Transformation of Engineering Tools to Increase Material Efficiency of Concrete

December 2021

A Research Report from the National Center for Sustainable Transportation

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16. Abstract
This report demonstrates how considerations across concrete material design and infrastructure design can be used together to change environmental impacts and costs by targeting appropriate constituents, materials, and system longevity. In this early-stage exploration, methods to compare concrete mixtures proportioning as they relate to environmental impacts, comparison indices based on common performance characteristics were used. This work was then built out to explore the role of steel reinforcement on reinforced concrete member environmental impacts to elucidate mechanisms to drive emissions reduction for these multi-material members. Finally, work was extended to understand how the longevity of concrete systems could influence environmental impacts associated with concrete production. Each stage of design considered was shown to have substantial effects on mitigating environmental impacts. In all cases, the primary environmental impact addressed was greenhouse gas emissions; however, this work can be extended to address other environmental impacts in future work. These methods from this work are demonstrated in this report through evaluation of mixtures in literature as well as a case study on an existing pavement overlay and potential alternative designs.

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EXECUTIVE SUMMARY

Concrete is an integral part of infrastructure systems. However, the high rate of consumption of concrete and other cement-based materials contributes to substantial emissions from this industry. Of these, greenhouse gas (GHG) emissions, which are predominantly attributable to Portland cement production in cement-based materials, are often considered to be difficult to decarbonize. As such, research on mitigating emissions has focused on methods to replace or lower production emissions from Portland cement. However, some alternatives considered can change material performance. Additionally, the effects of improving performance are often over-looked as a pathway to emissions reduction.

This report demonstrates how factors across material and infrastructure design can be used to mitigate environmental impacts for concrete systems. In this early-stage exploration, methods to compare concrete mixtures proportioning as they relate to environmental impacts, comparison indices based on common performance characteristics were used. This work was then built out to explore the role of steel reinforcement on reinforced concrete member environmental impacts to elucidate mechanisms to drive emissions reduction for these multi-material members. Finally, work was extended to understand how the longevity of concrete systems could influence environmental impacts associated with concrete production.

The topic covered in each section of this report are: (1) an introduction to concrete and life-cycle assessment, a critical review of literature and gaps in implementation, and an overview into existing tools for environmental impact analysis; (2) an introduction to and explanation of a model developed herein to quantify the environmental impacts of producing concrete mixtures in California; (3) An introduction to methods to facilitate multi-criteria evaluation and selection of materials; and (4) A case study on an existing concrete overlay to demonstrate how these models can be applied to infrastructure project during the design phase to facilitate cost-effective and environmental-impact-reducing design selection

Findings in this report suggest notable GHG emissions reduction is achievable as a result of design-stage decisions. These include that higher compressive strength can be more beneficial in certain loading conditions and approximately 30% lower emissions can be achieved through performance-based design methods by decreasing the over-use of material compared to prescriptive design standards. Future studies should include the examination of material efficiency methods for more complex systems to identify the most effective means to reduce environmental impacts through efficient concrete use.

1. Overview

This report demonstrates how considerations across infrastructure design, material design, environmental impact, and costs can be used together for the selection of appropriate materials for infrastructure systems to reduce environmental impacts. To facilitate this, tools were developed for quantitative environmental impact analysis of concrete composites and multi-criteria selection indices for comparing infrastructure material. These tools are demonstrated in this report through evaluation of mixtures in literature as well as a case study on an existing pavement overlay and potential alternative designs. The topic covered in each section of this report, in order of appearance, are as follows:

- An introduction to concrete and life-cycle assessment, a critical review of literature and gaps in implementation, and an overview of existing tools for environmental impact analysis.
- An introduction to and explanation of the model developed, for this report, to quantify the environmental impacts of producing concrete mixtures in California.
- An introduction to and explanation of the methods for a model developed, for this report, to facilitate multi-criteria evaluation and selection of materials and a demonstration of the model using mixture designs from literature
- A case study on an existing concrete overlay to demonstrate how these models can be applied to infrastructure projects during the design phase to facilitate cost-effective and environmental-impact-reducing design selection

2. Literature Review: Tools to Increase Material Efficiency of Concrete

This work reviews the current state of the knowledge and viability of potential research avenues for mitigating greenhouse gas (GHG) emissions from concrete production as they pertain to California. An introduction to how environmental impacts are assessed using life cycle assessment (LCA) methods is presented, as are a discussion of specific considerations for an LCA of cement and concrete, a review of recent literature on the environmental impacts of cement and concrete, and an overview of existing LCA tools. Together this information can inform directions for research, development, and implementation to fuel further work.

2.1. Introduction

The prevailing approach to evaluate a material's sustainability, i.e., by assessing the environmental impacts of its production from cradle-to-gate [1], is inadequate for structural materials. Commonly, changes to material constituents and/or processes are determined to mitigate environmental impacts of materials based on evaluation of the initial phases of material life cycle. In the case of concrete, researchers have assessed several means of reducing emissions in production. These include methods such as: using more efficient kilns for the pyroprocessing stage in cement clinker manufacturing, using alternative raw fuels with lower associated GHG emissions from use, recapturing cement kiln dust, using increased levels of supplementary cementitious materials (SCMs), and capturing CO_2 (e.g., [2], [3]). Frequently, these assessments are made based on cradle-to-gate production; however, this scope does not account for changes in mechanical and durability properties, changes in the maintenance or expected lifespan, or variations at the end of life.

For structural materials, such as concrete, the durability of the material, maintenance, and replacements can have a large influence on the overall environmental footprint (e.g., [4]–[6]). Changes to one component of material development, (e.g., different constituents and processing), can influence other stages of the life cycle and, thus, offset the potential benefits gained. For example, a mixture with lower upfront environmental impacts to produce but with higher permeability may lead to inferior durability characteristics, resulting in increased impacts from maintenance and/or replacement. Furthermore, improvements to mechanical properties, or through improved durability or design, can result in lower demand for materials and provide benefits to the overall footprint. Therefore, all phases from raw material acquisition through end-of-life should be considered concurrently to determine environmental impacts in the context of any changes to mechanical properties, durability, and/or maintenance.

2.1.1 Background: Cement and concrete for California

California is the second largest producer of cement in the United States [7]. Cement, which is the binding component in concrete and mortar, is often used in tandem with mineral admixtures. The most popular mineral admixture used in California is coal fly ash (referred to herein as fly ash), a byproduct of coal combustion. Currently, to meet environmental impact and performance goals, California uses approximately 900 thousand metric tons of fly ash annually [8] (approximately equivalent to 15% of the mass of Portland cement produced in the state [9]—the most commonly produced cement). However, because California does not combust coal as a primary source of energy, the fly ash it uses must be imported. This need to import materials increases costs and environmental impacts. The two nearest important sources of fly ash for California have been the Navajo coal power station in northeastern Arizona, which has been moving towards closing, and coal power stations in Wyoming, which are facing issues of economic and environmental viability, and cannot necessarily meet the needs of California. By 2050, it is projected that cement demand in California will increase by 65% beyond 2015 levels [8], [10] and with it, demand for SCMs will increase. In the research presented here, SCMs including fly ash as well as others will be examined for their ability to contribute to mitigation goals.

2.1.2 Challenges in assessing environmental impacts of concrete

Many frameworks and design methods are available to quantify the environmental impacts of and identify improvements to structural materials. These methods include: cradle to cradle design [11], design for the environment [12], principles of green chemistry/engineering [13], [14], process-based life cycle assessment, economic input-output life cycle assessment [15], and material flow analysis [16]. Recent work on material development has included environmental indicators from some of these methods to evaluate material alternatives with the goal of assessment and reduction of environmental impacts (e.g., [17], [18]). Additionally, some studies have assessed mechanical properties concurrently with environmental impacts (e.g., [6], [19], [20]).

For concrete, LCAs are commonly used to evaluate environmental impacts using a constant volume or constant mass of concrete as the functional unit for comparison (e.g., [1], [17], [21]). However, as discussed by Miller [22], this method ignores that later phases of a structural material's life cycle can outweigh the impacts from production (e.g., material losses due to waste [23], loading and boundary conditions affecting the amount of material required [20], the durability of a material changing maintenance regimes [24]). With the goal of improving the methods or metrics used to assess environmental impacts and consider the material performance, many authors have conducted LCAs of concrete to examine the use of alternative cementitious material (e.g., [21], [25]). Further, case studies have been used to determine the influence of mix proportions on material properties and environmental impacts (e.g., [26]). Efforts have been made to derive comparison methods to weigh characteristic strength and environmental impacts (e.g., [27], [28]) or fracture energy and environmental impacts to determine ideal mix proportions (e.g., [29]).

Due to the significant role of initial mechanical properties, material durability, and desired service performance in concrete infrastructure, this work expands upon these methodologies to emphasize the role of performance on environmental impacts. As mechanical properties are not the sole factor dictating concrete consumption in a specific application, the work also addresses design factors and application specific requirements to more accurately account for their role in concrete demand.

2.2. The life cycle assessment method

Recognition of the coupled high demand for and GHG emissions from the production of cement has increased the desire to mitigate burdens among international groups, industry representatives, and academics [30]–[33]. Cement, which is considered to be the “backbone of global infrastructure” [34], is near-exclusively used in buildings and infrastructure, and over 30% of the cement consumed in the United States is used in streets and highways [35]. To systematically quantify environmental benefits that could be achieved through changes in concrete mixtures and increased material efficiency, robust comparison tools must be applied. In this domain, a more in-depth discussion of process-based LCAs as a quantitative tool for assessing environmental impacts is presented.

LCA methodologies can be implemented to track environmental burdens and to target improvements [36]. This is a data-intensive, quantitative method of analysis, which has a structured approach stipulated by the International Standards Organization (ISO) in the 14040 series of standards (e.g., [37]–[40]). By applying LCA methodologies, a comprehensive accounting of environmental performance can be achieved. Such methods are often used during product development, product or process improvement assessment, strategic planning, policy making, and marketing, among others [41].

Using the ISO framework, the LCA methodology encompasses a four-part process (Figure 1). Notably, interpretation occurs with each of the other parts (i.e., goal and scope definition, inventory analysis, and impact assessment). These parts are discussed in more detail below.

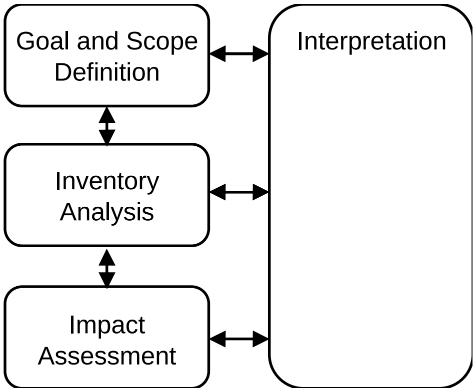

Figure 1. Phases of Life Cycle Assessment (Adapted from [42])

<u>1. Goal and scope definition:</u> The first phase of analysis includes defining the goals and scope for the assessment. In these definitions, the objectives of the work, the appropriate system boundaries, and the function of the system being assessed must be stipulated. A functional unit (which incorporates the function of the system as well as what would constitute equivalent service between comparisons) that provides a consistent basis for analysis is needed. Additionally, at this first phase, it must be determined which input and output flows (i.e., the flows into each phase of the system and the flows out of each phase of the system) will or will not be considered (i.e., the system scope). A simplified diagram that outlines such potential flows into and out of a system is shown in Figure 2. Additionally, whether allocation procedures are to be applied must be defined at this stage of analysis. Allocation methods may be incorporated when co-products or recycled products are part of the analysis. When allocation methods are used, they often are based on either physical flows or economic value of primary goods relative to their co-products or recycled matter [43], though there are other methods of allocation. However, as the cement and concrete industry often use coproducts from other industries, a commonly accepted allocation method has not been drawn for the cement and concrete industry [44].

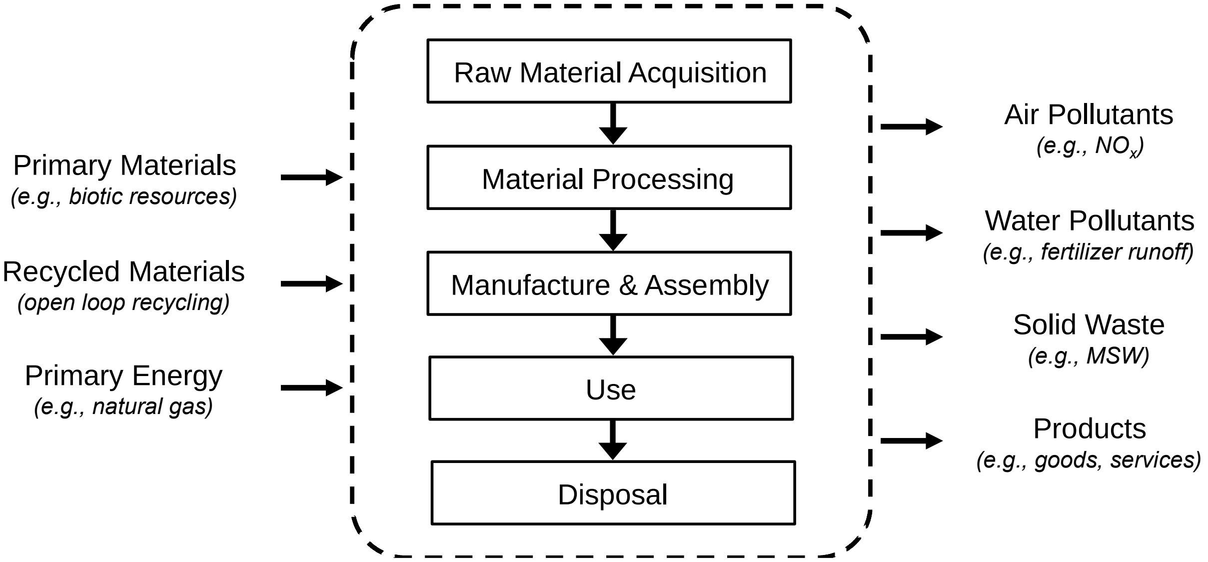

Figure 2. Simplified scope diagram for flows and life cycle phases considered (Adapted from [42]; note: MSW is municipal solid waste)

2. Life cycle inventory analysis: The next stage in assessment, after defining the goal and scope, is the quantification of life cycle inventory flows for the system(s) being analyzed. This inventory includes categorization of inputs (e.g., primary materials, secondary materials, energy) and outputs (e.g., gaseous emissions, liquid waste, solid waste, final products); common metrics analyzed are presented in Table 1. The appropriate quantification of these flows is critical to the assessment of environmental impacts associated with systems and must be performed in a similar manner across systems that are being compared. Due to the data-intensive nature of this phase in analysis, the development of a life cycle inventory is often a time-consuming process with considerable uncertainty.

3. Life cycle impact assessment: Next, a life cycle environmental impact assessment is performed to classify the environmental impacts associated with the life cycle inventory flows per product or system analyzed. At this stage of analysis, inventory flows are classified by their contribution to burdens, and characterization factors are applied to weight their contribution to each impact category. Typical categories considered in these assessments are presented in Table 1. Some impact categories have robust methods for classifying and characterizing flows, such as global warming potential. In the assessment of global warming potential impacts from a system, atmospheric GHGs emissions are classified together and characterization weighting factors, such as those defined by the Intergovernmental Panel on Climate Change (IPCC), are applied to each flow to quantify the impact (typically in terms of CO_2-eq). Not all impact categories have a similar global consensus in methods; for example, water-use has varied by means of analysis [36]. In cases such as this, greater uncertainty can arise in drawing robust comparisons—especially between studies—further emphasizing the need for data and modeling principles to be well defined.

