OpenConcrete: a tool for estimating the environmental impacts from concrete production

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Abstract
As the increasing global consumption of concrete drives notable environmental burdens from its production, particularly greenhouse gas (GHG) emissions, interest in mitigation efforts is increasing. Yet current environmental impact quantification tools rely on user decision-making to select data for each concrete constituent, have inconsistent scopes and system boundaries, and often utilize third-party life cycle inventories. These factors limit customization or tracking of data and hinder the ability to draw robust comparisons among concrete mixtures to mitigate its environmental burdens. To address these issues, we introduce a cohesive, unified dataset of material, energy, and emission inventories to quantify the environmental impacts of concrete. In this work, we detail the synthesis of this open dataset and create an environmental impact assessment tool using this data. Models can be customized to be region specific, expanded to varying concrete mixtures, and support data visualization throughout each production stage. We perform a scenario analysis of impacts to produce a representative concrete mixture across the United States, with results ranging from 189 kg CO₂-eq/m³ of concrete (California) to 266 kg CO₂-eq/m³ of concrete (West Virginia). The largest driver of GHG, nitrogen oxide, sulfur oxide, and volatile organic compound emissions as well as energy demand is cement production, but aggregate production is the largest driver of water consumption and particulate matter smaller than 2.5 microns (PM₂.₅) emissions.

1. Introduction
After water, concrete is the most consumed material worldwide [1], and demand for concrete is continuing to grow globally in both developed and less-developed regions [2]. Concrete is conventionally composed of Portland cement (a hydraulic binder), water, and aggregates. Other common cement-based materials include mortar and grout. The high level of cement-based material consumption drives environmental impacts from this class of materials, with their production leading to an estimated 8%–9% of global anthropogenic CO₂ emissions [1, 3–5], 1%–2% of total global water withdrawals [6], and over 6% of emissions of particulate matter smaller than 2.5 microns (PM₂.₅) [7]. The greenhouse gas (GHG) emissions, in particular, pose a significant challenge to the Intergovernmental Panel on Climate Change (IPCC) goal of reaching net zero CO₂ emissions by 2050 to control climate change [8].

Further, these notable GHG emissions from the cement and concrete industries have spurred a large amount of research (e.g., work summarized by Gursel et al 2014 [9], Miller et al 2021 [10], and Habert et al 2020 [11]), industry roadmaps (e.g., the Global Cement and Concrete Association [12], the Portland Cement Association (PCA) [13], and the California Nevada Cement Association [14]), and now regulatory efforts (such as a recent policy passed in California [15]) to curb emissions. To mitigate these emissions, it is imperative to have systematic, quantitative accounting methods that can capture the environmental impacts, are
available for public review, and can be easily audited. Yet, inconsistencies in the literature hinder robust comparisons. A brief survey of the literature assessing environmental impacts of concrete is summarized in the supplementary materials (table S1 (https://stacks.iop.org/ERIS/2/041001/mmedia)). When looking at the top 25 most cited papers published from 2015 to 2019: all report GHG emissions; 32% report acidification and eutrophication; 24% report particulate matter (PM) emissions (e.g., PM$_{2.5}$), particulate matter smaller than 10 microns (PM$_{10}$), and/or other particulate matter; 16% report nitrogen oxides (NO$_X$) or nitrogen dioxide (NO$_2$); and 16% report a measure of sulfur oxides (SO$_X$) or sulfur dioxide (SO$_2$) [16–39]. Beyond differences in environmental impact categories considered, varying methods and scopes of assessment are applied. In industry, Environmental Product Declarations (EPDs) are becoming prevalent sources for examining environmental impacts (e.g., the repository managed by the National Ready Mixed Concrete Association (NRMCA) [40]). Yet, similar to the academic literature, comparisons across EPDs with the goal of mitigating environmental burdens can be difficult as they were not originally developed for this purpose and have known weaknesses in this regard. These challenges include data quality issues, inconsistencies in information supplied, and varied application of cut-off rules [41].

While GHG emissions have been a focus within the literature, criteria air pollutants (e.g., NO$_X$, SO$_X$, PM$_{2.5}$, PM$_{10}$, volatile organic compounds (VOC), and carbon monoxide (CO)), heavy metals, and water consumption are of critical importance when addressing environmental and health concerns. This is particularly true if GHG mitigation methods could increase these other burdens. Reductions in air pollutant emissions from fuel resources are often seen in tandem with mitigation of GHG emissions [42]. However, in concrete production, environmental impacts can come from varied sources. For example, PM emissions occur throughout the production and supply chains, including from: transportation, raw material preparation (e.g., quarrying, crushing, grinding), clinker production, and concrete batching [43–45]. Likewise, heavy metal emissions (e.g., lead (Pb)) in concrete production come from both raw materials and the fuels used [11]. Water demands occur throughout the supply chain, including water as a constituent in concrete and water use during mineral extraction, material manufacturing, and construction [45–47].

