A unified approach to quantifying the key greenhouse gas emissions, air pollutant emissions, and water demand in concrete production

Sabbie A. Miller [a, †]
[a] Department of Civil and Environmental Engineering, University of California, Davis
2001 Ghausi Hall, One Shields Ave, Davis, CA, 95616
[†] Corresponding Author: T +1 530 754 6407, E sabmil@ucdavis.edu

Objective

The objective of this study is to develop a cohesive, unified dataset of life cycle inventories needed to quantify the effects of material, energy, waste, and emission flows on the environmental impacts of concrete. In this work, a set of environmental impact assessment models that capture specific materials and technologies used in the production of cement and concrete in California is developed. The models developed will consider greenhouse gas (GHG) emissions, air pollutant emissions (namely, NO_X, SO_X, $PM_{2.5}$, PM_{10}, VOCs, and CO), and water demands (both water consumption and water withdrawals) for the key components of cement and concrete production in California. The structure of the data will allow for tailoring of inputs to capture variations in different regions around the world, allowing for assessment of imported constituents.

1. Introduction

The objective of this work is to formulate life cycle environmental impact models of concrete production in California. Models developed will be open source, so alterations can easily be implemented. Currently, the primary means for environmental impact comparisons in procurement for materials such as concrete rely on data like those from Environmental Product Declarations. While these are an invaluable tools, they have known weaknesses in: (i) quality of data used; (ii) inconsistencies in information used and provided; (iii) clarity of definitions and applications of cut-off rules [1]. All of these weaknesses can lead to incomplete and/or difficult to compare assessments. As such, creating a more a robust means to assess concrete mixtures in California is critical to quantifying the effects of mitigation strategies. The primary consideration for environmental impact mitigation strategies discussed in other deliverables will focus on three GHG emissions: CO_2, CH_4, and N_2O. However, because of potential implications of GHG mitigation strategies on other environmental impacts [2], leading to potential co-benefits or unintended consequences, this work will also benchmark the six criteria air pollutants stipulated by the United States Environmental Protection Agency (namely, NO_X, SO_X, PM – here we examine $PM_{2.5}$ and PM_{10} –, Pb, CO and ground-level O_3 – here we capture a main precursor VOCs) [3], as well as energy demand for production, and both water consumption and withdrawals (referred to herein as water demand).

2. Methods

The environmental impact assessment models developed for this work considers flows associated with raw material acquisition through concrete production (i.e., a cradle-to-gate assessment), see scope outline in Figure 1. At each stage of assessment, material and energy inputs as well as emission outputs are quantified addressing both process-derived (i.e., from a raw material resource, such as PM from materials as they are ground, or calcination reactions) and energy-derived emissions (i.e., emissions from the production and/or use of energy resources, including transportation-related emissions). Water demands were also considered based on energy-derived and process-derived flows. As has been well established, there is an energy-water nexus in which water use requires a certain degree of energy and different energy resources require varying amounts of water for certain processes or result in water consumption through evaporation in cooling towers [4]. Each of these factors were addressed in the tool.