Table 1. Sustainability Metrics (From Horvath [45])

Inventory Assessment	Impact Assessment
Total primary energy use	Global warming potential
Carbon dioxide equivalent emissions/uptake	Ozone depletion potential
Ozone depleting substance emissions	Acidification potential
Criteria air pollutant emissions	Eutrophication potential
Toxic substance emissions	Photochemical ozone (smog) creation potential
Water consumption and degradation	Human health effects (intake fractions and DALYs)
Hazardous and non-hazardous waste generation	Eco-toxicity
	Material and energy resource depletion potential
	Land use
	Water resource depletion

<u>4. Interpretation:</u> The interpretation occurs throughout the LCA methodology, although it is especially important when evaluating and communicating the results of an LCA. In the final stage, interpretation involves making deductions from the quantified results to answer the objectives of the analysis. However, by interpreting throughout the LCA process, factors that inform decision making, optimization of environmental impacts, or alterations to processes can be examined within the context of the defined goal and scope while considering the extent and limitations of the inventories and impact assessment methodology. As such, this component can also inform how improved scopes of analysis, inventory data considerations, and impact assessments may be performed. Further, through the use of uncertainty or sensitivity assessments, interpretation can facilitate considerations of robustness and general applicability of the study performed.

2.3. Life cycle assessments for cement-based materials

While the use of LCAs is growing, only through meticulous assessment at each phase of the life cycle can adequate comparisons be drawn. LCA can be a powerful tool to quantify and understand emissions across many systems. As cement production alone accounts for nearly 8% of global anthropogenic CO_2 emissions [46], [47], LCA tools have been widely implemented throughout building and construction industries to better understand the environmental burdens. Reducing GHG emissions, along with other environmental burdens, is a primary component of green design, where LCA serves an important role in both problem identification as well as mitigation. With 90% of GHG emissions reported for concrete production attributable to the production of cement in some cases [48], a straightforward solution for reducing GHG emissions in conventional concrete is to use less clinker, the high emissions constituent of cement. For example, reductions can be achieved through partial substitution of high clinker-content cement with SCMs [49].

The use of SCMs, however, can alter material performance. For example, pozzolans (i.e., siliceous or siliceous-aluminous minerals that can react with calcium hydroxide with appropriate moisture) can reduce heat of hydration and increase time to reach high compressive strengths as well as improve several properties associated with improved durability [50]. Further, the typically long service life of cement-based materials can lead to a lock-in effect of sustainability-based decisions, in which a decision made at the design phase influences environmental burdens at much later stages of a material’s life [51]. Therefore, not only should mitigation strategies consider parameters such as the manufacturing of cement-based materials, but also how alterations to design decisions, material performance, use phases, and end-of-life can inform appropriate environmental impact mitigation strategies.

2.3.1. System Boundaries

When defining system boundaries for cement-based materials comparisons, considerations for which resources are needed, resource geographic distributions and temporal availability, the function of the cement-based material as well as its intended service-life, anticipated effects associated with maintenance, and potential end-of-life issues should all be specified. However, often, there are typically greater levels of uncertainty for assumptions of future scenarios (e.g., variability in use and end-of-life decisions). These and other factors result in the full life cycle (i.e., cradle-to-grave or cradle-to-cradle) perspective rarely being implemented. As such, there is potential for an immense, under-analyzed benefit that could be exploited through a broader scope of analysis as well as potential unintended consequences if too narrow of a scope (e.g., cradle-to-gate) is applied.

2.3.2. Inventory Modeling

As stated before, life cycle inventory analysis addresses the quantification of resource inputs and outputs, within the scope of analysis, for each phase of a material or product’s life cycle for the specified functional unit. In cement and concrete, the most common form of analysis addresses cradle-to-gate impacts (i.e., from raw material acquisition, through constituent processing and refinement, through material batching). Because cement and concrete require large masses of resources, an understanding of inventory flows, transportation demands, and regional production methods are critical in assessing cradle-to-gate production. In most regions, the materials used in concrete are typically dependent on regionally available resources, which can lead to resource scarcity issues if supplies are not utilized sustainably [52]. Additionally, in regions like California, which currently uses a great deal of SCMs from nonlocally available resources [8], transportation impacts can be notable. In sourcing sustainable resources to produce concrete, the scale of consumption, the temporal availability of resources (which can encompass changing availability of SCMs to seasonal fluctuations in water supplies), as well as factors such as constructability and necessary performance should be addressed.

Beyond the cradle-to-gate stage of assessment, material, energy, and waste flows must be determined for the service and end-of-life phases of the infrastructure system. These elements of the life cycle have been included in the analysis of concrete systems through methods such as determining frequency and scope of maintenance (e.g., [6]) and determination of carbonation during and after use (e.g., [53], [54]). However, environmental impacts must be further analyzed to determine potential benefits during design, use, and end-of-life, as is discussed in the following sections.

2.3.3. Application and Necessary Properties

A common approach to compare environmental impacts and material traits concurrently is to weigh these impacts directly against mechanical properties. The concept of cement efficiency based on desired application and necessary properties has been examined before by comparing GHG emissions to compressive strength (e.g., [27]) and the use of cement efficiency as an emissions reduction method has been touched on by the World Wildlife Fund [55].

Recently, the influence of specific applications and their required mechanical properties relative to the GHG emissions associated with the production of the required volume of concrete has been explored [56]. Findings showed that, depending on the desired function and constraints for some application, the influence of the environmental impact or resource consumption for a volume of concrete can vary as a function of both manufacturing decisions and mineral replacement. Notably, the findings indicate that selection of appropriate mitigation strategies should be driven by the performance requirements of the application.

2.3.4. Influence of Design Parameters

In addition to the mechanical properties of concrete, the specified design parameters can play a role in the impacts associated with concrete. These include, but are not limited to, the specified strength, the specified design age for concrete infrastructure components, and the parameters specified for construction (e.g., workability of concrete, the change in column size at different levels of a building).

Concrete strength is typically specified to meet design requirements. As a lower water-to-binder (for this report, binder is the cementitious powder) ratio for higher strength concrete is often linked to greater binder consumption, potentially higher associated environmental impacts and consumption of certain resources can be anticipated. While the use of some SCMs to offset use of Portland cement has been noted as a possible method to reduce certain impacts without compromising strength (e.g., [57], [58]), use of large quantities of SCMs may result in higher impact concrete systems if strength is compromised [59]. Therefore, designers must be cognizant that different quantities of Portland cement replacement will be beneficial depending on design requirements and know what strengths are necessary for a set application to avoid over designing with a higher impact mixture.

Considering the specified concrete compressive strength as a function of age as a design parameter, the influence of using SCMs and different types of cement on the strength development of concrete may change the strength achieved by the concrete and thus change the potential quantity of concrete needed for an application. This issue has been recognized by several authors and can be rectified by allowing certain concrete mixes to have a higher specified age if they contain certain materials, such as fly ash [60], [61]. At higher ages, different concrete mixes may become favorable in terms of both environmental impacts and resource consumption. In many cases, if designs specified higher ages, lower levels of Portland cement could potentially be specified for an application [62]. It should be noted that calcium silicate hydrate seeds could offer a benefit to reducing cement content and CO_2 emissions, while improving early-age properties [63].

The role of design requirements in creating favorable environmental impact and resource consumption profiles suggests contractors and engineers can play a role in reducing the footprint of concrete. When analyzing construction factors, such as constant column sizes throughout a building, it is possible that more concrete is used than what is required for structural purposes. If designers and contractors change the specifications of individual members based on loading and serviceability requirements, it is possible to reduce the quantity of concrete necessary. This could decrease material demand without changing mixture proportions, thus lowering the environmental impacts and material consumption of a structure. For example, Miller *et al.* showed that reducing column cross-sectional dimensions with increased building height met structural demands while reducing GHG emissions associated with concrete by approximately 4% [62].

2.3.5. Durability

Durability issues and other mechanisms that lead to deterioration can decrease the longevity of infrastructure materials, which can increase unintended environmental impacts [5], [64], [65]. If a material is designed based on initial application requirements, its rate of deterioration can result in more frequent replacement that can offset impacts from production [64]. The relationship between environmental benefits, deterioration, and replacement has led some to propose that improved durability can be more valuable than the low environmental impact from production in terms of reducing concrete's footprint [24]. However, these claims must be substantiated based on the practical lifespan of the concrete infrastructure being designed. Recent studies have shown that prolonging viable concrete service life, if corresponding to a reduction in concrete production, could lead to notable reductions in GHG emissions, but the period to prolong service would have to be great (50% elongation in service could contribute to a 14% reduction in emissions) [22]. Such analyses assume that elongating the longevity of concrete in service could contribute to less demand for concrete to replace structures upon reaching functional obsolescence.

Further, changes in impacts from maintenance and carbon mineralization processes that affect net GHG fluxes (e.g., the absorption of CO_2 as a function of time during concrete service and/or at end-of-life) must be incorporated into comparisons and improvement procedures. For example, in a case study of a bridge superstructure, Lepech *et al.* [6] considered the effects of maintenance on GHG emissions during the structure's lifespan and found that increasing concrete cover would lead to an overall lower emissions profile. Thus, greater upfront material input, which would correlate with higher production impacts, would contribute to a lower overall footprint for the structure.

2.4. Review of Literature and Current Tools

2.4.1. Review: Environmental Impacts of Cement

Many research efforts have focused on improving the environmental impacts associated with cement. Post-Roman era Portland cement classically consists of approximately 95% clinker and 5% gypsum [66]; there are also permutations with lower clinker content, such as Portland-limestone cement (PLC), which as up to 15% limestone composition. The production of clinker is an energy-intensive process and, in addition to GHG emissions from energy consumption, CO_2 is emitted in the production of CaO from $CaCO_3$ during manufacture. More energy-efficient methods for producing clinker have been developed [66] that have allowed for clinker production to become fairly efficient from a thermodynamic standpoint for combustion in air [25], [67]. However, the energy demand is still large and clinker in cement remains the largest contributor to CO_2 emissions associated with concrete production. The International Energy Agency (IEA) has categorized methods to reduce environmental impacts into four main strategies: (1) improve thermal and electric efficiency in clinker production; (2) use alternative (non-fossil) fuels in clinker production; (3) use substitution materials that reduce the demand for clinker in cement manufacture; and (4) employ methods for carbon capture storage at clinker manufacturing sites [68]. Summaries of recent publications investigating these four areas are shown in Table 2.

Some obstacles in this area of research include the appropriate selection of a functional unit and a lack of consensus for scope, goals, impacts analysis, and other LCA assumptions. First, basing analyses on a mass or volume functional unit is a limitation. While material attributes would be application dependent, the use of mass or volume as a functional unit can be misleading. If alterations in material properties were to arise, such as has been noted by using non-fossil fuels in the production of cement [69], these alterations should be represented in the functional unit or at least documented so designers could choose accordingly. Second, the lack of consistency in scope, assumptions, and environmental impacts analyzed make comparisons between analyses difficult. Better approaches may include use of a standardized scope and standardized method for assumptions when necessary. Also, using a standardized functional unit (or comparison indicator) and/or required reporting of changes to material properties in conjunction with reporting changes to environmental impacts would aid the ability to draw comparisons between studies.

Table 2. Summaries of recent publications on improving environmental impact attributes of cement

Publication	Brief Summary & Key Findings
Chen [70]	The authors analyzed environmental impact variations among cement production plants in France. Global warming impact differences between plants were found to result in ~20% variation; however, variations were greater in some impact categories. It was noted that if variations were a function of uncertainty in life cycle inventory inputs, then the differences would have been similar regardless of impact category. Therefore, the authors concluded that differences were likely a result of many factors including uncertainty, variation in technology used, variation in raw material content, variation in measurement accuracy, etc.
Schneider [69]	This research examined methods implemented to improve the sustainability of concrete and potential levers to further lower environmental impacts. Improvements discussed included the use of alternative fuel sources, alternative raw materials, grinding efficiency in clinker production (and the effects of particle size on cement strength), carbon capture storage (might only be reasonable in certain economies at this point), use of clinker replacement (namely: blast furnace slag, fly ash, and natural pozzolanic materials), new clinker substitutes, and standardization in environmental impact restraints (particularly in a global context). The benefits of education were also discussed.
Josa [71]	The authors analyzed the life cycle environmental impacts of different life cycle inventories for cement in the European Union. The results showed inconsistencies in the inventories. Based on a previous analysis by the authors, key issues in the life cycle inventories for cement production were summarized: inventories used theoretical models to estimate some environmental impacts; emissions are primarily linked to the production of clinker; less energy was required for cements with more additives. The authors attributed differences in environmental impacts to "errors and ambiguities in system boundaries." They attributed most of the global warming potential to CO_2 emissions associated with the production of clinker; differences between sources for cement data & associated differences in winter smog were attributed to mining and preparation of energy resources in different countries analyzed; variability in photochemical ozone formation was associated with the fuels and raw materials used.

Publication	Brief Summary & Key Findings
Valderrama [72]	In this research, authors analyzed the different life cycle environmental impacts associated with clinker production lines that had been operated for 30 years to a new clinker production line built using the best available technologies in the same clinker production plant in Spain. Life cycle analysis was conducted for cradle-to-gate production. Most improvements in environmental impact per kg of clinker associated with the new production line were attributed to less consumption of electricity & pet coke. The authors found 5, 15, and 17% reductions in global warming, acidification, and eutrophication respectively with the new production line relative to the older lines. A 13% resources savings, 14% reduction in damage to resources, 11% reduction in damage to ecosystem quality, and 11% reduction in damages to human health were all noted for the new production line relative to the old lines.
Huntzinger [21]	In this research, life cycle environmental impacts for cradle-to-gate production of four cement-manufacturing processes were examined. The four processes examined were: "(1) the production of traditional Portland cement, (2) blended cement (natural pozzolans), (3) cement where 100% of waste cement kiln dust is recycled into the kiln process, and (4) Portland cement produced when cement kiln dust (CKD) is used to sequester a portion of the process-related CO_2 emissions." The same energy was considered for each process and use/disposal phases were not considered. Therefore, while the results showed the greatest decrease in GHG emissions associated with the use of blended cement, the authors claimed this reduction could be an illusion and were more confident in the decrease in GHG emissions associated with using the CKD as a method for CO_2 sequestration even though a smaller reduction in GHG emissions relative to traditional Portland cement was noted with this option.
Habert [25]	This research examined 5 potential scenarios for cement production and compared projected CO_2 emissions to the IPCC goal of reducing CO_2 emissions from 1990 levels by a factor of four (factor 4 objectives). The scenarios were: (0) all parameters held at 2005 values; (1) 30% clinker substitution, 30% raw material substitution; (2) 50% clinker substitution, 10% raw material substitution; (3) 50% clinker substitution, 10% raw material substitution, 45% alternative fuel substitution; (4) all technologies set to extreme values. It was found that factor 4 objectives can only be achieved with the last scenario. Thus, the authors conclude that technological improvements in cement technology are not adequate to meet the IPCC goals. Two key assumptions were made in this research: (1) there are no cement alternatives, such as alkali-activated materials; and (2) the intensity of cement use is dependent on improved building technologies. The authors suggest these areas may be a key method to reaching environmental impact goals.

