharia dos Materiais* (ed. Isaia, G. C.) 761–794 (IBRACON, 2007).

27. ABNT. *NBR 12653 - Materiais pozolânicos - Requisitos*. 6 (ABNT, 2014).

28. Gómez, D. R. *et al.* Chapter 2: Stationary Combustion. *2006 IPCC Guidel. Natl. Greenh. Gas Invent.* 47 (2006). doi:10.1016/S0166-526X(06)47021-5

29. DNPM. *Sumário Mineral 2015*. **35,** (2015).

30. MME. *Perfil de areia para construção civil*. (2009).

31. ABNT. *NBR 7211 - Agregados para concreto - Especificação*. 1–8 (ABNT, 2005). doi:01.080.10; 13.220.99

32. Almeida, A. dos S. in *MINERAÇÃO & MUNICÍPIO - BASES PARA PLANEJAMENTO E GESTÃO DOS RECURSOS MINERAIS* (eds. Tanno, L. C. & Sintoni, A.) (2003).

33. Torres, R. J. Uma Análise Preliminar dos Processos de Dragagem do Porto de Rio Grande, RS. (2000).

34. TÉCNICAS, A.-A. B. D. E. N. *NBR 7211 - Agregados para concreto - Especificação*. 1–8 (ABNT, 2005). doi:01.080.10; 13.220.99

35. USEPA. 11.19.2 Crushed Stone Processing and Pulverized Mineral Processing. *Compilation of Air Pollutant Emission Factors, Volume I: Stationary Point and Area Sources, AP-42* 1–17 (2004).

36. Taniguti, E. & ABCP. *Panorama e tendências técnico-mercadológicas do setor de concreto*. (2013).

37. Castro, A. L., Silva, F. B., Arduin, R. H., Oliveira, L. A. & Becere, O. H. Análise da viabilidade técnica da adaptação de dados internacionais de inventário de ciclo de vida para o contexto brasileiro : um estudo de caso do concreto para paredes moldadas no local. in *Anais do 57º Congresso Brasileiro do Concreto* 1–16 (IBRACON, 2015).

38. Neville, A. M. & Brooks, J. J. *Tecnologia do Concreto*. (Bookman, 2013).

39. Figueiredo, A. D. de & Ceccato, M. R. Workability Analysis of Steel Fibre Reinforced Concrete Using Slump and Ve-Be Test. *Mater. Res.* **18,** 1284–1290 (2015).

40. Mehta, P. & Monteiro, P. *Concrete: microstructure, properties, and materials. Concrete* (McGraw-Hill, 2006). doi:10.1036/0071462899

41. Figueiredo, A. D. de & Ceccato, M. R. Workability Analysis of Steel Fibre Reinforced Concrete Using Slump and Ve-Be Test. *Mater. Res.* **18,** 1284–1290 (2015).

42. Figueiredo, A. D. de & al., et. Mix design method of steel fibre reinforced concrete for pavements. in *Anais do 48º Congresso Brasileiro do Concreto* (ed. IBRACON) 1–15 (IBRACON, 2006).

43. Weidema, B. P. *et al. Overview and methodology - Data quality guideline for the ecoinvent database version 3. Swiss Center For Life Cycle Inventories* **3,** (2013).

44. Garg, A., Kazunari, K., Pulles, T. & IPCC -Intergovernmental Panel on Climate Change. in *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy* **2,** 29 (2006).

45. EPE. *Balanço Energético Nacional 2016: Ano base 2015*. (2016).

46. IPCC. IPCC Emission Factor Database. Available at: http://www.ipcc-nggip.iges.or.jp/EFDB/main.php. (Accessed: 19th September 2017)

47. IPCC. IPCC Emission Factor Database.

48. Garg, A., Kazunari, K., Pulles, T. & IPCC -Intergovernmental Panel on Climate Change. in *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2: Energy* **2,** 29 (2006).

49. Koppe, J. C. & Costa, J. F. C. L. in *Manual de Agregados para Construção Civil - CETEM* (eds. Almeida, S. L. M. de & Luz, A. B. da) 23 (CETEM, 2009).