Life cycle assessment (LCA) methods allow for quantification of environmental impacts from products, such as concrete. Multiple tools capable of performing LCAs of concrete mixtures currently exist, 15 of which we reviewed in a prior study [48]. The supplementary materials (table S2) provides a synopsis and further details of each tool. Among these tools, seven focus on construction projects and buildings with limited customization for different concrete permutations, seven require purchasing of a license (thus limiting public review and auditing), and three are dedicated pavement tools. Only two tools (GreenConcrete [49] and Global Cement and Concrete Association (GCCA) EPD tool [50]) are dedicated concrete tools.

Here, we introduce a unified, environmental impact assessment tool for concrete and other cement-based materials (herein referred to jointly as concrete) production called OpenConcrete. For this tool we have developed calculations in Excel, and we synthesize herein, for the first time, structured open data for determining the environmental impacts of concrete. This paper presents the OpenConcrete tool’s scope of analysis, data sources, input assumptions, and modeling methods used to estimate environmental impacts of concrete.

To demonstrate how OpenConcrete is adaptable to different regions, scenarios, and material mixtures, a case study examining the production of a representative concrete mixture in each of the 50 states within the United States (US) is shown. The case study results are also used to examine primary drivers of different environmental impact categories. A sensitivity analysis investigating OpenConcrete’s input parameter’s influence on the 11 environmental impact categories modeled is provided.

2. Methods—development of OpenConcrete

OpenConcrete quantifies flows that contribute to emissions of GHGs, NO$_X$, SO$_X$, VOCs, CO, PM$_{10}$, PM less than 2.5 microns (PM$_{2.5}$), and Pb, as well as direct energy demand, water consumption, and water withdrawals. (Note: herein, when both water consumption and withdrawals are discussed concurrently, they are referred to as water demand). The scope includes impacts associated with raw material acquisition through concrete production (i.e., a cradle-to-gate assessment), see figure 1. OpenConcrete addresses both process-derived (i.e., PM emissions from raw material resources as they are ground or limestone decarbonation emissions) and energy-derived (i.e., emissions from the production and/or use of energy resources, including transportation-related emissions) flows. For this analysis, emissions of three key GHGs are quantified: CO$_2$, CH$_4$, and N$_2$O. These emissions are examined concurrently using 100a global warming potentials from the IPCC [51]. Modeling assumptions and data sources for each constituent and production process considered are discussed below.

Cement production. Energy-derived emissions for cement production are predominantly from kiln thermal energy fuel requirements and electricity demands. Due to high variability in material resource acquisition and the propensity for cement plants to be placed at quarries that produce the majority of the natural resources
(required [45], transportation of raw materials to the kiln is considered negligible. In this tool, kiln efficiency by type is based on data from the Getting the Numbers Right initiative (GNR) [52], using values reported for the world average in the year 2016 (note: data used are from the GNR when it was under management by the World Business Council for Sustainable Development; this project is now managed by the GCCA). The kiln efficiency for each cement producing state is from the PCA [45]. For states that do not produce cement (based on United States Environmental Protection Agency (USEPA) data) [53], but use cement, the US average value for kiln efficiency and electricity mix is used. The electricity requirements, by kiln type, are based on data from the PCA [45].

Process-derived emissions for cement production include both calcination emissions and emissions of air pollutants from the processing of raw material and limestone decarbonation. The calcination emissions included are based on stoichiometry, assuming 65% lime content in clinker and 95% clinker in cement, with the remaining 5% of cement modeled as gypsum. The tool’s default setting is type 1 Portland cement; however, users can select different types of cements from a drop-down menu (e.g., LC3, Portland limestone cements) in the tool or manually specify proportions of clinker and gypsum (see supplemental materials). The process-derived air emissions are calculated as cement manufacturing total emissions minus energy-derived emissions using data from the USEPA [43], the United States Geological Survey (USGS) [54], and GNR [52]. Water demands are based on median data from distributions by process reported in Miller et al 2018 [6].