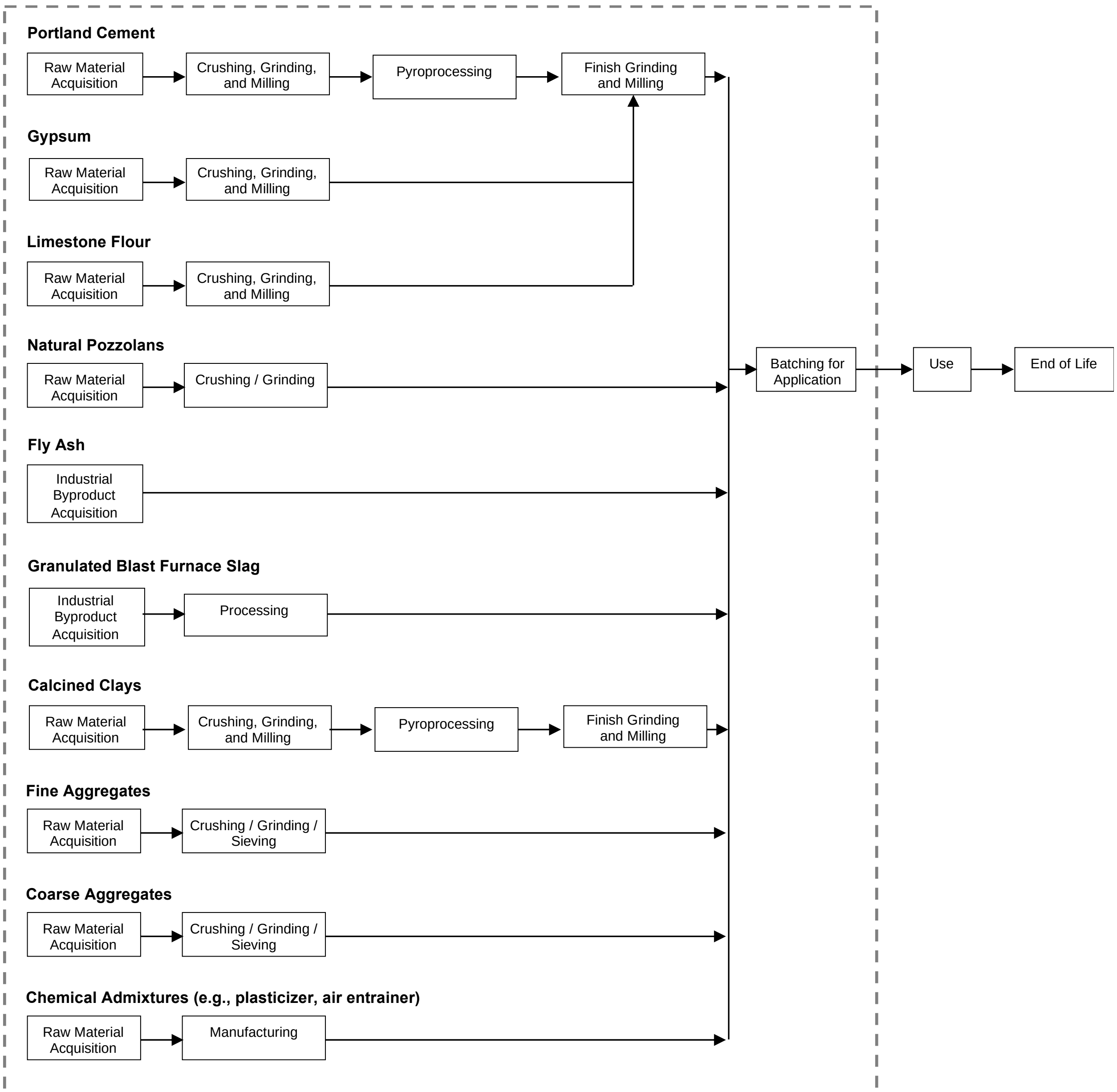

Figure 1. Simplified process flow diagram to show the scope of the assessment

For this analysis, three key GHG emissions were quantified: CO_2 emissions, CH_4 emissions, and N_2O emissions. These emissions flows were examined concurrently using 100a GWPs from the Intergovernmental Panel on Climate Change (IPCC) [5]. Modeling assumptions and data sources for each constituent considered and processing, such as concrete batching, are discussed individually below.

Cement Production. Energy-derived emissions for cement production are predominantly from kiln energy requirements and electricity demands. Due to high variability in material resource acquisition and the propensity for cement plants to be placed at quarries with the majority of natural resources required [6], transportation of raw materials to the kiln was considered negligible. For this tool, kiln efficiency by type was based on data from [7], using on values reported for the world average in the year 2016. California kilns are reported as nearly or entirely preheater/precalciner kilns [6,8]. As such, those highly efficient kilns are modeled as the default selection, but other kiln types can be selected as suited. The electricity requirements, by kiln type, are based on data from the Portland Cement Association (PCA) [6].

Process-derived emissions for cement production include both calcination emissions as well as emissions of air pollutants from the processing of raw material and kilning. The calcination emissions calculated are based on stoichiometry, assuming 65% lime content in clinker and 5% gypsum in cement. The process-derived air emissions calculated as cement manufacturing emissions total emissions minus energy-derived emissions using data from [9–11]. Water consumption and withdrawals are based on median data from a recent publication [12]

Mineral admixtures. Several mineral admixtures were incorporated into this tool, namely: limestone filler, gypsum, natural pozzolans, interground limestone, fly ash, blast furnace slag, and calcined clay. For the limestone filler, to be mixed in with other concrete constituents, the energy demand was based on [13]. The energy demand was adapted to reflect electricity use at each processing stage, with the default using the California electricity grid. This adaptation was made using lower heating value (LHV) factors from [14]. Process-based air emissions for the limestone filler were based on [15] and the water demand from [12]. For this work, the energy demand and process-based emissions for gypsum and natural pozzolans were modeled as the same as those for as limestone filler. The water demands were based on median values for the production of each of these materials as reported by [12].