Appendix 1

List of datasets created (Brazilian scope)

Activity name	Geogra-phy	Reference product
cement production, blast furnace slag 6-34%	BR	cement, blast furnace slag 6-34%
market for cement, blast furnace slag 6-34%	BR	cement, blast furnace slag 6-34%
cement production, blast furnace slag 35-70%	BR	cement, blast furnace slag 35-70%
market for cement, blast furnace slag 35-70%	BR	cement, blast furnace slag 35-70%
cement production, pozzolana and fly ash 6-14%	BR	cement, pozzolana and fly ash 6-14%
market for cement, pozzolana and fly ash 6-14%	BR	cement, pozzolana and fly ash 6-14%
cement production, pozzolana and fly ash 15-50%	BR	cement, pozzolana and fly ash 15-50%
market for cement, pozzolana and fly ash 15-50%	BR	cement, pozzolana and fly ash 15-50%
cement production, limestone 6-10%	BR	cement, limestone 6-10%
market for cement, limestone 6-10%	BR	cement, limestone 6-10%
cement production, Portland	BR	cement, Portland
market for cement, Portland	BR	cement, Portland
cement production, sulphate resistant	BR	cement, sulphate resistant
market for cement, sulphate resistant	BR	cement, sulphate resistant
clinker production	BR	clinker
market for clinker	BR	clinker
concrete block production	BR	concrete block
market for concrete block	BR	concrete block
concrete production 25 MPa, with cement, blast furnace slag 6-34%	BR	concrete, 25MPa
concrete production 25 MPa, with cement, limestone 6-10%	BR	concrete, 25MPa
concrete production 25 MPa, with cement, blast furnace slag 35-70%	BR	concrete, 25MPa
market for concrete, 25MPa	BR	concrete, 25MPa
concrete production 30 MPa, with cement, blast furnace slag 6-34%	BR	concrete, 30MPa
concrete production 30 MPa, with cement, limestone 6-10%	BR	concrete, 30MPa
concrete production 30 MPa, with cement, blast furnace slag 35-70%	BR	concrete, 30MPa
market for concrete, 30MPa	BR	concrete, 30MPa
concrete production 35 MPa, with cement, blast furnace slag 6-34%	BR	concrete, 35MPa
concrete production 35 MPa, with cement, limestone 6-10%	BR	concrete, 35MPa
concrete production 35 MPa, with cement, blast furnace slag 35-70%	BR	concrete, 35MPa
market for concrete, 35MPa	BR	concrete, 35MPa
concrete production 40 MPa, with cement, blast furnace slag 6-34%	BR	concrete, 40MPa
concrete production 40 MPa, with cement, limestone 6-10%	BR	concrete, 40MPa
concrete production 40 MPa, with cement, blast furnace slag 35-70%	BR	concrete, 40MPa
market for concrete, 40MPa	BR	concrete, 40MPa
fibre reinforced concrete production	BR	fibre reinforced concrete

Activity name	Geogra -phy	Reference product
market for fibre reinforced concrete	BR	fibre reinforced concrete
gravel production, crushed	BR	gravel, crushed
market for gravel, crushed	BR	gravel, crushed
granulated blast furnace slag production	BR	granulated blast furnace slag
market for granulated blast furnace slag	BR	granulated blast furnace slag
sand production, extraction from open pit	BR	sand
sand production, extraction from river bed	BR	sand
market for sand	BR	sand
calcined clay production	BR	calcined clay
market for calcined clay	BR	calcined clay

Appendix 2

List of datasets cited during the text and corresponding access date.

Ecoinvent activity name	Geography	Reference	Referred to in this report as
clinker production	CH	clinker production, CH, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	clinker production/CH
market for industrial machine, heavy, unspecified	GLO	market for industrial machine, heavy, unspecified, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	industrial machine, heavy, unspecified/GLO
treatment of waste plastic, mixture, municipal incineration	GLO	treatment of waste plastic, mixture, municipal incineration, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	treatment of waste plastic, mixture, municipal incineration/GLO
phosphoric acid production, dihydrate process	GLO	phosphoric acid production, dihydrate process, GLO, undefined unit process, ecoinvent database version 3.4, accessed (14/03/2018)	phosphoric acid production, dihydrate process/GLO
market for silica sand	GLO	market for silica sand, GLO, undefined unit process, ecoinvent database version 3.4, accessed (14/03/2018)	silica sand/GLO
market for nickel smelter slag	GLO	market for nickel smelter slag, GLO, undefined unit process, ecoinvent database version 3.4, accessed (14/03/2018)	nickel smelter slag/GLO
cement production, Portland	CH	cement production, Portland, CH, undefined unit process, ecoinvent database version 3.4, accessed (08/10/2017)	cement production, Portland/CH
market for cement factory	GLO	market for cement factory, GLO, undefined unit process, ecoinvent database version 3.4, accessed (08/10/2017)	cement factory/GLO
market for heat, district or industrial, natural gas	GLO	market for heat, district or industrial, natural gas, GLO, undefined unit process, ecoinvent database version 3.4, accessed (14/03/2018)	heat, district or industrial, natural gas/GLO
market for heat, district or industrial, other than natural gas	GLO	market for heat, district or industrial, other than natural gas, GLO, undefined unit process, ecoinvent database version 3.4, accessed (14/03/2018)	heat, district or industrial, other than natural gas/GLO