Mineral admixtures. This tool incorporates several mineral additives, namely: limestone filler, gypsum, natural pozzolans, interground limestone, fly ash, blast furnace slag, calcined clay, silica fume, and shale ash. The energy demand for limestone filler, a constituent added during concrete batching, is based on data from the National Renewable Energy Laboratory (NREL) [55]. The energy demand is adapted to reflect electricity use at each processing stage. This adaptation is made using lower heating value (LHV) factors from the greenhouse gases, Regulated Emissions and Energy use in Technologies (GREET) model [56]. Process-based air emissions for the limestone filler are based on data from the USEPA [57] and, as with cement, the water demand is from Miller et al 2018 [6]. For this work, the energy-derived and process-based emissions for gypsum and natural...
pozzolans are modeled as the same as those for limestone filler. The water demands are based on median values for the production of each of these materials as reported by Miller et al. 2018 [6].

Interground limestone, which is limestone ground in during cement manufacturing, is extended from the limestone filler model by using the same energy required for limestone filler with an additional electricity demand for grinding. The additional grinding electricity is approximated at the lower end of clinker electricity demand (30% of the 110 kwh/t reported by Jankovic et al. 2004 [58], which is on the lower end of energy reported by Ghiasvand et al. 2015 [59]). The lower end is selected because limestone is softer than clinker; but it must be noted that studies have shown that intergrinding, especially in a laboratory setting, could lead to higher processing times to achieve the desired gradation. The model for interground limestone reflects the same process-based PM emissions and water demands as is modeled for limestone filler.

Two primary industrial byproduct mineral admixtures are modeled: fly ash and blast furnace slag. The fly ash is modeled as not requiring energy inputs, following an assumption published by the USEPA [60]. While the degree to which it is done varies, the transport of fly ash sometimes includes the use of water and is incorporated based on data from Miller et al. 2018 [6]. For granulated blast furnace slag, the energy demand for the production of reactive slag is based on an industry EPD [61]. The water demand for this admixture is based on the same report [61]. For the purposes of this work, shale ash and silica fume are incorporated as additional mineral admixtures; they are modeled as having the same impacts as fly ash based on a modeling suggestion for silica fume from the PCA [62].

Finally, the thermal energy and electricity demands to produce calcined clay as a mineral admixture are considered, based on Miller et al. 2018 [63]. The air pollutant emissions for calcined clay production are based on those reported for cement (accounting for differences in quantity of raw material needed and excluding calcination emissions). Water demand is based on modeling inputs from Miller et al. 2018 [6].

**Aggregates.** For fine and coarse aggregates, energy demand is based on a report from the PCA [62], with slightly lower energy demands being reported for fine aggregates. The process-based air emissions are from the USEPA [57] and water demand is from Miller et al. 2018 [6]. Process-based air emissions capture factors such as PM from practices including crushing, grinding, and sieving. Water demand incorporates process-related water consumption, such as that for dust suppression.

**Chemical admixtures.** The energy demand and water demand for six classes of chemical admixture are modeled in this work based on EPDs from the European Federation of Concrete Admixtures Associations Ltd: (a) plasticizers and superplasticizers [64]; (b) air entrainers [65]; (c) hardening accelerators [66]; (d) set accelerators [67]; (e) water resisting admixtures [68]; and (f) retarders [69]. Process-based emissions are not modeled for these admixtures.

**Batching.** Additional energy-derived and process-derived impacts are considered for the batching of concrete constituents listed above. The energy demand is based on the approximate electricity consumption reported by the Lawrence Berkeley National Lab [70]. Regardless of other inputs selected by the user, this electricity demand remains a constant per unit volume of concrete. Process-based emissions for batching, as well as aggregate transfer, cement unloading, SCM unloading, hopper loading, and mixture loading are based on data from the USEPA [71]. Based on available data, uncontrolled air emissions are modeled for batching, aggregate transfer, and hopper loading; controlled emissions are modeled for SCM unloading. Controlled emissions for cement unloading and mixture loading are modeled based on estimates using a fraction of total emissions reported by the USEPA to reflect emissions controls for similar processes [71]. Water demands are from Miller et al. 2018 [6]; including the energy-derived emissions and the water as a constituent (modeled as the quantity of water required for the batch itself). The water used as a concrete constituent is modeled as not requiring any energy to get to the batching location. While this is an underestimate of energy demand in most cases, the variability in energy demand and associated emissions with getting the water to the concrete manufacturing site is considered too great to include.