A model for interground limestone, which is limestone ground in with the manufacturing of cement, was developed based upon the limestone filler model. Namely, this interground limestone was modeled using the energy required for the limestone filler with an additional electricity demand for grinding. The additional griding electricity was approximated at the lower end of clinker electricity demand (30% of the 110 kwh/t reported by [16], which is on the lower end of energy reported by [17]). The lower end was selected because limestone is softer than clinker, even though studies have shown that intergrinding, especially in a laboratory setting could lead to higher processing times to achieve the desired gradation. No additional process-based PMs or water demands were modeled for the interground limestone beyond those modeled for the limestone filler.

Two primary industrial byproduct mineral admixtures were modeled: fly ash and blast furnace slag. The fly ash was modeled as not requiring any energy inputs, which is based on an assumption published by the United States Environmental Protection Agency (USEPA) [18]. While the degree to which it is done varies, the transport of fly ash sometimes includes the use of water, which was incorporated based data from [12]. For granulated blast furnace slag, the energy demand for the production of reactive slag was based on an industry Environmental Product Declaration (EPD) [19]. The water demand for this admixture was based on the same report. For the purposes of this work, shale ash was incorporated as an additional mineral admixture; however, it is modeled as having the same impacts as fly ash.

Finally, the production of calcined clay as a mineral admixture was considered. The thermal energy and electricity demands to produce this as a reactive material were based on [20]. The air pollutant emissions were based on those reported for cement (accounting for differences in quantity of raw material needed and without calcination emissions). Water demands were based on [12].

Aggregates. For fine and coarse aggregates, energy demand was based on a report from the PCA [21], with slightly lower energy demands being reported for fine aggregates. The process-based air emissions from [15] and water demand from [12]. Process-based air emissions in this case captured factors such as particulate matter from practices including crushing, grinding, sieving. Water demand incorporated process-related water consumption such as that for dust suppression.

Chemical admixtures. Six chemical admixtures are modeled in this work: (a) plasticizers and superplasticizers; (b) air entrainers; (c) hardening accelerators; (d) set accelerators; (e) water resisting admixtures; and (f) retarders. For each of these (a-f), energy demands and water demands were based on EPDs from the European Federation of Concrete Admixtures Associations Ltd.: [22], [23], [24], [25], [26], and [27], respectively. Process-based emissions were not modeled.

Batching. Batching of the concrete constituents listed above was considered for additional energy-derived impacts as well as process-derived impacts. The energy demand for batching was based on a report from the Lawrence Berkeley National Lab [28], which stipulated approximate electricity consumption for the process. Process-based emissions for batching, as well as aggregate transfer, cement unloading, SCM unloading, hopper loading, and mixture loading were based on [29]. Based on available data, uncontrolled air emissions were modeled for batching, aggregate transfer, and hopper loading. For SCM unloading, controlled emissions were modeled. While there were limitations in the dataset, for cement unloading and mixture loading controlled emissions were modeled; these were based on estimates using controls as a fraction of total emissions reported by [29]. Water demands were from [12]; including the energy-derived emissions and the water as a constituent (modeled as requiring a 1:1 factor of the water required for the batch itself). Despite it being a primary constituent in concrete, water was modeled as not requiring any energy to get to the site. While this is an underestimate in most cases, the variability in energy demand and associated emissions with getting the water to the concrete manufacturing site was considered too great to include.

Transportation. For this model, three modes of transportation (truck, rail, and ship) are included. For transportation by truck, energy demand is based on the average value reported by [30]. For energy demand for the other modes and air emissions for all three modes, inputs were based on medians from distributions fit to data from [31,32]. For these distributions, a single point was used if there was only one datum, a uniform distribution was used if there were two data, a triangular distribution was used if there were three data, and a lognormal distribution was used for four or more data. Water consumption and withdrawal were based on medians of the distributions reported in [12] for each of these transportation modes. It should be noted, no process-based emissions were considered in the transportation models; all energy demand, air emissions, and water demand are a function of energy production and use.