2.4.2. Review: Environmental Impacts of Concrete

Beyond improvement efforts in cement manufacture, researchers have examined methods for reducing environmental impacts associated with concrete. Typical concrete mixes contained aggregate to cement ratios by-weight of approximately 5.5:1 [73]. While the aggregate contributes a larger fraction of the concrete mass than cement, it typically has a lower environmental impact [74]. However, sources for high-quality concrete aggregate are becoming depleted in certain regions, sometimes requiring aggregate to be transported large distances [75]. Therefore, to examine the potential to reduce environmental impacts of concrete, in large part, research has focused on methods for using recycled material flows for aggregate, improving concrete properties to reduce material demand, and using less clinker and/or cement in concrete [76]. A summary of recent publications on reducing concrete environmental impacts can be found in Table 3.

Table 3. Summaries of recent publications on improving environmental impact attributes of concrete

Publication	Brief Summary & Key Findings
Collins [53]	In this research, an LCA of concrete in bridge application (100yrs 1st service) recycled concrete as aggregate (30yrs 2nd service) was conducted. Considerations were made for carbonation & 4 binder types. The authors found "if carbonation is ignored, the emissions estimates can be overestimated by as much as 13-48% depending on the type of cement binder and the application of RCA during the secondary life"; "Significant reductions in emissions can be achieved by partly substituting Portland cement with fly ash or slag, with reductions as high as 54% in the case of a binder comprising 65% slag/35% [ordinary Portland cement]"
Kelly [73]	This analysis examined crushed concrete material flow and its potential use as a replacement for natural aggregate. The authors found "the amount of crushed concrete substituted influences the amount of other materials in the flow." Factors such as cost, availability, transportation, and physical properties play a role in the use of crushed concrete; in 1998 ~5% of aggregate in the US was crushed concrete. The crushed cement has different properties (such as more angular edges & potential for dissolution) that require different quantities of other materials in the concrete & could lead to different durability properties

Publication	Brief Summary & Key Findings
Meyer [77]	This research discussed alternatives to cement and aggregate. Fly ash, slag, and silica fume were discussed as alternatives to cement and claimed to provide beneficial material properties (although the fly ash was stated to not be beneficial in projects with a needed high early strength). The slag and fly ash were also mentioned to have potential as aggregate replacement. Recycled concrete was discussed as an alternative to natural aggregate with potential for loss of mechanical properties or durability but was presented as a cost-benefit analysis for most regions. Post-consumer glass was mentioned as an alternative to natural aggregate with one of the largest deterrents being cost. Recycled tires were discussed as an alternative fuel source as well as an alternative aggregate, yet their use results in potentially great losses of material properties when used as an aggregate. Recycled plastics were also mentioned as an aggregate replacement, but poor adhesion between cement and the polymers was noted as a potential cause for loss of material properties. Finally, other recycled materials, such as agricultural wastes, ashes, dredged material, and recycled carpet were mentioned.
Provis [78]	This research discussed the use of alkali-activated binders (including geopolymers) in "green concrete." The authors discussed the potential for increased durability with alkali-activated binders and reviewed the environmental impacts of geopolymer concrete. The authors mention issues arising from economic and environmental considerations in specific regions rather than relying on "data for western Europe [and the US]"
Flatt [79]	This research discussed some methods that could be applied to lower the environmental footprint of concrete, claiming small changes can have a large influence due to the volumes of concrete used and the volumes that will be required in the future. The authors mention the main possible solutions to environmental impacts associated with concrete are: "(1) Partial cement (clinker) replacement by SCMs; (2) Development of alternative binders; (3) Broader use of concrete mix designs that limit cement content; (4) Recycling of demolished concrete in new concretes; (5) Enhancement of durability (designing new infrastructures for longer service life); (6) Rehabilitation of existing infrastructures (extending the service life of existing infrastructures)."
Mehta [76]	This research provided a brief review of climate change & the role of concrete in providing sustainable construction materials. The author discusses several initiatives & organizations setting goals for the concrete sector.

Publication	Brief Summary & Key Findings
Purnell [80]	This research discussed the use of variations in common mix parameters to lower the environmental impact of concrete. The authors considered influences on mechanical properties and durability properties by altering concrete mix designs with pulverized fuel ash, aggregate, superplasticizer, and water to cement ratio. Carbon dioxide emissions associated with each of these constituents were considered and 16 characteristic strength classes were analyzed (mixes were theoretical and validated by eight real mix designs).
Heede [74]	In this research, a review was made on each step in the LCA of concrete. There was an emphasis on the definition of a functional unit, which can strongly influence the outcome of an LCA of materials. The authors suggested using a functional unit that incorporates differences in strength, durability, and service life. The authors also dealt with different allocation methods for impacts associated with certain concrete constituents. There was a discussion of the potential improvements associated with fly ash and slag, as well as the lower environmental impacts associated with aggregate than cement
Talukdar [81]	This research assessed the mechanical properties of concrete using recycled materials as aggregate alternatives to natural aggregates. The recycled aggregates considered all resulted in lower strength materials & materials that were more susceptible to freeze-thaw deterioration
Chen [44]	Environmental impacts associated with using blast furnace slag and fly ash as SCMs were analyzed in this research. Life cycle environmental impact assessments were conducted for these SCMs and for Portland cement. Cradle-to-gate assessments were made using different allocation methods for the impacts associated with the slag and fly ash.
Habert [28]	"In this study, two different environmental options for sustainable concrete mix-design were considered and evaluated. The first one is the substitution of clinker by mineral additions in cement in order to reduce the environmental cost of the material for a given volume of concrete produced. The second one is the reduction of the concrete volume needed for a given construction process by enhancing the concrete performances. It has been estimated that, in France, the CO_2 emissions could be reduced by 15% by increasing the level of substitution in concrete. It has also been estimated that the second option could lead to reduction of the order of 30%. But it has to be kept in mind that ... it is possible to combine cement substitution and mechanical strength increase ... this could lead to CO_2 emissions reduction of the order of 40% (15% for the substitution and 30% for the mechanical strength increase)."

Publication	Brief Summary & Key Findings
Pelisser [82]	In this research, various ratios of recycled tires and metakaolin were examined for their influence on the properties of concrete with the goal of producing more lightweight concrete. Different processing conditions were examined. The plasticity, compressive strength, and thermal conductivity of the resulting composites were analyzed. The authors found "the use of tire rubber and metakaolin in lightweight mortar or concrete contributes to the reduction of raw materials consumption, to material recycling and permits the production of materials with improved thermal efficiency."
Jayapalan [83]	This research discussed the use of inert nano and microparticles on early-age behavior and properties of cement-based materials. LCAs were conducted for a mass-based functional unit. The research indicated "identification of an 'optimum' inert filler material, from both particle size and embodied energy perspectives, should be the subject of further investigation... the introduction and optimization of additional functionalities such as photocatalytic properties (binding pollutant gases, antimicrobial effect), self-sensing capability and development of lower-embodied energy nanoparticles could enhance sustainability and result in a sustainable construction product."

While articles summarized by no means exhaust the research on improving environmental impacts associated with concrete production, the papers review typically aligned with one of the following two general categories: (1) research considering novel materials, which discuss the potential benefits of the material and seek to characterize or quantify said benefits, or (2) research iterating on previous works that seek to build fundamental knowledge by providing additional material characterizations or assessments (e.g., [81], [83]).

As with the cement literature, the literature for concrete lacked consensus when reporting environmental impacts, reporting material properties, and selecting appropriate functional units. While, again, many functional units used a mass or volume basis; several authors discussed material strength and durability concerns (e.g., [53], [79], [80]). The IEA and WBCSD state that a, “documented assessment of substitution material properties is needed, to understand and communicate which substitutes are best for which intended applications” [2]. Thus, research in this area could benefit from a unified method for assessment and potentially collocation of data.

2.4.3. Tools for quantifying the environmental impacts of concrete

LCAs are often used to compare mixtures with varying SCMs, allowing a designer to choose or propose the least impactful mixture design for a certain project. For an LCA tool to accomplish this, it must address emission data inventories for each of the materials in the concrete mixture. Data availability becomes a limiting factor as inputs and outputs can vary greatly by technology, by region, and over time.

As noted above, it is important that LCA tools for concrete mixtures have inventories that include SCMs in addition to other concrete constituents. In conventional concrete mixtures, fine and coarse aggregates are held together by a hydrated cement paste; however, the use of SCMs and chemical admixtures are common to achieve desired properties. The following tools (see summary in Table 4) have databases capable of performing LCA for concrete mixtures, in addition to pavement design. The best databases are constantly evolving and expanding as data become more available. One form of database expansion that is becoming increasingly popular in LCA packages is the implementation of environmental product declarations (EPDs), determined from Product category rules (PCRs). PCRs are guidelines published by an organization, such as the NSF International, specifying how to conduct LCA for products using standardized methods (such as ISO 21930:2017 or EN15804) [84]. Following the guidelines, third parties and vendors may then form what are known as EPDs from product emission data. The use of EPDs in procurement is increasing [85]. EPDs can be used by an LCA tools to effectively grow their databases for particular kinds of materials. Notably, as databases can vary between tools, comparing results between databases can be challenging [86]. EPDs produced by the same PCR overcome this limitation and allow for like-for-like comparisons. However, there are variations between PCRs; further, PCR standards do not require data for use stages and end-of-life stages, and so cradle-to-grave assessments using EPDs can sometimes be challenging [87]. In addition to inventories, other factors that are important to consider for LCA tools are cost/accessibility as well as limitations in system boundaries and life-cycle impact assessment (LCIA) methodologies.

It must be noted that the tools reviewed and their inventories are not exclusively representative of materials produced in the United States or North America. Rather, these tools have been developed in a variety of regions and have different degrees of ability to tune inputs to reflect variations in production methods. Further, while some tools, such as the GreenConcrete tool, allow for variations in concrete mixture proportions, many of these tools currently possess a limited number of concrete mixtures that can be compared. A more detailed discussion of each of these tools and references to these tools are presented in the subsequent section.

Table 4. List of LCA tools for concrete mix design

Tool	Owner/Developer	LCA System Boundary	Dedicated Pavement Tool* Y/N	Cost Y/N
Green Concrete Tool	UC Berkeley	Cradle-to-Gate	N	N
GaBi	Sphera	Cradle-to-Grave	N	Y
SimaPro	PRé Sustainability	Cradle-to-Grave	N	Y
OpenLCA	GreenDelta	Cradle-to-Grave	N	N
Athena	Athena Sustainable Materials Institute	Cradle-to-Grave	Y	N
eLCAP	UC Davis	Cradle-to-Grave	Y	-
GCCA EPD tool	Global Cement and Concrete Association	Cradle-to-Grave	N	-
Umberto	ifu hamburg	Cradle-to-Grave	N	Y
One Click LCA	Bionova	Cradle-to-Grave	N	Y
Tally	Kieran Timberlake	Cradle-to-Grave	N	N
e-tool	e-tool	Cradle-to-Grave	N	Y
Embodied Carbon in construction calculator (EC3) tool	Carbon Leadership Forum (CLF)	Cradle-to-Gate	N	N
Climate Earth EPD	Climate Earth	Cradle-to-Gate	N	Y
BEES	NIST	Cradle-to-Grave	N	N
ECORCE	IFSTTAR	Cradle-to-Grave	Y	N

*Tools with Y have a dedicated pavement component but are still capable of analyzing concrete mixtures. Most other tools listed can perform pavement LCA as well, but to the best of the authors' knowledge do not necessarily have a dedicated component for it.

2.4.3.1 GreenConcrete Tool

The GreenConcrete Tool [88] is a cradle-to-gate software that considers detailed supply-chain impacts, accounting for all manufacturing processes throughout the entire system boundary (i.e., cradle-to-gate). A version of this tool can be freely accessed online [88]. The tool's database includes SCMs, particularly fly ash, granulated blast furnace slag, and natural pozzolans. Commonly used chemical admixtures such as plasticizers, accelerants, and retardants can also be inputs. References to the entire database including fuel, electricity, and transportation data are available through the webpage (including EPDs). The database is worldwide and thus accurate to different geographical locations. The tool outputs 12 impact categories (including TRACI[1] impacts).

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[1] Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) - LCIA methodology developed by the Environmental Protection Agency (EPA)

2.4.3.2. GaBi

GaBi is a popular, at-cost software [89] capable of assessing concrete mixes with an extensive database that allows for analysis of many SCMs and admixtures, including alkali activators [90]. Researchers have also used GaBi for pavement LCA [91]. Its database is worldwide and third-party databases, such as ecoinvent, can also be used within it. The software allows for full cradle-to-grave LCA. In addition to environmental assessments, GaBi can also perform social and economic material analyses [92]. GaBi can be used with several impact methodologies.

2.4.3.3. SimaPro

SimaPro is an LCA package [93] that is widely used around the world. Similar to GaBi, SimaPro’s databases can be complemented with third-party databases, such as ecoinvent. SimaPro can be used to conduct LCAs for both concrete mixes and pavements [94], [95]. Limitations in SimaPro have been noted, one of which is difficulty in quantifying certain supply chain impacts within the production phase, such as accounting for transportation from the material extraction site to the production facility [96]. Simapro can be used to perform uncertainty assessments based on data quality.

2.4.3.4. openLCA

openLCA is an open-source LCA tool [97]. It includes a built-in database, and access to databases such as those from GaBi and ecoinvent can be purchased. openLCA has been used for concrete mix design with geopolymers [98] and for pavement design [99]. Cradle-to-grave assessments are possible and, again, several impact methodologies can be used. openLCA has a built-in uncertainty analysis tool, which allows for Monte Carlo simulations within the software.

2.4.3.5. Athena

Athena is a commonly used LCA tool for building construction, and it has a dedicated pavement component [100]. Parameters for the pavement tool include control of the base, sub-base, surface pavement materials as well as the number of lanes and more. The tool also allows for user-specified control of concrete mixtures, including the incorporation of SCMs [101]. Athena can perform complete cradle-to-grave assessments. Outputs include all TRACI impact categories.

2.4.3.6. eLCAP

eLCAP is a regional pavement LCA tool designed at the University of California Pavement Research Center [102]. It can be used for complete cradle-to-grave analysis, but it was not broadly available at the time of this work. The tool has access to the GaBi database. The software also allows for user-provided EPDs, allowing for even greater control and potential growth of the database.

2.4.3.7. Global Cement and Concrete Association (GCCA) EPD

The Global Cement and Concrete Association (GCCA) maintains the international Getting the Numbers Right initiative [103]. This group has also provided stipulations for metrics to monitor the development of environmental impact models for cement [104], which it launched in 2019. As it is fairly new, its current usage rates in academia and industry are not well reported.

2.4.3.8. Umberto

Umberto is a commercial software capable of performing full cradle-to-grave LCA for both concrete mix design and pavement design [105]. It can use databases from GaBi and ecoinvent. With a complete database, recent studies have shown Umberto's ability to conduct LCA for a wide range of concrete with a range of additives, ranging from fly ash to geopolymers [106]–[108]. Research suggests its applicability to pavements [109]. A variety of impact methodologies can be used. Output schemes are elaborate and include less common options, such as Sankey diagrams. It also has cost and ecological performance integration for design optimization.

2.4.3.9. One Click LCA

One Click LCA software [110] has its own built-in database, but it may also be used with databases such as ecoinvent. Additionally, the user can input EPD data, to build and customize their project. One Click LCA capabilities vary by license type. An "Expert" level license is required to design a unique concrete mix in the tool. The tool can output several environmental impact schemes and can perform full cradle-to-grave LCA. One Click LCA also provides access to Climate Earth (discussed below) data and the EPD library.