**Transportation.** OpenConcrete contains models for three modes of transportation: truck, rail, and ship. For transportation by truck, energy demand is based on the average value reported by Michaelis et al. 1995 [72]. These data sets can be updated by the user to model region specific fuel efficiency, different transportation modes, and potential future changes in transportation modes; the user can directly change the data within the OpenConcrete excel tool (see supplemental materials). The energy demand for the remaining transportation modes and the air emissions for all three modes are based on median values from distributions fit to data from NREL and the European Commission [73, 74]. For these distributions, a single point is used if there is only one datum, a uniform distribution is used if there are two data, a triangular distribution is used if there are three data, and a lognormal distribution is used for four or more data. Water demands are based on medians of the distributions reported in Miller et al. 2018 [6] for each of these transportation modes. It should be noted, no process-based emissions are considered in the transportation models; all energy demand, air emissions, and water demands are a function of energy production and use in transport.
Thermal energy. The use of thermal energy, predominantly in the cement kilns, is a large contributor to total energy demand, air pollutant emissions, and energy-related water demand. The GHG and air pollutant emissions associated with this energy use, by resource type, are quantified using the median values of distributions for GHG emissions and air pollutant emissions from Miller et al 2020 [7]. Water demand, by thermal energy resource, are median values from estimates and modeling assumptions by Miller et al 2018 [6]. The default thermal energy mix modeled in the tool is based on national statistics reported by the USGS [54]; however, this can be updated as desired by the end-user.

Electricity. As with thermal energy, the resources used in the production of electricity contribute to GHG emissions, air pollutant emissions, and water demands. The GHG emissions, by energy resources, are taken as the median values from distributions presented by Miller et al 2020 [7]. Air pollutant emissions, by energy resource, are based on the same estimates and modeling assumptions discussed in Miller et al 2020 [7], again reflecting median values from distributions. Water demands are based on the median values of distributions presented in Miller et al 2018 [6]. The tool allows manual user-input for electricity mix or selection from a drop-down menu of US state electricity grids, which are based on 2018 USEPA data [75], such that a different electricity mix can be selected for every constituent.

Impacts by constituent and process. OpenConcrete allows users to manually enter concrete mixtures, based on concrete constituent amounts (in kg) per volume of concrete (in m$^3$). To perform an assessment for concrete mixtures with varying constituents, an intermediary step in which all flows for any given constituent or process that could be used in the mixtures (e.g., aggregates, batching) is tabulated on a separate sheet within the tool. These constituents and processes can then be used to determine GHG emissions, air pollutant emissions, energy demand, and water demand from production of concrete. It should be noted that energy demand is modeled based on assuming the amount of MJ required for cradle-to-gate production. It does not reflect differences in energy resources, or differences between electricity and thermal energy, nor does it capture differences between high temperature processes and low temperature processes (beyond differences in their required MJ).

Functional units. The functional unit of the outputs from this tool is per 1 m$^3$ of concrete. Impacts for each constituent (e.g., cement, fly ash, aggregates) are calculated per 1 kg of that material. Batching has a functional unit of 1 m$^3$ of concrete. Transportation impacts are measured per 1 metric ton-km traveled. For mixtures of cement-based materials, the functional unit is 1 m$^3$ of cement-based material.

Data flow. OpenConcrete accepts user-input data to output environmental impact results (see tool data flow diagram in figure 2). The user inputs data in the ‘inputs and outputs’ sheet, which is then coupled with data in the inventory database to perform calculations in the ‘constituent and process impacts’ sheet, with final outputs reported in the ‘inputs and outputs’ sheet. All sheets within the tool are detailed in the supplementary materials. The ‘process emissions’ box in figure 2 includes the environmental impacts from the previously discussed sections: cement production, mineral admixtures, aggregate, chemical admixtures, batching, and transportation.

Figure 2. Flow diagram of tool and user data through the OpenConcrete tool.
Table 1. National benchmark concrete mixture from NRMCA [76] used to perform analyses.

| Constituent materials, kg/m³ concrete | Portland cement | Fly ash | Slag | Mixing water | Coarse aggregate | Fine aggregate | Air entraining admixture | Plasticizer and Superplasticizer | Set accelerator |
|-------------------------------------|----------------|---------|------|--------------|-----------------|---------------|------------------------|-----------------------------|-----------------|
|                                     | 210            | 37      | 10   | 181          | 996             | 861           | 0.028                  | 0.085                      | 0.709           |

3. Results

3.1. US National comparison of GHG emissions

To demonstrate the capabilities of OpenConcrete, an analysis to determine the environmental impacts of concrete production in each state within the US is presented here. To do this, the electricity grids (from [75]) and cement kiln efficiencies (from [45]) of each state are input into the tool. As mentioned in section 2, the US averages for electricity grid and cement kiln efficiencies are used for states that do not produce cement. Although this tool can output multiple environmental impacts, this analysis focuses on GHG emissions (kg CO₂-eq/m³ of concrete). The results for the other environmental impacts can be found in the supplementary materials (figure S1). A US national benchmark concrete mixture from the NRMCA (table 1), is used to compare the environmental impacts of concrete production across the US.