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. To capture the GHG and air pollutant emissions associated with this energy use, median values are taken from distributions for GHG emissions and air pollutant emissions from estimates and modeling assumptions by energy resource in [33]. Median values for water consumption and withdrawal by thermal energy resource are used from estimates and modeling assumptions by [12]. The default thermal energy mix modeled in the tool is based on national statistics reported by the United States Geologic Survey (USGS) [10]; 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 and air pollutant emissions as well as water consumption and withdrawal. To model these, the GHG emissions by energy resources are taken as the medians from distributions presented by [33]. Air pollutant emissions by energy resource are based on the same estimates and modeling assumptions discussed in [33], again reflecting medians of the distributions. Water consumption and withdrawal are based on the medians of distributions presented in [12]. For the baseline scenario, all processes requiring electricity were modeled by default as occurring in California, with an exception discussed below. For the default case, the CA electricity mix was based in-state generation from report by the California Energy Commission [34]. The exception to this case was for the electricity demand to produce reactive slag, which was modeled as occurring in Pennsylvania (a large steel producing state in the US). For this case, the PA electricity mix was based on USDOE data [35].

Constituent and Process Impacts. To perform a simple assessment for concrete mixtures with varying concrete 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 accompanying tool. These constituents and processes can then be used to determine GHG emissions, air emissions, energy demand, and water demand from production of concrete. It should be noted that energy demand was modeled based on a summing 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).

Example LCA of a Mixture. To implement an example of the calculation of environmental impacts for a concrete mixture, a mixture with limestone filler is presented. Transportation for the constituents of this mixture are listed in Table 1. A separate transportation tab is present in the tool that allows users to change distances that materials travel.

Table 1. Transportation distances modeled for the example assessment of GHG emissions from the production of a concrete mixture

constituent	**distance (km)**
Portland Cement	20
Limestone, interground	20
Limestone Filler	150
Natural Pozzolans	150
Shale Ash	2000
Calcined Clay	150
Silica Fume	2000
Fly Ash	2000
Blast Furnace Slag	2000
Fine Aggregates	50
Coarse Aggregates	50

Superplasticizer	3000
Water	0

References

[1] M.D.C. Gelowitz, J.J. McArthur, Comparison of type III environmental product declarations for construction products: Material sourcing and harmonization evaluation, J. Clean. Prod. 157 (2017) 125–133. https://doi.org/https://doi.org/10.1016/j.jclepro.2017.04.133.

[2] L. Cifuentes, V.H. Borja-Aburto, N. Gouveia, G. Thurston, D.L. Davis, Hidden Health Benefits of Greenhouse Gas Mitigation, Science (80-.). 293 (2001) 1257–1259. https://doi.org/10.1126/science.1063357.

[3] USEPA, Criteria Air Pollutants, 2019 (2017). https://19january2017snapshot.epa.gov/criteria-air-pollutants_.html.

[4] USDOE, The Water-Energy Nexus: Challenges and Opportunities, Washington, D.C., USA, 2014.

[5] D.R. Gomez, J.D. Watterson, B.B. Americano, C. Ha, G. Marland, E. Matsika, L.N. Namayanga, B. Osman-Elasha, J.D.K. Saka, K. Treanton, R. Quadrelli, I.P. on C. Change, 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 2: Energy: Stationary Combustion, Intergovernmental Panel on Climate Change, Hayama, Kanagawa, 2007.

[6] M.L. Marceau, M.A. Nisbet, M.G. VanGeem, P.C. Association, Life Cycle Inventory of Portland Cement Manufacture, Portland Cement Association, Skokie, Illinois, 2006.

[7] GNR, Global Cement Database on CO_2 and Energy Information, 2016 (2016). http://www.wbcsdcement.org/GNR-2013/index.html.

[8] A. Hasanbeigi, C. Springer, California’s Cement Industry: Failing the Climate Challenge, Global Efficiency Intellegence, San Francisco, CA, 2019.

[9] GNR, Global Cement Database on CO_2 and Energy Information, 2015 (2014). http://www.wbcsdcement.org/GNR-2013/index.html.

[10] H.G. van Oss, B. of Mines, Minerals yearbook: cement 2012, United States Geological Survey, 2015.

[11] USEPA, Emission Factor Documentation for AP-42, Section 11.6: Portland Cement Manufacturing., 1994.

[12] S.A. Miller, A. Horvath, P.J.M. Monteiro, Impacts of booming concrete production on water resources worldwide, Nat. Sustain. 1 (2018). https://doi.org/10.1038/s41893-017-0009-5.

[13] Franklin Associates, Limestone, at mine, 21: Mining, Quarrying, and Oil and Gas Extraction / 2123: Nonmetallic Mineral Mining and Quarrying, Fed. LCA Commons, Natl. Renew. Energy Lab. (2011). https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/49e563d8-0cea-3f97-96b8-15787be48b91 (accessed May 18, 2020).