2.4.3.10. Tally

Tally has a component specifically designated for concrete mixtures with an extensive database including SCMs such as fly ash and slag [111]. The tool is free, capable of full LCA through end-of-life, and it has six main impact output categories: global warming, energy demand, acidification, eutrophication, ozone depletion, and smog formation. According to ZGF, a design firm using Tally, the tool does not require input or use of EPDs [111], which may indicate access to extensive regional databases. Tally can be used in tandem with Carbon Leadership Forum's (CLF) Embodied Carbon in Construction Calculator (EC3, discussed below) tool, where a material modeled with EC3s library of EPDs can be used in Tally. Through EC3, a user could add data for a unique concrete mixture to Tally.

2.4.3.11. e-tool

e-tool is a subscription based LCA program that can assess concrete mixtures. The software allows for cradle-to-grave analysis. e-tool's e-tool's specific database is not readily identifiable. Additionally, the company website does not provide the LCIA methodology. e-tool does claim to accept EPDs as part of their growing database [112]. A recent study using e-tool to assess GHG emissions for 6 different concrete mixtures includes fly ash and granulated blast furnace slag [86]. e-tool can also be used to conduct cost assessments.

2.4.3.12. Building for Environmental and Economic Sustainability (BEES)

BEES [113], from the National Institute for Standards and Testing (NIST), is a popular LCA software in the US for structures [114]. The developers have indicated intentions of expanding to pavements in the future [115]. The software allows for prescribed combinations of SCMs in a mixture design, but not complete user control of percentages. This limits which SCMs may be considered (i.e., only fly ash and slag). The software is also component based and considers full LCAs. BEES can output several environmental impact categories, and is noted for having strong economic cost and performance integration [116], [117]. BEES mentions that their LCIAs abide by the same PCR guidelines used for producing EPDs [113].

2.4.3.13. Embodied Carbon in Construction Calculator (EC3) tool

The Embodied Carbon in Construction Calculator (EC3) tool uses environmental product declarations (EPDs) to calculate LCA for concrete mixtures [118]. Carbon Leadership Forum (CLF), the producers of EC3, implemented a concrete PCR project recently published through NSF International in 2019 for concrete reporting databases and EPD inventories. However, life cycle inventories (LCIs) for SCMs appear limited. For example, an inventory for granulated blast furnace slag is reported in NSF International PCR for concrete; yet, fly ash and silica fume are labeled as “recovered materials,” have no dedicated LCI, and are said to be limited as material inputs [119]. There is also a transparent database for chemical admixtures, similar to the Green Concrete tool. This indicates that, at the moment, the EC3 tool is perhaps best for mixtures with Portland cement as the only binder material as it is limited for SCMs. Also, within the system boundary, transportation can only be specified for the product stage to-and-from a production plant. Transportation to the construction site is not considered in the EC3 tool [84]. The tool only conducts a cradle-to-gate system boundary.

2.4.3.14. Climate Earth

Climate Earth is a paid, consulting service that allows for embodied emission LCA of any concrete mix including SCMs. Climate Earth can create EPDs for concrete producers and vendors. The user community EPDs make up the databases for the concrete design LCA tool. Climate Earth emphasizes its EPD capabilities and growing/expandable inventory, claiming access to over 20,000 data profiles [120]. Environmental impact categories include, but are not limited to, global warming potential, ozone depletion potential, acidification potential, and photochemical smog creation potential. It is not clear how vast the database is beyond EPDs.

2.4.3.15. ECORCE

ECORCE is a free, dedicated pavement LCA tool. The system boundary is through construction and maintenance phases with limited end-of-life options. Specifically, the tool does not consider complete removal of the structure and only removal of upper pavement layers [121]. ECORCE has its own internal database (updated annually) which consists mostly of data from France. Yet, it can be extended to other countries, such as the USA, through the international version [121], [122]. The tool outputs GHG, acidification, eutrophication, tropospheric ozone, ecotoxicity, and chronic toxicity impact categories.

2.5. The case for efficient design of concrete utilizing properties

A large obstacle in selecting materials for sustainable concrete system design is the complexity within infrastructures systems and variability between systems. This is reflected in the literature, as much of the present analyses are individual case studies that cannot be directly applied to other applications. Additionally, the scope varies between studies (e.g., some analyses are for infrastructure materials, some analyses do not include end-of-life, some analyses make assumptions about service behavior that are not founded in empirical evidence). Defining a consistent analysis methodology and finding a means to simplify analysis without losing integrity is vital to creating pathways for GHG emissions mitigation.

While reducing environmental impacts from material production has great potential to contribute to reduced impacts for a system of materials, the structural design can also have a significant influence on environmental burdens. In addition to Lepech *et al.* [6], others have examined the effects of design on the environmental impacts we attribute to infrastructure materials. Recent work on appropriate functional units for structural material comparisons, discussed by Purnell and critics of his work [123]–[125], have led to different conclusions, suggesting mass-based analyses can yield misleading results (an issue also discussed by Lifset [126]). Yeo *et al.* [127] presented a method of minimizing the total embodied energy of buildings by applying structural optimization techniques. For the case examined (a structural beam) the results indicated a potential to reduce the embodied energy by 10%.

However, despite knowing certain mitigation alternatives for concrete can alter material performance, the two areas are not typically considered together. For example, Damtoft *et al.* [128] discussed the influence the cement and concrete industry has on contributing to climate change initiatives. The authors discuss methods used to reduce CO_2 emissions from cement production, reduce CO_2 emissions and energy consumption in clinker production, and reduce clinker contents in cement while also noting the changes in physical properties that can occur from the methods discussed. Yet, a comparative environmental impact analysis of alternatives was not performed. This type of limitation could lead to issues in comparisons of scopes of assessment.

The selection of concrete mixture proportions, the quantity and type of steel reinforcement, and other design decisions can have significant implications for the environmental impacts associated with concrete systems. Depending on the application of interest, different concrete performance metrics (e.g., strength, permeability, workability) may be the guiding criteria—these differences could lead to the minimization of environmental impacts through the selection of different mixture proportions [56]. For example, to minimize chloride ingress, a certain concrete mixture may be selected over one designed to maximize compressive strength. Noting that concrete is largely used in transportation infrastructure and building applications [129], the difference in properties required for these uses could lead to notable differences between which concrete mixtures can minimize environmental impacts. Additionally, most structural concrete is used with reinforcing steel to support the tensile loads on members. Because the production of steel also has high GHG emissions, there becomes a multi-material system tradeoff. Namely, identifying when to use a smaller or larger member, or to use more or less steel rebar to mitigate environmental impacts [130], [131].

2.6. Future Directions

This review discusses common methods for analyzing environmental impacts that could allow for consideration of mechanical properties and durability to increase potential reductions to system impacts. Application of such methods requires the use of methods and inputs from LCA, material science, and structural engineering, as well as application-specific demands.

The incorporation of environmental impact assessment at every stage through material development, manufacture, structural design, construction, use, and end-of-life will better inform decision making and the potential interplay between phases. Development of such methods for incorporation of environmental impact assessment could also aid in avoiding previously unforeseen impacts. Several questions for further study are:

- What new methods/metrics/indicators would ease designer decision-making and increase the adoption of complete material impacts (i.e., not using highly simplified models that miss critical aspects)?
- What processes or practices can be targeted within the industries that use the most concrete to have the greatest influence on environmental impact?
- How much concrete production can be sustained per capita? How do different material alternatives change these projections?
- How can strength/durability be weighed adequately with other material efficiency goals? (Goals: (a) longer-lasting; (b) modularization; (c) component re-use; (d) less material)
- How can cement be used more efficiently in transportation infrastructure? How does this vary depending on climate and exposure conditions?
- How can the multiple attributes of the environmental impacts/constituents/processing technologies/material properties/application dependent service-behavior be used to identify the lowest impact material?
- Is the lowest environmental impact material the one with the lowest mass flows? (e.g., Are there situations in which greater yield loss or more material replacement result in lower environmental impact products with respect to construction materials?)
- Under what circumstances would stakeholders be justified in compromising material performance for lower environmental impact materials?

3. A unified approach to quantifying the key greenhouse gas emissions in California concrete production

The objective of this section is to develop a cohesive, unified dataset of inventories, which are needed to quantify the effects of material, energy, waste, and emission flows on the environmental impacts of concrete. The models developed will consider GHG emissions, namely CO_2, CH_4, and N_2O emissions, for the key components of cement and concrete production in California. The structure of the data will allow for tailoring inputs to capture variations in different regions around the world. This allows the user to adapt for production in other regions or for importing material from other regions.

3.1. Introduction

Current stock and new concrete infrastructure that are anticipated in the coming decades need to be transformed in fundamental ways to reduce environmental burdens. This work focuses on the formation of requisite datasets to support informed decision-making and management solutions for innovative concrete infrastructure that can meet performance requirements while mitigating environmental impacts.

Robust datasets are needed to accurately assess the environmental impacts and financial costs associated with alternative concrete mixtures, use phases, and end-of-life options. Many cost implications from the construction industry are available through sources such as the RS Means [132], but data that reflect US-specific environmental impacts from concrete are limited to Environmental Product Declarations (EPDs) and individual academic studies (e.g., [18]). These current assessment methods lead to difficulties in drawing direct comparisons between material alternatives and consideration of adjustments in concrete design.

To build a foundation for the advancement of work in this area, this study focuses on the development of a database that can readily be used by decision-makers to compare GHG emissions of varying concrete mixtures.

3.2. Methods

For this work, both process-based emissions (e.g., from limestone decarbonation) and energy-based emissions (e.g., from combusting fossil fuels for thermal energy) were quantified to assess GHG emissions from the production of concrete mixtures. The energy-based emissions were determined through energy demands and energy-derived emissions (factors for energy modeling and sources are discussed below); emissions from fuels used in transportation were included as energy-based emissions. The GHGs that were considered in this work are the three most emitted GHGs: CO_2, CH_4, and N_2O. These gases were assessed in terms of CO_2-eq using the 100a global warming potentials from the IPCC [133]. The scope of the impacts assessed is outlined in Figure 3. Comparisons of concrete mixtures were based on a cubic meter of production. While the use phase was not directly a component of the environmental impact comparisons in this section, it was considered in the accompanying sections of this report through the inclusion of performance-based comparison methods. Specific modeling assumptions for individual concrete constituents, transportation, batching, and end-of-life are stipulated in Appendix A.

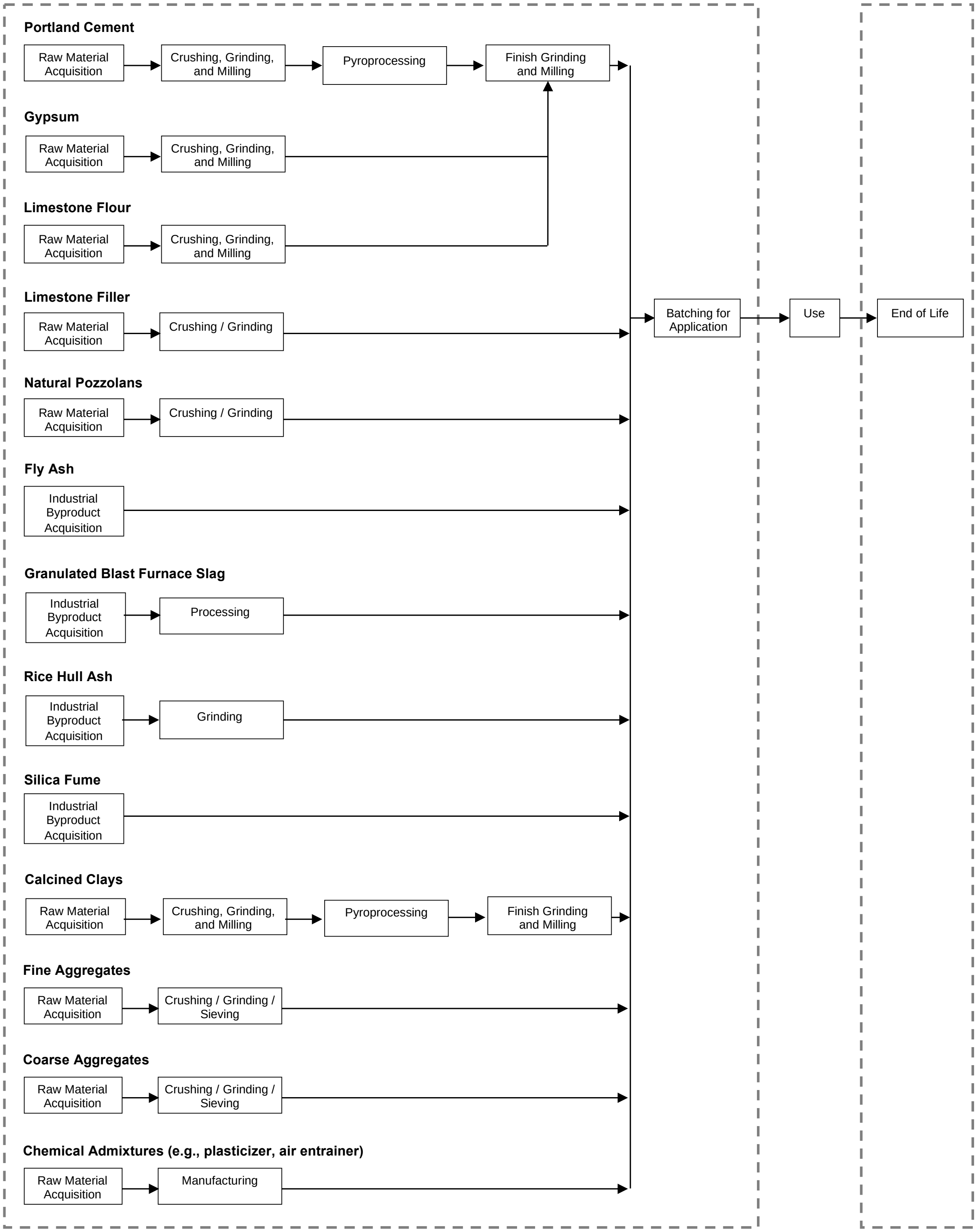


Figure 3. Scope Diagram (gray dashed lines are considered within the scope of assessment; emissions calculated based on process- and energy-based emissions, which included transportation emissions).

To capture an approximation for end-of-life-related GHG emissions, demolition and crushing energy demand was modeled based on data from [134]; these data facilitated use of California-specific energy grids to determine emissions.

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., natural pozzolans, batching) was tabulated. These constituents and processes can then be used to determine GHG emissions from the production of concrete by being weighted based on the mass of constituents used in a given concrete mixture.

These constituent and process impacts from the intermediary step are utilized in the spreadsheet in an example impact assessment of a mixture. Namely, to implement an example of the calculation of GHG emissions for a concrete mixture, a mixture with limestone filler is presented. Transportation distances for the constituents of this mixture are listed in Table 5. In this example, all transportation was modeled as being transported by truck.

Table 5. 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	150
Calcined Clay*****	150
Silica Fume	150
Fly Ash	2000
Blast Furnace Slag	2000
Fine Aggregates	100
Coarse Aggregates	100
Superplasticizer	1000
Water	0

*** model for 95% clinker content;** ** can be added as a portion of cement; *** can be added as a mineral admixture in concrete; **** model for pozzolans that only require quarrying and grinding; ***** model for pozzolans that require calcining

4. Multi-criteria selection tool for the engineering of concrete

The objective of this section is to address several key questions in the design and selection of concrete mixtures including how changes in member size affect environmental impact and performance. This work will provide means to quantify under what circumstances materials with less cement can be used while maintaining infrastructure performance. Consideration will be given to several opportunities for partial cement replacement with alternative materials.