The CO₂-eq intensity to produce concrete in each state ranges from 189 to 266 kg CO₂-eq/m³ concrete, with California as the lowest and West Virginia as the highest (figure 3). The variation in each state’s electricity mix and kiln efficiency drives the range of CO₂-eq intensity of concrete production shown in figure 3. This variability highlights the influence of regionally specific inputs when performing environmental accounting. This analysis is incorporated in OpenConcrete by allowing the user to select a state where concrete is produced.

3.2. Environmental emissions per constituent

Using the mixture from table 1 in OpenConcrete, we are able investigate the contributions of various concrete constituents to the different environmental impact categories (figure 4). For this chart, the US average electricity mix, and kiln efficiencies are applied. For simplicity and to highlight key impact categories, figure 4 shows a subset of 7 of the 11 impact categories (all categories shown in supplementary materials figure S2). For this concrete mixture, the GHG, VOC, NOₓ, and SOₓ emissions, and energy demand are largely driven by the cement content. However, PM₂.₅ emissions are driven by aggregate content. Aggregate production results in high amounts of PM₂.₅ emissions largely due to the dust released during quarrying and preparation operations. Water consumption is also driven by aggregate content rather than cement content; significantly, while batching water is discussed as a key area to mitigate resource consumption in concrete, it contributes only about 10% of water consumption. For a cradle-to-gate analysis of aggregates, water is used...
Table 2. High and low scenarios for each parameter analyzed in sensitivity analysis.

|                         | Electricity mix | Thermal energy          | Kiln efficiency |
|-------------------------|-----------------|-------------------------|-----------------|
| Higher GHG emissions    | 100% coal       | 100% solid waste        | 100% wet        |
| scenario (high)         |                 |                         |                 |
| Lower GHG emissions     | 100% wind       | 100% natural gas        | 100% preheater/precinciner |
| scenario (low)          |                 |                         |                 |

3.3. Sensitivity analysis

A sensitivity analysis was performed with OpenConcrete to exemplify the effect of input parameters on the 11 environmental impacts modeled. The sensitivity analysis was conducted by independently varying three inputs (a) electricity grid (b) kiln thermal energy (i.e., the fuel mix in cement kilns) and (c) cement kiln efficiency. Scenarios were selected to result in either the greatest reductions or increases in GHG emissions based on resources already used and potentially scalable using current technologies (e.g., coal has the highest GHG intensity for electricity production, wind has the lowest GHG intensity for electricity, solid waste has the highest GHG intensity for thermal energy production, natural gas has the lowest GHG intensity for thermal energy, etc), provided in table 2. The baseline to which these scenarios are compared is the NRMCA concrete mixture (from table 1) produced in California. The results in figure 5 show the sensitivity of each environmental impact category to the inputs from table 2 to create 1 m³ of concrete, presented here as a percent (%) increase or decrease in impact relative to the baseline.

While the scenarios selected had notable, and anticipated shifts in GHG emissions, complementary reductions or increases were not consistently noted in the other environmental impact categories. The VOC emissions were the most sensitive to change, particularly for shifts in thermal energy mix, which resulted a −64% to 369% difference from the baseline. Pb emissions were among the least sensitive to the scenarios examined, with negligible variation based on a change in electricity mix and −0.012% to 0.44% change with altered kiln efficiency. In most cases, the environmental impacts increase in the high GHG emissions scenarios and decrease in the low GHG emissions scenarios. However, in the following cases the high scenario GHG emissions results in a decrease in impact: the change in thermal energy mix for NOₓ and SOₓ emissions, and the electricity mix for CO emissions and water consumption. The thermal energy for CO is the only case that results in an increase in impact for the low scenario. Notably, because the energy demand impact does not change with adjustments to electricity mix or thermal energy mix, there is no sensitivity to their alteration (figure 5(k)). It should also be noted that the minimal shifts in the low kiln efficiency scenarios are due to the baseline scenario taking place in California, where 85% of the cement plants have already utilize preheater/precinciners systems (note: this is
Figure 5. Results of a sensitivity analysis considering scenarios with a change in each of three parameters: (i) electricity; (ii) thermal energy; or (iii) kiln efficiency, selected based on anticipated increases in GHG emissions (high) or decreases in GHG emissions (low). Percent change in impacts from the production of the NRMCA concrete mixture in California are shown for (a) GHG emissions, (b) NO\textsubscript{X} emissions; (c) SO\textsubscript{X} emissions; (d) PM\textsubscript{10} emissions; (e) PM\textsubscript{2.5} emissions; (f) VOC emissions; (g) CO emissions; (h) Pb emissions; (i) water consumption; (j) water withdrawal; and (k) energy demand. Note: all figures are to the same scale except for figure (f).