Ecoinvent activity name	Geography	Reference	Referred to in this report as
market for transport, freight, inland waterways, barge tanker	GLO	market for transport, freight, inland waterways, barge tanker, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	transport, freight, inland waterways, barge/GLO
concrete production 25 MPa, RNA only	GLO	concrete production 25 MPa, RNA only, GLO, undefined unit process, ecoinvent database version 3.4, accessed (10/10/2017)	concrete production 25 MPa, RNA only/GLO
market for chemical, organic	GLO	market for chemical, organic, GLO, undefined unit process, ecoinvent database version 3.4, accessed (10/10/2017)	chemical, organic/GLO
market for reinforcing steel	GLO	market for reinforcing steel, GLO, undefined unit process, ecoinvent database version 3.4, accessed (07/12/2017)	reinforcing steel/GLO
concrete block production	GLO	concrete block production, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	concrete block/GLO
market for concrete, normal	GLO	market for concrete, normal, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	concrete, normal/GLO
market for propane, burned in building machine	GLO	market for propane, burned in building machine, GLO, undefined unit process, ecoinvent database version 3.4, accessed (20/02/2018)	propane, burned in building machine/GLO
heat production, natural gas, at boiler modulating > 100 kWh	GLO	heat production, natural gas, at boiler modulating > 100 kWh, , GLO, undefined unit process, ecoinvent database version 3.4, accessed (20/02/2018)	heat production, natural gas, at boiler modulating > 100 kWh/GLO
heat production, heavy fuel oil, at industrial furnace 1 MW	GLO	heat production, heavy fuel oil, at industrial furnace 1 MW, , GLO, undefined unit process, ecoinvent database version 3.4, accessed (20/02/2018)	heat production, heavy fuel oil, at industrial furnace 1 MW/GLO
heat production, mixed logs, at furnace 100 kW	GLO	heat production, mixed logs, at furnace 100 kW, GLO, undefined unit process, ecoinvent database version 3.4, accessed (20/02/2018)	heat production, mixed logs, at furnace 100 kW/GLO
market for blasting	GLO	market for blasting, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	blasting/GLO
market for vegetable oil methyl ester	GLO	market for vegetable oil methyl ester, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	Vegetable oil methyl ester/GLO
market for sewage sludge, dried	GLO	market for sewage sludge, dried, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	Sewage sludge, dried/GLO
market for waste wood, untreated	GLO	market for waste wood, untreated, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	waste wood/GLO
market for waste paint	GLO	market for waste paint, GLO,	waste paint/GLO

Ecoinvent activity name	Geography	Reference	Referred to in this report as
		undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	
market for iron scrap, unsorted	GLO	market for iron scrap, unsorted, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	iron scrap/GLO
market for gypsum, mineral	GLO	market for gypsum, mineral, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	gypsum, mineral/GLO
market for hard coal ash	GLO	market for hard coal ash, mineral, GLO, undefined unit process, ecoinvent database version 3.4, accessed (28/02/2018)	hard coal ash/GLO
gravel production, crushed	GLO	gravel production, crushed, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	gravel production, crushed/GLO
limestone quarry operation	GLO	limestone quarry operation, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	limestone quarry operation/GLO
bauxite mine operation	GLO	bauxite mine operation, GLO, undefined unit process, ecoinvent database version 3.4, accessed (15/09/2017)	bauxite mine operation/GLO