4.1 Introduction

The design of concrete infrastructure, through requirements for member geometry, material properties, construction timeline, and the use phase, affects the concrete type and amount of material required and, thus, influences what materials are selected [131]. Typically, a screening process is used to sort materials based on a certain requirement and thus, eliminate materials that do not meet the criteria. Those that do meet the criteria are considered to be viable options [135]. However, small modifications to mixture design, such as the amount or type of mineral admixture, can yield a suitable mixture that may also contribute to notable changes to the environmental impact of the material [136], [137].

In this section, the comparison metrics are presented that focus on the role of mixture proportioning in concrete to mitigate GHG emissions. It has been shown that partial replacement of cement in concrete can lead to reductions in GHG emissions without compromising properties such as compressive strength [57], [136], [138]. However, there are scenarios under which changing constituents can have significant effects on properties—typically when changes are made that necessitate higher volumes of material; for example, a weaker concrete for which a larger cross-section of material is required to support a load. As such, this work expands multi-criteria selection methods, originally developed for the design of mechanical components (e.g., [139]), in the selection of concrete mixture proportions. In doing so, this work addresses differences in concrete mixture proportions and their concurrent effects on GHG emissions and several different performance criteria. These comparisons account for how material properties influence the required volume of concrete necessary for common transportation infrastructure applications. The volume, in turn, influences GHG emissions from the production of different quantities of material.

This work focuses on a multi-criteria selection tool for concrete. The method presented facilitates decisions in proportioning of concrete constituents (i.e., Portland cement, water, aggregates, mineral admixtures) to improve the utilization of individual constituents in concrete based on its intended application.

4.2. Comparison Indices

4.2.1. Methods

To address the simultaneous influence of upfront decisions in concrete mixture proportioning on both environmental impacts and material properties, ratios—as discussed below—can be used to express environmental impacts due to concrete production as a function of mechanical properties depending on design scenarios. The role of the mixture proportions in the environmental impacts—here focusing on greenhouse gas (GHG) emissions—from concrete production was assessed for several hundred concrete mixtures using the comparison indices by Miller *et al*. [56]. These indices weigh how the volume of concrete required for a certain application would change as a function of the material properties against the changes in environmental impacts for different concrete mixtures. Here, only one material property is considered to be controlling (e.g., compressive strength) and the effects of changing concrete constituents on other properties is considered to not affect the volume of concrete needed. If more than one property can contribute to volume changes, concurrent assessments can be performed in future work.

To exemplify the implementation of this tool for comparisons, concrete mixtures were compared from several data sources: [58], [140]–[164]. These papers were used to assemble a set of 399 concrete mixtures, which were selected to reflect a variety of material properties, SCMs, aggregate quantity, and water quantity (note: strength for these mixtures was adjusted using the methods stipulated by [165] to account for differences in test specimen dimensions). The GHG emissions for these mixtures were calculated using the methods discussed in Section 3. The methods implemented using these data can be extended to mixtures from ready-mixed concrete plants with the availability of the same inputs.

The selected design cases for this study are a beam member in bending, a column member under axial load, a beam member in deflection, and the required concrete cover under chloride ingress (Table 6). For each of these indices, a lower value is more favorable and is commensurate to a reduction in environmental impacts, a reduction in the demand for material from improved material performance, or both. Properties such as clinker content, water-to-cement (w/c) ratio, binder content, water-to-binder (w/b) ratio, and mineral additives content of concrete mixtures were plotted against the comparison indices. Note: for the data plotted, cement contains 95% clinker and 5% gypsum by weight; binder contains cement and SCMs.

Table 6. Comparison indices to relate environmental impacts and material properties

Index	Definition
$X_{bending}$	This index would be applied for a member in bending controlled by rupture of the extreme fiber on the tensile face. A concrete mixture with a low value of this index would either indicate a high modulus of rupture and/or low environmental impact.
$X_{deflection}$	This index would be applied for a member in bending controlled by deflection. A concrete mixture with a low value of this index would either indicate a high elastic modulus and/or low environmental impact.
X_{axial}	This index would be applied for an axially loaded member controlled by compressive strength. A concrete mixture with a low value of this index would either indicate a high compressive strength and/or low environmental impact.
X_{Dcl}	This index would be applied for the examination of the influence of chloride penetration on the necessary concrete cover depth. A concrete mixture with a low value of this index would either indicate a low chloride diffusion coefficient and/or low environmental impact.

4.2.2. Results

The statistical relationships (abbreviations are as follows: r is the correlation coefficient, p is the p–value, and n is the number of data points) between the comparison indices and the material properties were evaluated for each case (see Table 7). To simplify the presentation of results, all SCMs considered in this work are examined concurrently in the Table 7, but it is noted that different SCMs have varying reactivity and could lead to different properties at different ages.

Table 7. Evaluation of the statistical relationship between the comparison indices and the material properties related to Portland cement content and SCM content

		clinker content	w/c	binder content	w/b	SCM content
$X_{bending}$	*r*	0.93	-0.77	0.61	-0.38	-0.24
	p	<0.001	<0.001	<0.001	<0.001	<0.001
	n	378	291	326	326	326
$X_{deflection}$	*r*	0.98	-0.85	0.67	-0.60	-0.31
	p	<0.001	<0.001	<0.001	<0.001	0.034
	n	63	63	46	46	46
X_{axial}	*r*	-0.16	0.19	-0.17	0.38	0.05
	p	0.002	0.001	0.002	<0.001	0.341
	n	378	291	326	326	326
X_{Dcl}	*r*	-0.50	0.53	-0.45	0.41	0.35
	p	<0.001	<0.001	0.002	0.005	0.020
	n	48	48	45	45	45

Among the material properties studied, the clinker content shows the strongest correlation to the index that represents an unreinforced concrete member in flexure whose design is controlled by strength, $X_{bending}$, (determined by Equation 1) with r = 0.93 and p < 0.001 (Figure 4). Similarly, an increasing trend is observed between the binder content and the $X_{bending}$ (Figure 5); however, the correlation is not as strong as the relation shown by the clinker content. The w/c ratio (i.e., the ratio of water to Portland cement) also shows a strong correlation to the index (r = −0.77, p < 0.001, and Figure 4); however, the behavior is not linear, suggesting a limited benefit with high w/c ratios.

$$X_{bending} = \frac{i}{f_c^{0.25}} \qquad \textbf{Equation 1}$$

where $X_{bending}$ is as previously defined, *i* is the environmental impact of the concrete mixture per unit volume and f_c is the concrete compressive strength used in the design.

Although there is no significant correlation between the mineral additives content and the index (Figure 6), the behavior resulting from the use of different SCMs alone may have specific trends. Fly ash and limestone correlate to the index with r = −0.44 (p<0.05) and r = 0.59

(p<0.05), respectively. Due to limitations in the data, it is difficult to fully assess whether this is a function of the properties from these additions or a function of smaller sample size; however, within a concrete producer's database, trends associated with individual SCM types can be used to better target mixture design.

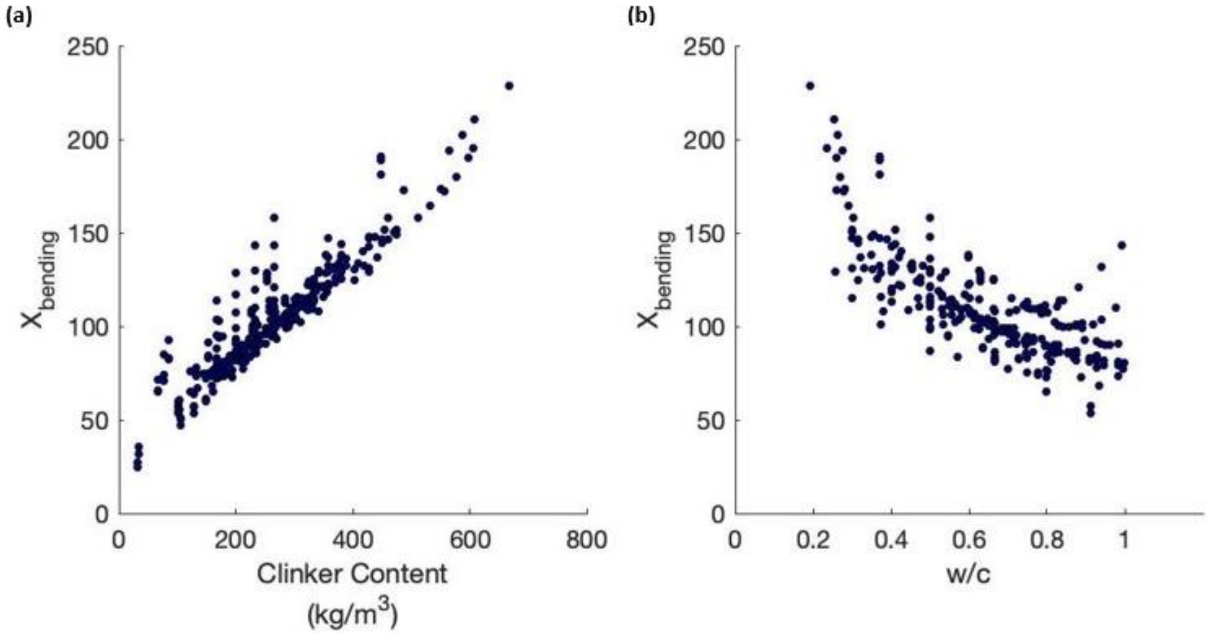


Figure 4. The comparison index for a strength controlled unreinforced concrete in flexure relative to (a) clinker content and (b) w/c ratio. (a) clinker content (note: a higher clinker content is correlated with higher emissions), and (b) w/c ratio (note: a higher w/c ratio is correlated with lower strength and this dataset has overlap between low strength and low emissions mixtures)

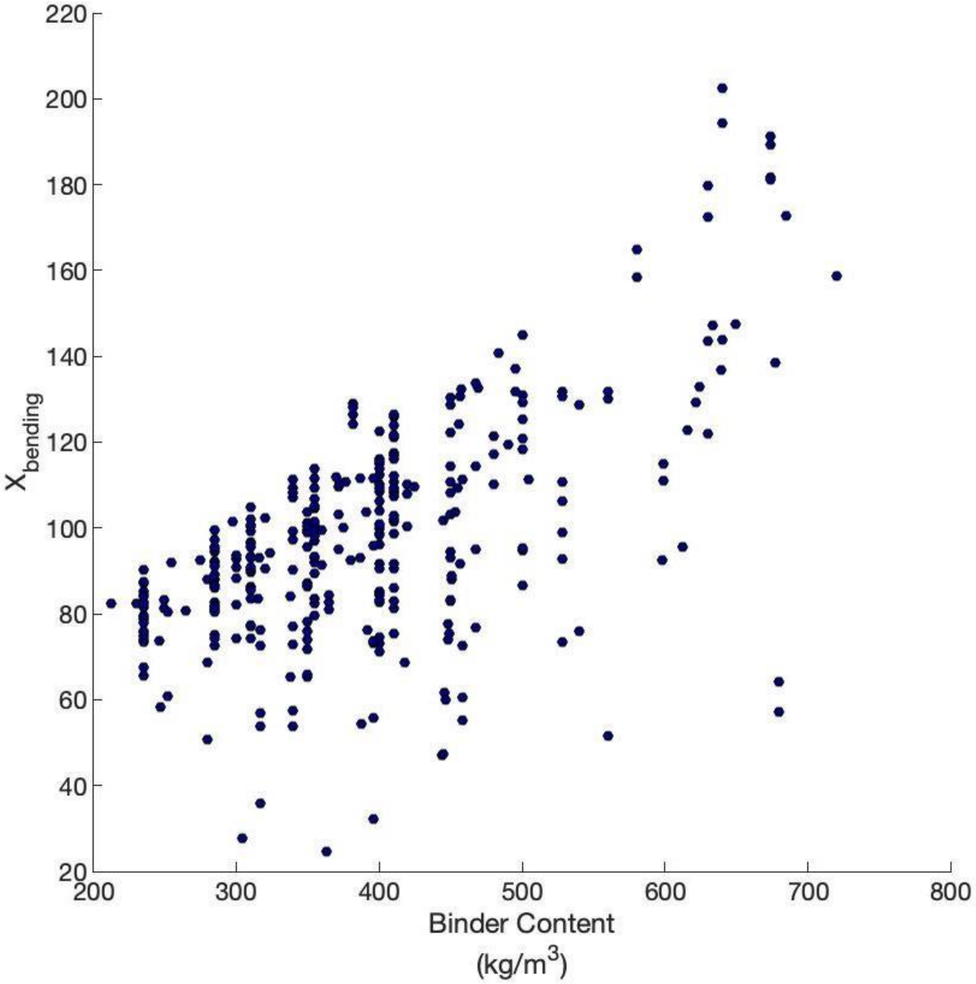


Figure 5. The comparison index for a strength controlled unreinforced concrete in flexure relative to binder content