[14] GREET, A.N. Laboratory, The Greenhouse Gases, Regulated Emissions, and Energy Use In Transportation Model, GREET 1.8d.1, Argonne, IL, 2010.

[15] USEPA, Air Emissions Inventories, Volume 2 Chapter 14: Uncontrolled Emission Factor Listing for Criteria Air Pollutants, 2001.

[16] A. Jankovic, W. Valery, E. Davis, Cement grinding optimization, Miner. Eng. 17 (2004) 1075–1081.
[17] E. Ghiasvand, A.A. Ramezanianpour, A.M. Ramezanianpour, Influence of grinding method and particle size distribution on the properties of Portland-limestone cements, Mater. Struct. 48 (2015) 1273–1283. https://doi.org/10.1617/s11527-013-0232-0.
[18] USEPA, Background Document for Life-cycle Greenhouse Gas Emission Factors for Fly Ash Used as a Cement Replacement in Concrete, United States Environmental Protection Agency, 2003.
[19] SCA, Slag Cement Association Industry Average EPD for Slag Cement, Farmington Hills, MI, 2015.
[20] S.A. Miller, V.M. John, S.A. Pacca, A. Horvath, Carbon dioxide reduction potential in the global cement industry by 2050, Cem. Concr. Res. 114 (2018) 115–124. https://doi.org/https://doi.org/10.1016/j.cemconres.2017.08.026.
[21] M.L. Marceau, M.A. Nisbet, M.G. VanGeem, P.C. Association, Life Cycle Inventory of Portland Cement Concrete, Portland Cement Association, Skokie, Illinois, 2007.
[22] EFCA, Environmental Product Declaration: Concrete Admixtures – Plasticizers and Superplasticizers, European Federation of Concrete Admixtures Association Ltd., Berlin, Germany, 2015.
[23] EFCA, Environmental Product Declaration: Concrete admixtures – Air entrainers, Berlin, Germany, 2015.
[24] EFCA, Environmental Product Declaration: Concrete admixtures – Hardening Accelerators, Berlin, Germany, 2015.
[25] EFCA, Environmental Product Declaration: Concrete admixtures – Set Accelerators, Berlin, Germany, 2015.
[26] EFCA, Environmental Product Declaration: Concrete admixtures – Water Resisting Admixtures, Berlin, Germany, 2015.
[27] EFCA, Environmental Product Declaration: Concrete admixtures – Retarders, Berlin, Germany, 2015.
[28] K. Kermeli, E. Worrell, E. Masanet, Energy Efficiency Improvement and Cost Saving Opportunities for the Concrete Industry, Berkeley, California, 2011.
[29] USEPA, AP 42, Fifth Edition, Volume I Chapter 11: Minerals Products Industry: Concrete Batching, Research Triangle Park, NC, 2006.
[30] L. Michaelis, D. Bleviss, J.-P. Orfeuil, R. Pischinger, J. Crayston, O. Davidson, T. Kram, N. Nakicenovic, L. Schipper, G. Banjo, D. Banister, H. Dimitriou, D. Greene, L. Greening, A. Grubler, S. Hausberger, D. Lister, J. Philpott, J. Rabinovitch, N. Sagawa, C. Zegras, Climate Change 1995: The IPCC Second Assessment Report: Chapter 21: Mitigation Options in the Transportation Sector, Intergovernmental Panel on Climate Change, Cambridge, 1995.
[31] NREL, U.S. Life Cycle Inventory Database, 2012 (2012). https://www.lcacommons.gov/nrel/search.
[32] E. Commission, Joint Research Centre, 2018 (2017). http://eplca.jrc.ec.europa.eu/ELCD3/.
[33] S.A. Miller, F.C. Moore, Climate and health damages from global concrete production, Nat. Clim. Chang. 10 (2020) 439–443. https://doi.org/10.1038/s41558-020-0733-0.
[34] CEC, Total System Electric Generation, Calif. Energy Comm. (2018). http://www.energy.ca.gov/almanac/electricity_data/total_system_power.html (accessed

May 24, 2018).
[35] USDOE, State of Pennsylvania Energy Sector Risk Profile, Office of Electricity Delivery and Energy Reliability, United States Department of Energy, 2015. https://www.energy.gov/sites/prod/files/2015/05/f22/PA-Energy Sector Risk Profile.pdf.