based on data from the PCA [45]). Greater reductions for the low kiln efficiency scenario would be seen if the baseline scenario was in a region with lower cement kiln efficiency (e.g., West Virginia, where 0% of cement plants use preheater/precalciners [45]).

4. Limitations

OpenConcrete has several limitations that should be considered in its implementation. It does not include regional thermal energy fuel mixtures for different states in the US within the data set, as these data were not readily available; however, users can update the thermal energy mix with their own inputs. The only environmental impacts considered for chemical admixtures (e.g., plasticizers, air entrainers) are from their energy
demands, so additional burdens associated with chemical- or other process-derived impacts are not captured in this tool. Models for CO and Pb emissions are limited to cement kilning and transportation, based on available models [43, 54]. NOX emissions are only considered from energy demand, including transportation. This tool focuses on cradle-to-gate impacts, and as a result, construction, use, and end-of-life are not within the scope. However, studies have suggested these life cycle phases can lead to notable effects on environmental impacts; for example, carbonation during use and end-of-life stages has been reported to uptake as great as 43% of CO₂ production emissions (note: uptake from carbonation is influenced by various factors such as clinker-to-cement ratio, compressive strength and surface area) [77]. The model for fly ash is based on assumptions from the USEPA, which treats the material as a waste product and does not allocate emissions from its production. However, allocation of impacts from the industrial processes (e.g., coal power plants) could be included by users, as the inventories are readily editable, or in future work expanding the tool. The kiln efficiency per state is based on data from 2002 due to data availability; however, cement plants in some states have improved significantly in recent years and should be updated in future versions. This kiln efficiency per state data is also from the PCA, whose membership does not encompass all cement plants in the US. Inclusion of cement plants beyond those who are member of the PCA should be considered in future work. While OpenConcrete can be used to evaluate the environmental burdens associated with different concrete mixtures, it does not consider performance metrics (e.g., compressive strength, durability, etc) and, by itself, should not be used to determine the eco-efficiency of concrete mixtures. Recent studies that have addressed the issue of eco-efficiency should be reviewed for incorporation into future work [78–80].

5. Conclusion

With the need to mitigate GHG emissions, there have been recent policy and industry efforts to lower CO₂-eq emissions from cement and concrete production. However, there remain limitations in availability of transparent, customizable models to draw robust comparisons among concrete mixtures to mitigate environmental burdens. OpenConcrete is a freely available tool and presents a new synthesis of open data that allows user-control when performing environmental impact assessments of cement-based materials. The scope of this tool focuses on cradle-to-gate impacts from concrete production (i.e., the scope does not include construction, use phase, or end of life). OpenConcrete includes environmental impacts beyond CO₂-eq, which can inform efforts to advance climate change mitigation while providing a broader perspective of environmental burdens. This can support selection of mixtures or GHG emissions mitigation strategies that lead to co-benefits in other impact categories and help avoid unintended consequences. The inclusion of multiple chemical and mineral admixtures allows for robust evaluation of many variations of concrete mixture designs.

Cement and concrete production are continuing to increase, which poses a barrier to achieving most climate goals. As such, a robust and methodological means of calculating the environmental impacts of concrete production which provides for specific conditions (e.g., kiln efficiencies, electricity mixes) will assist in understanding and monitoring the burdens of concrete production, allowing for region-specific decision making toward concrete with improved environmental impacts.

Author contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Notes

The authors declare no competing financial interest.
Data availability statement

The data that support the findings of this study are openly available. These data are included within the article and/or publicly available datasets: https://doi.org/10.25338/B8SW6V and https://doi.org/10.25338/B88S7J.

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