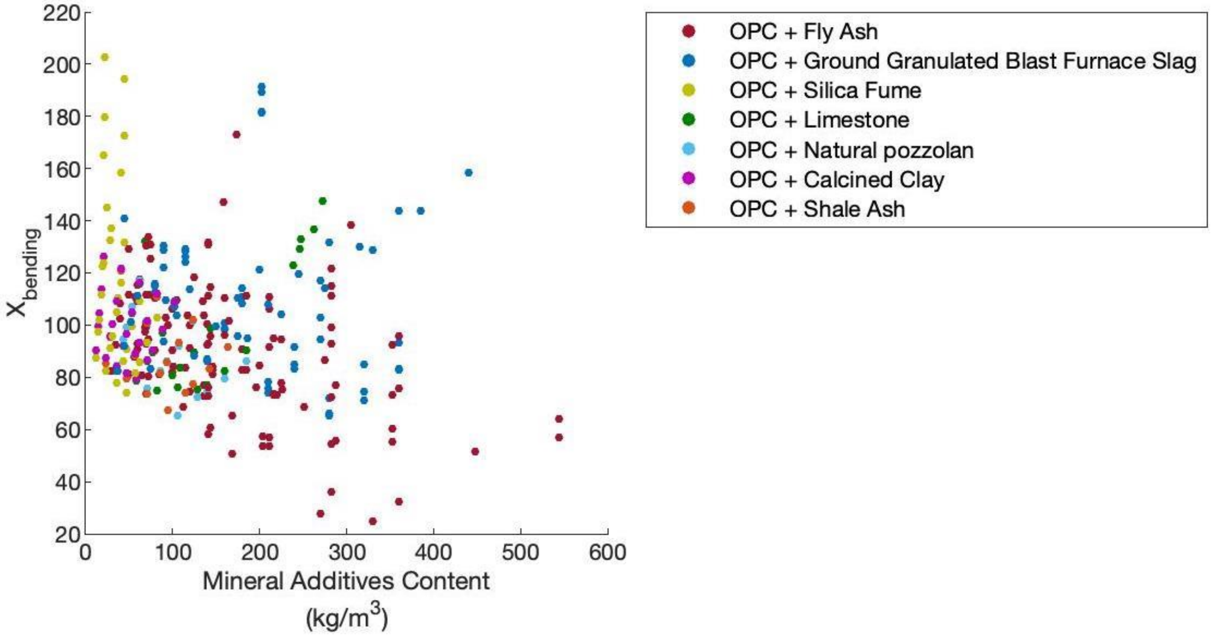


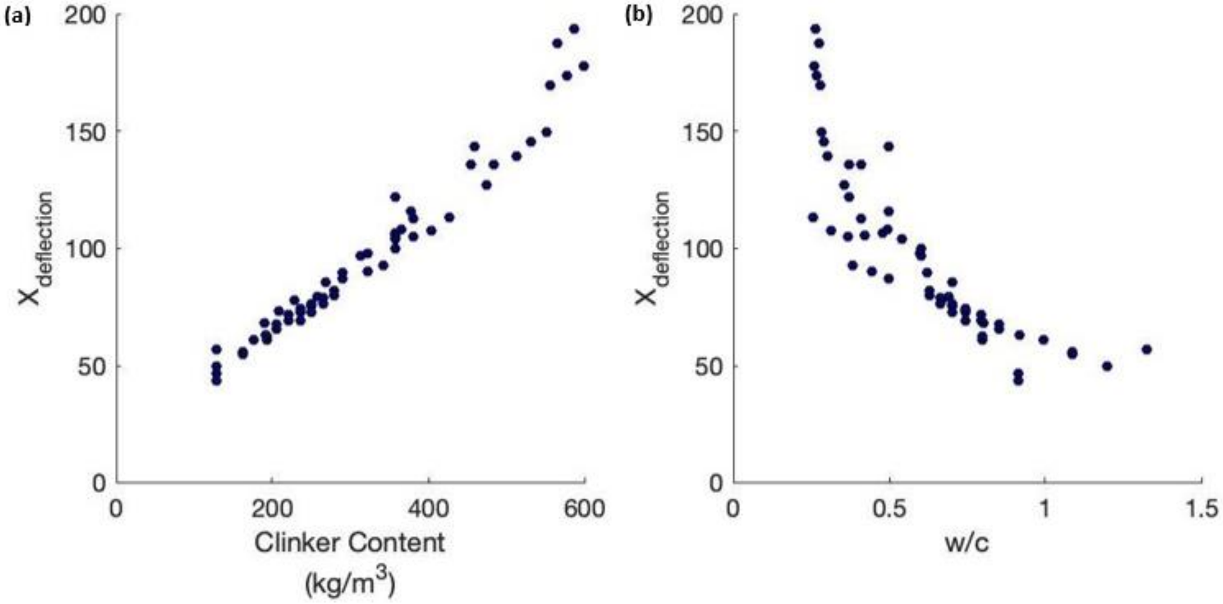
Figure 6. The comparison index for a strength controlled unreinforced concrete in flexure relative to mineral additives content broken out by type of additive

The next comparison index used allows for rapid comparison of concrete mixtures used in a design for an unreinforced concrete member in flexure controlled by deflection, $X_{deflection}$ (determined by Equation 2).

$$X_{deflection} = \frac{i}{E^{\frac{1}{3}}} \qquad \textbf{Equation 2}$$

where $X_{deflection}$ and i are as previously defined and E is the concrete modulus of elasticity.

Similar to the $X_{bending}$ index, the Portland cement properties (i.e., clinker content and w/c ratio) relate to the $X_{deflection}$ with strong linear trends (Figure 7). A high r-value of 0.98 and a negative trend of r = −0.85 were obtained for the clinker content and w/c ratio, respectively (Table 7). Although the correlation analysis in Table 7 implies a statistical significance between the binder content and the index ($p < 0.05$ and r = 0.67), the outliers in Figure 8 make the relationship questionable. The effect of mineral additives content on the index seems poor (Figure 9). Increasing the number of data points may improve the relation; again, suggesting the applicability for a stakeholder with more mixtures to compare.



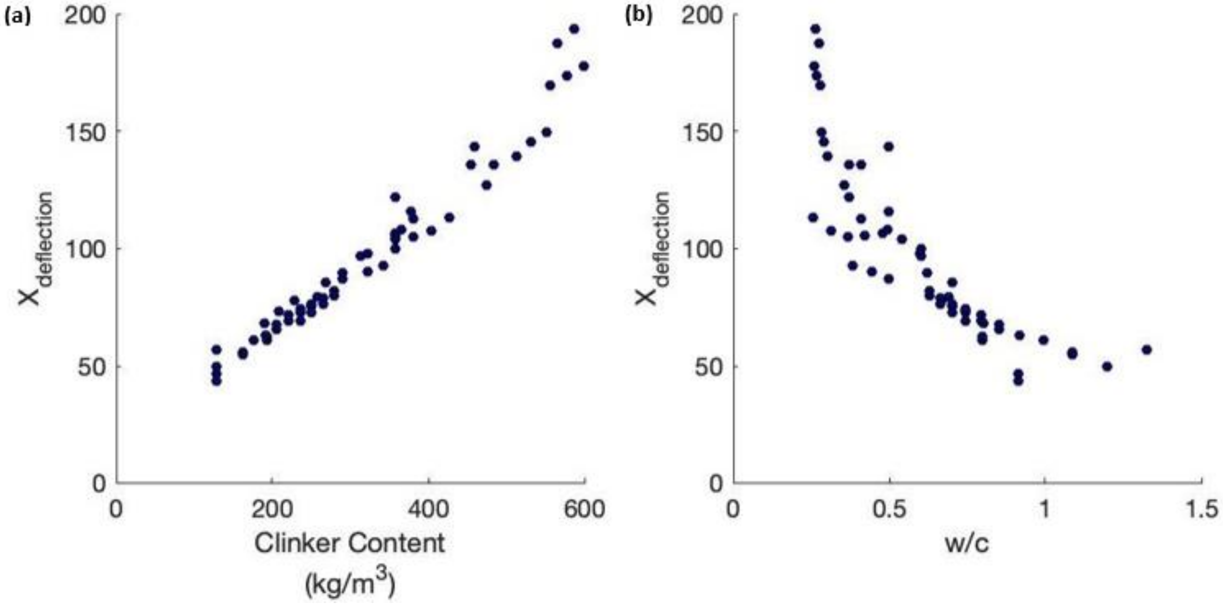


Figure 7. The comparison index for a deflection controlled unreinforced concrete in flexure relative to (a) clinker content and (b) w/c ratio. (a) clinker content (note: a higher clinker

content is correlated with higher emissions), and (b) w/c ratio (note: a higher w/c ratio is correlated with lower strength and this dataset has overlap between low strength and low emissions mixtures)

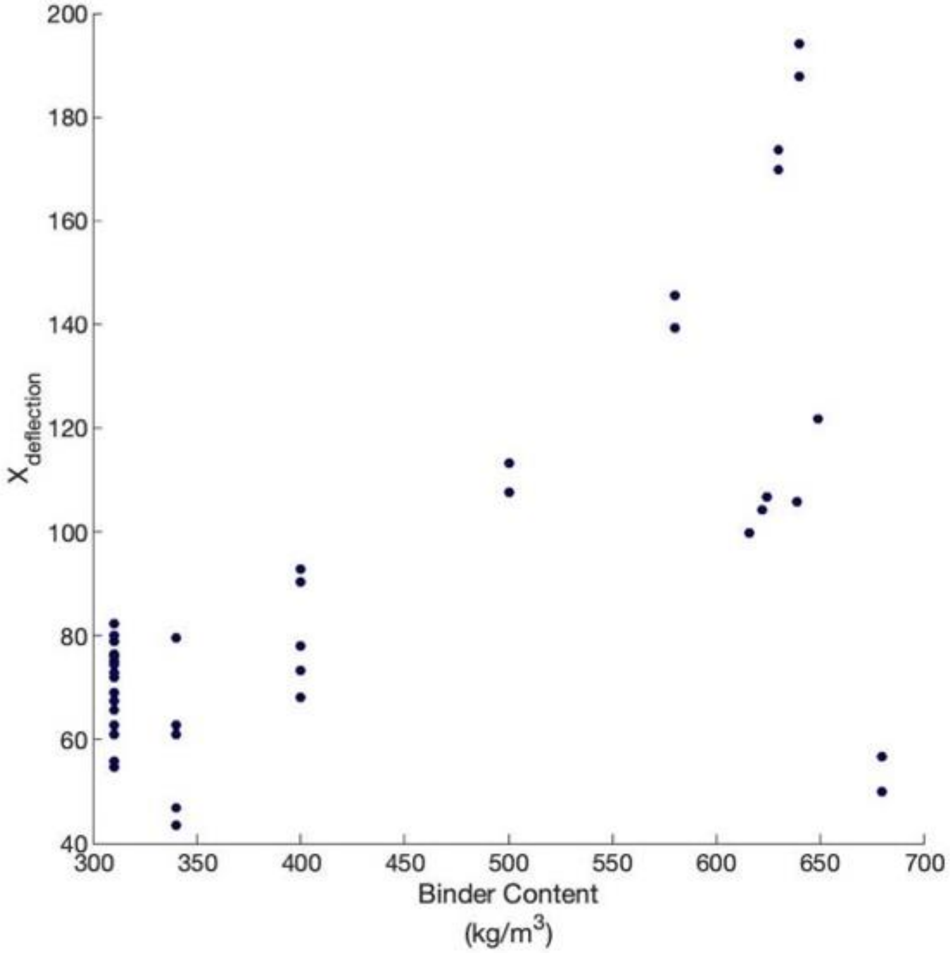


Figure 8. The comparison index for a deflection controlled unreinforced concrete in flexure relative to binder content

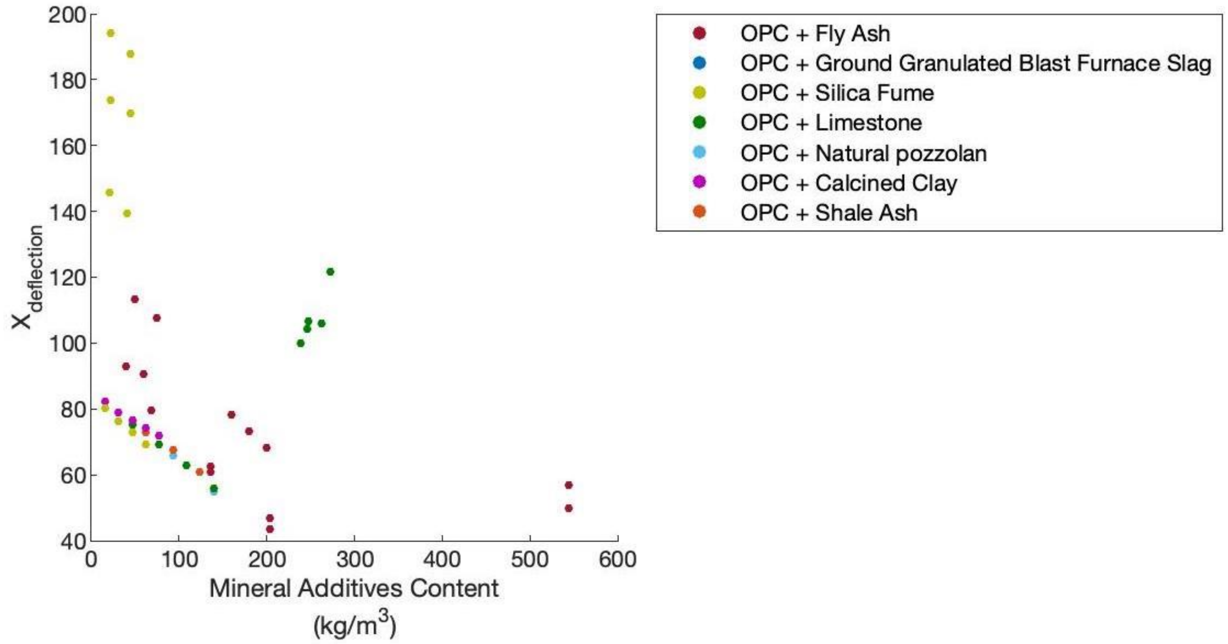


Figure 9. The comparison index for a deflection controlled unreinforced concrete in flexure relative to mineral additives content within the mixtures assessed; colors indicate different types of additive

For rapid comparison of concrete mixtures to be used in an unreinforced concrete member controlled by strength, X_{axial} was applied (determined by Equation 3). The material properties did not appear to contribute to the trend of the index (Figure 10). This finding is despite the strong statistical significance at $p < 0.05$ found for most relationships studied; the notable exception being for the mineral additives content (Figure 11). To further exemplify the effects of using mineral additivites, this index is also plotted relative to the w/b ration (Figure 12)

$$X_{axial} = \frac{i}{f_c} \qquad \textbf{Equation 3}$$

where X_{axial}, i, and f_c are as previously defined. It should be noted, due to the 1 to 1 relationship between environmental impact and compressive strength noted for X_{axial}, different trends appear. In this case, there can be greater benefits to higher emissions mixtures if even greater improvements in strength can be achieved and outweigh emissions (by driving a lower volume) with this simple index.

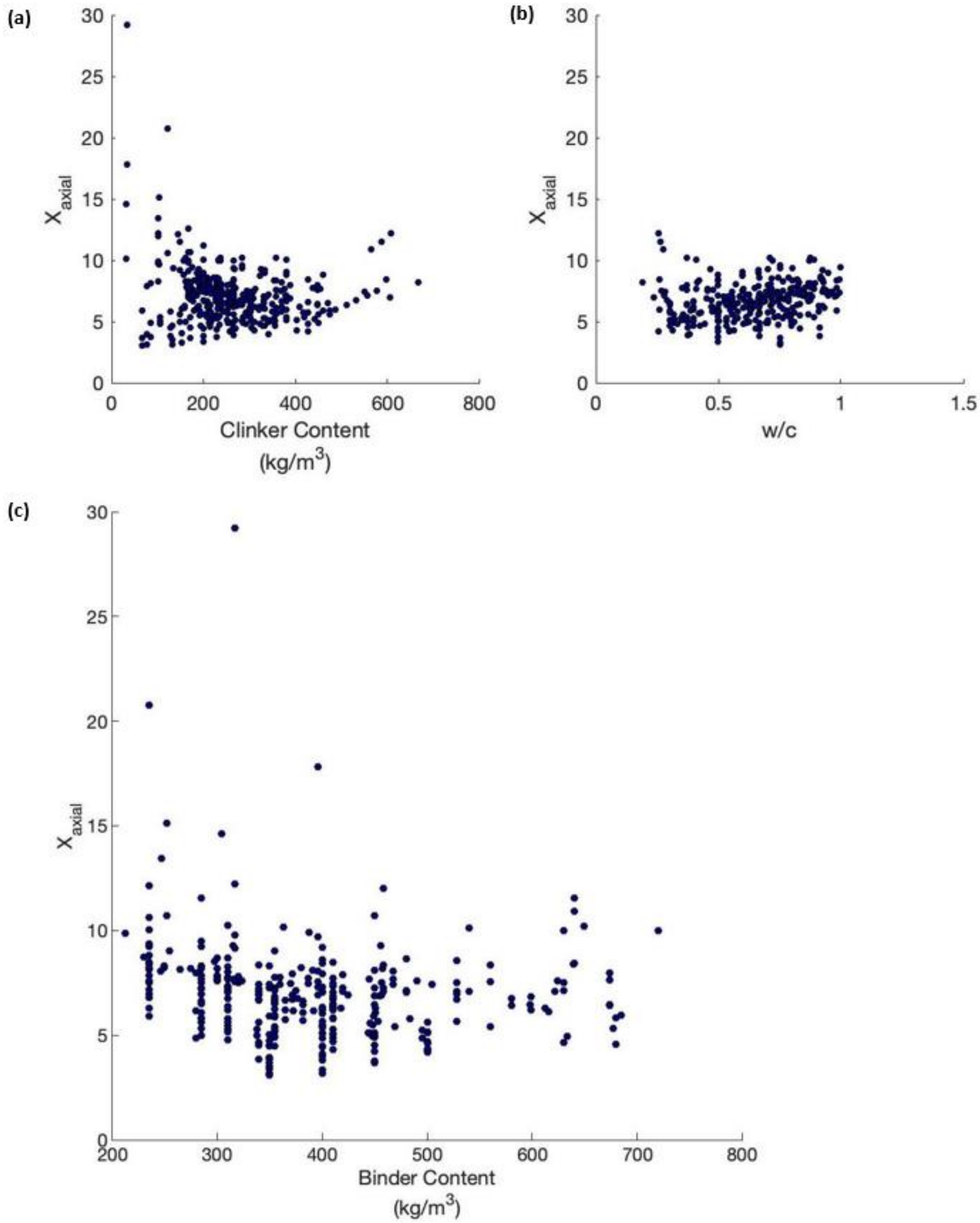


Figure 10. The comparison index for an axially loaded unreinforced concrete member controlled by strength to (a) clinker content, (b) w/c ratio, and (c) binder content. (a) clinker content (note: a higher clinker content is correlated with higher emissions), (b) w/c ratio (note: a higher w/c ratio is correlated with lower strength and this dataset has overlap between low strength and low emissions mixtures), and (c) binder content

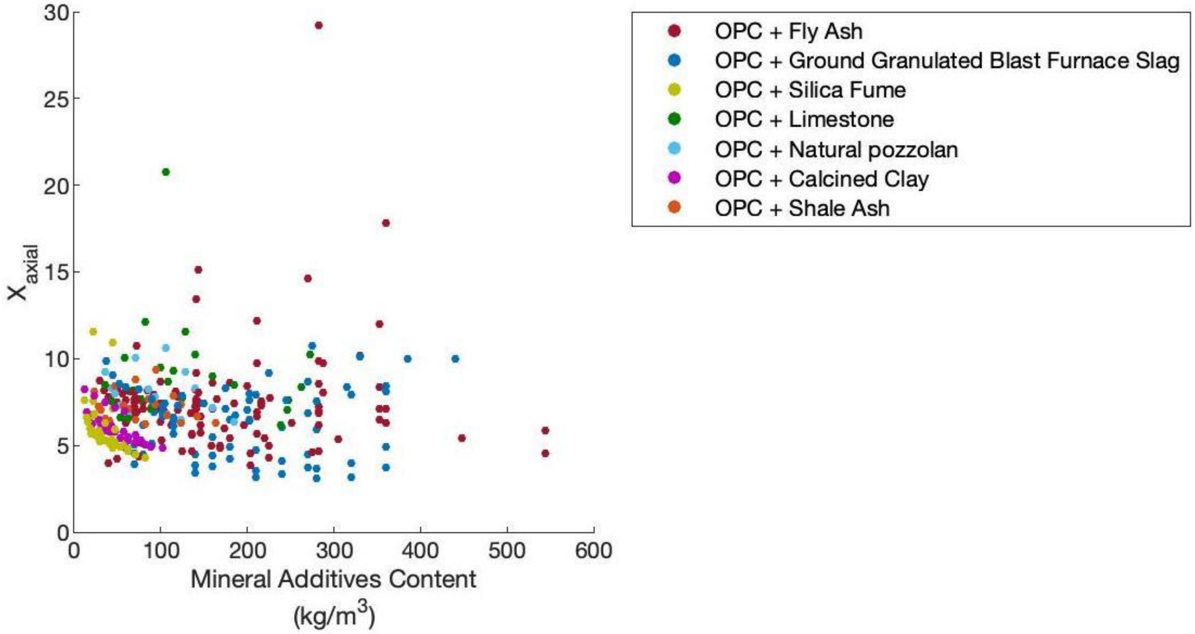


Figure 11. The comparison index for an axially loaded unreinforced concrete member controlled by strength relative to mineral additives content within the mixtures assessed; colors indicate different types of additive

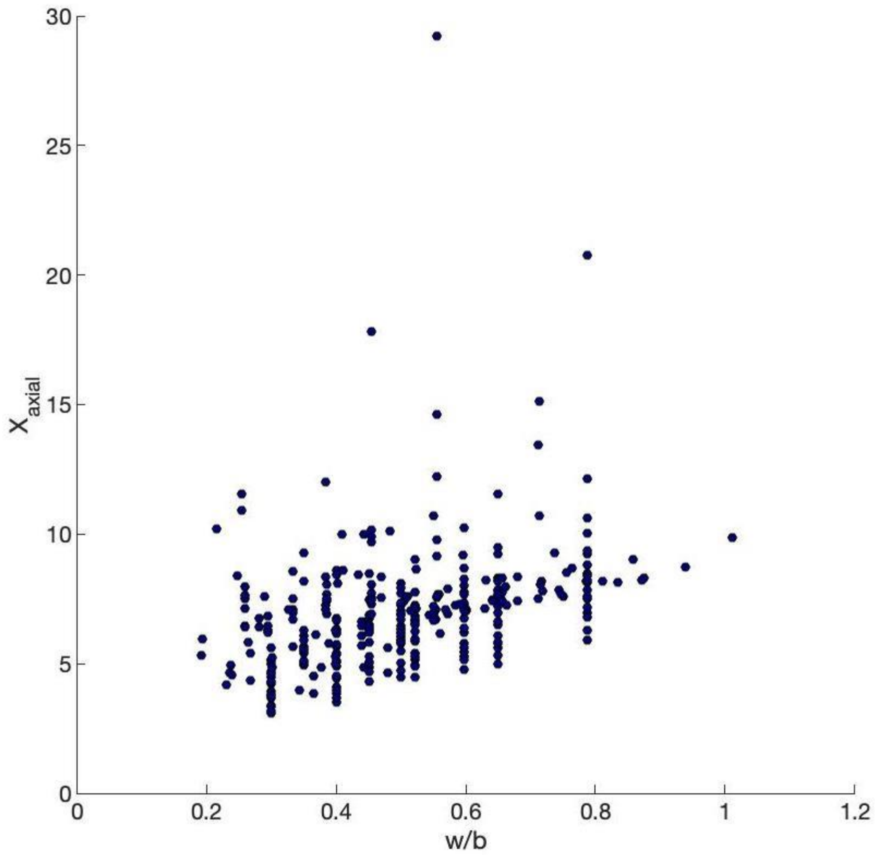


Figure 12. The comparison index for an axially loaded unreinforced concrete member controlled by strength relative to w/b ratio

For rapid comparison of concrete mixtures to be used, a concrete member controlled by the thickness of material needed to cover rebar, X_{Dcl}, was applied (determined by Equation 4). Despite the high statistical significance acquired in the analysis (Table 7), the low number of data sources reporting chloride diffusivity makes the contribution of the material properties questionable. The effect of this limitation in the data is observable in Figure 13 and Figure 14. It should be noted, the data used to make the plots in this section contain some mixtures with limestone filler. These mixtures possessed properties that did not follow the same chloride diffusion trends as the other concrete mixtures when mineral admixture content increased (see Figure 14). However, this form of blending limestone into concrete mixtures is also not currently common for Caltrans projects.

$$X_{Dcl} = iD_{cl^{0.5}} \qquad \textbf{Equation 4}$$

where X_{Dcl} and i are as previously defined and D_{cl} is the chloride diffusion coefficient.

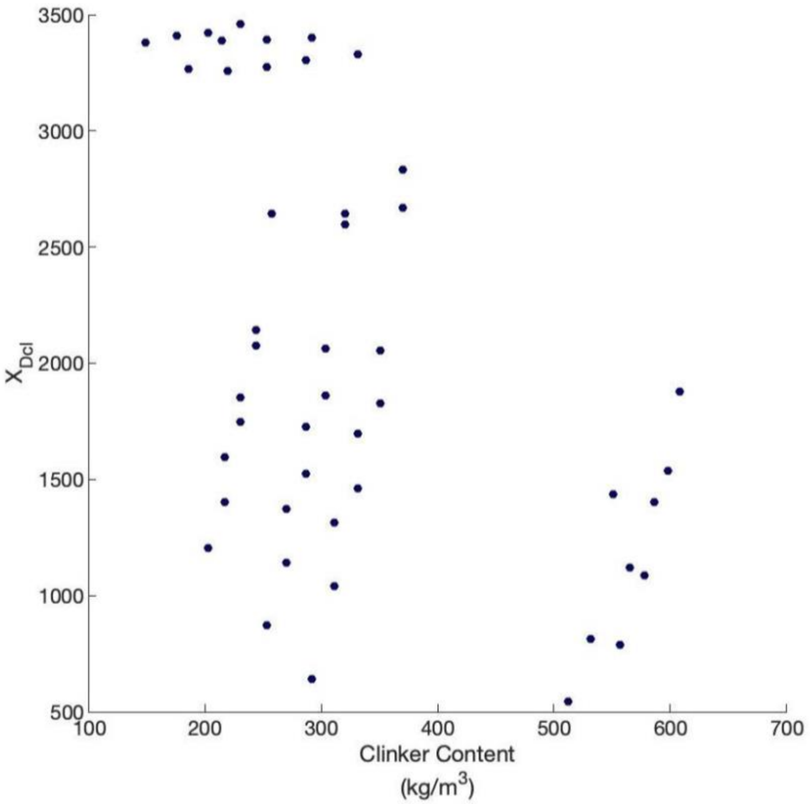


Figure 13. The comparison index for a concrete member controlled by the thickness of material needed to cover rebar relative to clinker content

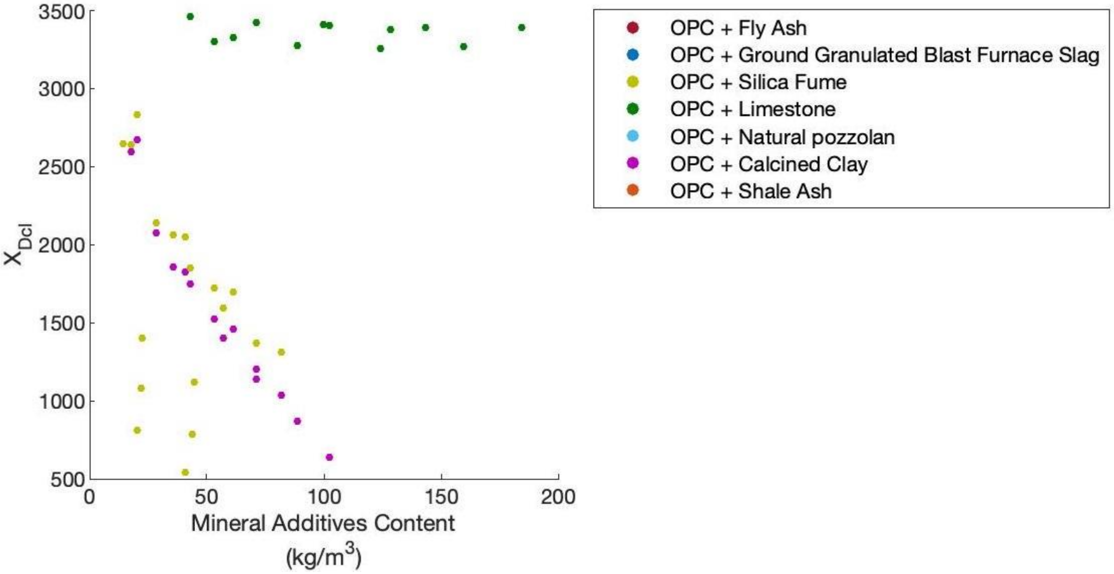


Figure 14. The comparison index for a concrete member controlled by the thickness of material needed to cover rebar relative to relative to mineral additives content within the mixtures assessed; colors indicate different types of additive

4.3. Summarizing remarks

Comparison indices, such as those presented in this section, facilitate comparisons of both environmental impacts and material properties. To do this, these comparison indices incorporate the effects of material properties on the volume of material required for a simplified application and then relate that volume of material to the environmental impacts per unit volume of concrete. In doing so, many mixtures can be compared rapidly to understand beneficial combinations of material properties and environmental impacts in order to reduce the latter. However, there are limitations of such indices as they are presented here, including a lack of consideration for the effects of steel reinforcement and material longevity in use.

5. Multi-criteria selection for multi-material systems

The objective of this section is to address opportunities to improve the environmental impacts of concrete materials use through the reduction of material demand. Specifically focusing on reinforced concrete members, the study examines the tradeoffs between altering concrete mixture properties and the effects of longitudinal reinforcement. This work will provide a preliminary means to quantify under what circumstances concrete with different strength and reinforcement ratios can be used while maintaining infrastructure performance. Further, consideration will be given to several opportunities for partial Portland cement (PC) replacement with mineral admixtures. The methods developed will provide insights into means to reduce greenhouse gas (GHG) emissions through the efficient use of concrete and steel rebar in reinforced concrete components.

5.1. Introduction

This work focuses on the concurrent assessment of steel and concrete to improve the efficient use of both materials in reinforced concrete designs. As both steel and concrete production contribute large amounts of GHG emissions to civil infrastructure [166], [167], it is important to evaluate the environmental impacts contributed by both materials concurrently when designing reinforced concrete (RC) components [131]. The environmental impact of RC members varies as a function of both the concrete used and the demand for steel reinforcement. Namely, the reinforcement quantities, often discussed in the context of reinforcement ratio (the cross-sectional area of steel reinforcement as a function of the cross-sectional area of the concrete member), will contribute to the total environmental impact of an RC member. In addition, the volume and mixture proportions of the concrete will contribute to the total impact. Both the quantity of steel reinforcement and the compressive strength of the concrete will influence the cross-sectional area of material needed to withstand loads; and thus, they will influence the volume of material required. Here, we focus on GHG emissions as the environmental impact of interest; however, the equations presented can be extended to other environmental impacts in future work.

This work compares the environmental impacts of RC members based on concrete mixture strength achieved as well as steel reinforcement ratio for reinforced columns and beams in bending at three stages in the moment-curvature relationship of reinforced concrete bending members. These quantitative assessments will be extended to concrete constituents, focusing on the amount of SCMs used. All of these considerations will be made within the confines of current reinforced concrete design requirements.

5.2. Reinforced Members

5.2.1. Methods

To address the complex interaction between steel and concrete material and environmental impact properties, this work builds from the series of formulae developed by Kourehpaz and Miller [131] following the American Concrete Institute design guidelines for reinforced concrete members (ACI-318) [168]. This series of equations relates environmental impacts to the mechanical and geometric aspects of both the steel and concrete components of RC members. The environmental impacts of several RC members are determined, namely for an axially loaded column member, and three stages of beam bending under uniformly distributed loading: initial cracking stage, yield stage, and nominal stage.

Building upon Kourehpaz and Miller's work, two scenarios are presented to compare the environmental impacts reflecting two simplified variations on drivers in design. The first scenario is reflective of conventional comparisons being drawn today; namely, comparisons drawn for materials on a per-volume basis. The second scenario examines the GHG emissions for members designed to withstand a given loading. In order to equilibrate the stresses in the RC member, the dimension of the member is designed according to the selection of material properties (e.g., concrete compressive strength, rebar yield strength) for the specified loading.

The second scenario incorporates the design objective for RC members into the environmental impact assessment. While varying member sizes based on loading conditions is not always possible, by drawing comparisons from both of these scenarios in parallel, more robust conclusions can be drawn.

To show the influence of concrete and steel properties on the environmental impacts of RC members, change of impacts due to varying ranges of concrete strength and steel rebar area are depicted in 2D contour plots. This study examines relationships between concrete compressive strength and environmental impacts while controlling for potential variability in concrete constituent selection. For relationships based on reinforced concrete, only longitudinal steel reinforcement is considered. The effects of lateral reinforcement on environmental impacts are considered to be negligible for this work. In cases where lateral reinforcement contributes to a significant fraction of the volume of steel specified, (i.e., Equation 7, Equation 8, Equation 9, Equation 10, Equation 11, Equation 12, Equation 14) would need to be modified. Namely, the volume of steel for lateral reinforcement would need to be subtracted from the terms used to define environmental impacts from concrete (i.e., the first term in Equation 7 & Equation 8 and the first two terms in Equation 9, Equation 12, & Equation 14). The volume of steel for lateral reinforcement would then need to be multiplied by the volumetric impact of steel (i_s) and added as a final term to each equation.

5.2.1.2. Unit Volume Comparisons

To derive relationships for the influence of concrete compressive strength on reinforced concrete member design, equations were used to describe the environmental impacts of a volume of concrete as a function of the specified compressive strength. To do this, relationships derived by Fan [138] were used to link the powder content of the cementitious system (i.e., the PC and SCMs content—referred to herein as the binder content) to concrete strength and GHG emissions from production. These relationships assume higher strength is achieved by increasing the binder content while maintaining the same level of water usage per cubic meter; although, it must be noted that increased strength can be achieved through other means, such as lowering the w/c ratio. While the approach used herein is simplified, it does reflect general trends in which higher strength concrete mixtures typically have higher environmental impacts.

Further, using this method allows for analysis excluding varying effects of changing aggregate gradation, aggregate properties, chemical admixture usage, and other common methods used to change concrete strength beyond increasing binder content.

In the original study by Fan [138], relationships between specified concrete compressive strength and environmental impacts were derived for concrete mixtures containing one of four SCMs: fly ash (FA), ground granulated blast furnace slag (GGBS), limestone filler (L), or natural pozzolans (NP). For this work, relationships are also considered for three additional SCMs: shale ash (SA), calcined clay (CC), and silica fume (SF). These are in addition to concrete mixtures containing only PC as the binder.

Because the use of these different SCMs has varying effects on concrete strength development and GHG emissions, parameters to fit Fan's equations were derived using experimental data from [143], [144], [150]–[152], and GHG emissions were calculated using the tool developed as a previous deliverable for this project. The relationship between binder constituents and compressive strength was derived based on Abram's law (Equation 5):

$$f_c = \frac{k_1}{k_2^{w/b}}$$ **Equation 5**

where f_c is the concrete compressive strength, w/b is the water-to-binder ratio, and k_1 and k_2 are fitting parameters. These values are presented in Table 8. The GHG emissions for different SCM types were simplified into a linear relationship, based on Fan's derivation method as follows (Equation 6):

$$i_c = k_A \bullet c + k_B + k_C \bullet s + k_D$$ **Equation 6**

where i_c is the GHG emissions per cubic meter of concrete (here in kg CO_2-eq/m^3), and k_A, k_B, k_C, and k_D are fitting parameters. These values are presented in Table 9.

For the GHG emissions from the steel rebar, a value of 8876 kg CO_2-eq/m^3 was used for i_s. This value reflects GHG emissions of 1.03 kg CO_2-eq/kg of rebar from [169], an approximate density of 7800 kg/m^3, and 3000 km of transportation.

Table 8. Parameters to relate concrete constituents to GHG emissions per cubic meter of concrete (from [2])

Mineral Admixture	k_A	k_B	k_C	k_D
Limestone (L)	8.47E-01	7.85E+00	-7.24E-05	-8.92E-02
Natural Pozzolans (NP)	8.47E-01	7.85E+00	2.36E-02	-1.10E+00
Shale Ash (SA)	8.47E-01	7.85E+00	5.48E-02	-4.49E-01
Calcined Clay (CC)	8.47E-01	7.85E+00	3.88E-01	-6.42E-01
Silica Fume (SF)	8.47E-01	7.85E+00	1.34E-01	6.48E-01
Fly Ash (FA)	8.44E-01	3.90E+00	-2.39E-03	-9.33E-03
Blast Furnace Slag (GGBS)	8.42E-01	6.98E+00	3.55E-01	3.40E-02

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[2] Olsson, Alexander, and Miller. *In Preparation.*

Table 9. Parameters to relate water-to-binder ratio (from [3])*

Mineral Admixture	*mineral admixture to PC ratio*	k_1	k_2
Limestone (L)**	8.18E-01	1.72E+02	6.85E+01
	5.38E-01	1.26E+02	2.13E+01
	3.33E-01	1.35E+02	1.53E+01
	1.76E-01	1.37E+02	1.11E+01
	0.00E+00	1.41E+02	9.72E+00
Natural Pozzolans (NP)	8.18E-01	1.26E+02	2.29E+01
	4.29E-01	1.45E+02	1.84E+01
	1.76E-01	1.34E+02	1.24E+01
	0.00E+00	1.41E+02	9.72E+00
Shale Ash (SA)	6.67E-01	1.25E+02	1.66E+01
	4.29E-01	1.31E+02	1.38E+01
	2.50E-01	1.42E+02	1.23E+01
	1.11E-01	1.41E+02	1.01E+01
	0.00E+00	1.41E+02	9.72E+00
Calcined Clay (CC)	3.33E-01	2.19E+02	1.50E+01
	2.50E-01	2.15E+02	1.46E+01
	1.76E-01	2.08E+02	1.44E+01
	1.11E-01	1.84E+02	1.25E+01
	5.26E-02	1.71E+02	1.19E+01
	0.00E+00	1.41E+02	9.72E+00
Silica Fume (SF)	2.50E-01	2.16E+02	1.28E+01
	1.76E-01	2.06E+02	1.23E+01
	1.11E-01	1.99E+02	1.23E+01
	5.26E-02	1.76E+02	1.14E+01
	0.00E+00	1.41E+02	9.72E+00
Fly Ash (FA)	5.81E-01	1.63E+02	1.90E+01
	5.00E-01	1.63E+02	1.57E+01
	4.23E-01	1.62E+02	1.33E+01
	3.31E-01	1.49E+02	1.04E+01
	2.50E-01	1.46E+02	9.21E+00
	1.49E-01	1.35E+02	7.76E+00
	0.00E+00	1.38E+02	8.42E+00
Blast Furnace Slag (GGBS)	1.57E+00	1.85E+02	4.31E+01
	1.29E+00	1.92E+02	3.01E+01
	1.00E+00	1.79E+02	1.91E+01
	7.14E-01	1.59E+02	1.20E+01
	4.29E-01	1.29E+02	7.67E+00
	2.14E-01	1.12E+02	6.51E+00
	0.00E+00	1.15E+02	6.70E+00

* based on data from the literature, not necessarily representative of Caltrans mixtures; ** limestone blended in during concrete batching

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[3] Olsson, Alexander, and Miller. *In Preparation.*

5.2.1.3. Axially Loaded Column – Reinforced Concrete Member

For the analysis of the reinforced members, the same general equation was implemented, allowing for accounting of concrete environmental impacts per unit volume, steel environmental impacts per unit volume, and the requisite volume of each of these materials to meet performance requirements. The general form of this equation, based on [131], is:

$$I_{RC} = l * (bh - A_s) * i_c + A_s l i_s$$ **Equation 7**

where I_{RC} refers to the environmental impact of a reinforced concrete member, b is the column or beam width, l is the column height or beam length, h is the column width or beam height, A_s is the area of steel. The other terms as previously defined are: i_c is the volumetric environmental impact of concrete (i.e., the environmental impact of the concrete mixture selected per unit volume), i_s is the volumetric impact of steel. Using the formula, the GHG emissions associated with the production of RC members were estimated for the typical values of concrete compressive strength between 20 to 40 MPa and steel yield strength of 420 MPa.

For the design of a column, **Equation 7** is rewritten as:

$$I_{column} = l * (F - f_y A_s) * \frac{i_c}{\ddot{f}_c} + A_s l i_s$$ **Equation 8**

where I_{column} is the environmental impact of the designed column, F is the axial force applied, f_y is the steel yield strength, and other terms are as previously defined. For this member, the reinforcement ratio was set to be between 0.01 and 0.08. A case study was used to show example relationships between the GHG emissions, concrete compressive strength, and steel reinforcement area for a reinforced concrete column. The case study implementing this equation was performed using the constraints for the column example given in [131]. In this case, the member volume was determined through specified height and width, but the depth of the member was able to vary with varying concrete compressive strength and reinforcement ratio. This depth of the member was calculated based on the given force needed to be withstood. The case study was applied to all types of SCMs examined herein (see Results and Appendices).

5.2.1.4. Beam at the Cracking Stage – Reinforced Concrete Member

In the initial cracking stage of beam bending, it is assumed that the stress at the extreme fiber of a section, experiencing the largest moment, reaches the modulus of rupture of concrete. The GHG emissions per unit length of the beam were determined by extending Equation 7 to capture this behavior, which is based on an adaptation from [131]:

$$I_{cracking} = 1.1 l^2 \sqrt{wb} \left(\frac{i_c}{f'^{0.25}_c} \right) - A_s l i_c + A_s l i_s$$ **Equation 9**

where $I_{cracking}$ is the environmental impact of the designed member at the cracking stage, M is the moment of a section and other terms are as previously defined. This equation relies on the relationship between f_r, the modulus of rupture, and the compressive strength of concrete given by the ACI-318 [168]:

$$f_r = 0.62\sqrt{f'_c}$$ **Equation 10**

In addition to the case study for the column, a case study of the implementation of Equation 9 was performed to show an example application of this relationship, reflecting GHG emissions as a function of concrete mixture characteristics and area of steel reinforcement. The case study applied used the constraints for the example given in [131]. Namely, a simply supported, uniformly loaded member in bending. For these beams, the allowable reinforcement ratio was set using:

$$0.85\beta_1 \frac{f'_c}{f_y} \leq \frac{A_s}{A_{section}} \leq max\left(\frac{1.4}{f_y}, 0.25\frac{\sqrt{f'_c}}{f_y}\right)$$ **Equation 11**

where β_1 is a factor relating depth of equivalent rectangular compressive stress block to depth of neutral axis, defined by the ACI-318 [168], and all other terms are as previously defined. In this case, the member volume was determined through specified length and width, but the height of the member was able to vary with varying concrete compressive strength and reinforcement ratio. This height of the member was calculated based on the given moment needed to be withstood. This case study was applied for all of the types of SCMs examined in this work (see Results and Appendices).

5.2.1.5. Beam at the Yield Stage – Reinforced Concrete Member

In addition to the initial cracking stage previously studied, the effect of concrete and steel properties on the GHG emissions of RC members was examined for a beam at the yield and nominal stages of the moment-curvature relationship. The GHG emissions in the yield stage of beam bending were determined by applying Equation 12, which extends Equation 7 to incorporate design constraints for this type of member based on [131]:

$$I_{yield} = 0.67lA_sf_y\frac{i_c}{f_c} + l\left(\frac{wl^2b}{8A_sf_y} + bm - A_s\right)i_c + A_sli_s$$ **Equation 12**

where I_{yield} is the environmental impact of the designed member at the yield stage, m is the cover depth plus the radius of the rebar, and all other terms are as previously defined. In this case, the influence of the moment, M_y, on the required volume of the concrete and steel used were based on the ACI-318 [168] as follows:

$$M_y = A_sf_y\left(d - 0.67\frac{A_sf_y}{f_cb}\right)$$ **Equation 13**

This equation describes the load state of the beam in terms of mechanical properties and dimensions. In the yield stage of the analysis, the concrete strength could be assumed as $0.7f'_c$. Here, d refers to the effective depth of the member and the remaining terms are as previously defined.

Again, a case study was used to show the implementation of Equation 12. The case study was performed using the constraints for the example given in [131]. Namely, the design of a simply supported, uniformly loaded member in bending was used with reinforcement ratios meeting code specifications. In this work, a 0.075 m concrete cover was used to acquire the height of the section. The member volume was determined through specified length and width, but the height of the member was able to vary with varying concrete compressive strength and reinforcement ratio. This height of the member was calculated based on the given moment needed to be withstood. This case study was applied for all types of SCMs examined in this work (see Results and Appendices).

5.2.1.6. Beam at the Nominal Stage – Reinforced Concrete Member

The GHG emissions of an RC beam designed at the nominal stage of the moment-curvature relationship were modeled using Equation 14, which is based on [131]:

$$I_{ultimate} = 0.59 l A_s f_y \frac{i_c}{f'_c} + l\left(\frac{wl^2 b}{8A_s f_y} + bm - A_s\right) i_c + A_s l i_s \qquad \textbf{Equation 14}$$

where $I_{ultimate}$ is the environmental impact of the designed member at the nominal stage and the moment, M_n, is defined as (Equation 15):

$$M_n = A_s f_y \left(d - 0.59 \frac{A_s f_y}{f'_c b}\right) \qquad \textbf{Equation 15}$$

And all other terms are as previously defined. As with the previous relationships derived, a case study example of the implementation of Equation 14 was performed. For this case study, the constraints for the example given in [131] were used. Namely, this design was for a simply supported, uniformly loaded member in bending. Reinforcement ratios were within code specifications. A cover depth of 0.075 m was used to acquire the height of the section. In this case, the member volume was determined through specified length and width, but the height of the member was able to vary with varying concrete compressive strength and reinforcement ratio. This height of the member was calculated based on the given moment needed to be withstood. The case study was extended to all types of SCMs examined in this work (see Results and Appendices).

5.2.2. Results

5.2.2.1. Unit Volume Comparisons

Per unit volume comparisons are the most common way to examine the environmental impacts of construction materials. For concrete, Environmental Product Declarations (EPDs) usually are reported per volume (e.g., [18]). For a constant volume, the inclusion of SCMs to replace clinker content typically reduces GHG emissions [170]. This trend is seen in this work too, even at constant compressive strength (Figure 15a).

The SCMs considered in this work have varying effects on changing the GHG emissions per cubic meter of concrete. Of the materials examined, the use of 15% SCM content as a cement replacement resulted in approximately 10% reductions in GHG emissions. Slightly greater reductions were noted for the use of L (~18% reduction), and a moderate increase in emissions was noted for the use of NP (~2% increase—note, this is within the margin of error for such studies). For the L, due to the local nature of the material resource and limited energy demands for processing, there are negligible GHG emissions from its production. The similarities in strength that can be achieved through the appropriate use of mineral filler [171] allow for its inclusion to lead to notable reductions in emissions at both strengths considered. For the NP, this small increase in emissions, instead of a reduction, is reflective perhaps of the use of limited reactivity pozzolans. The trends presented by the authors from which the experimental data were retrieved suggest that the material did not contribute to strength development, particularly at low replacement levels [143]. Due to the variety in mineralogy of NP, this trend is not reflective of what would be expected for all NP.

While the moderate fluctuations in GHG emissions achievable through use of SCMs provides valuable insights into specifying concrete mixtures, the design of multi-material systems is more complicated. The use of steel reinforcement in structural concrete design is common. While the reinforcement is typically a very low portion of the volume of the total RC member design, steel rebar has notably higher emissions for production than concrete, nearly 30-50 times the impact per cubic meter (Figure 15b). As such, despite the low fraction of the total volume of an RC member, the impacts from steel rebar can be a notable contributor to the total impact of the member: at volume fractions of 0.02 to 0.03, the steel reinforcement, as modeled here, would have approximately equivalent GHG emissions from production as the concrete in member. Again, this finding emphasizes the criticality of examining full member design to guide environmentally sustainable decisions.

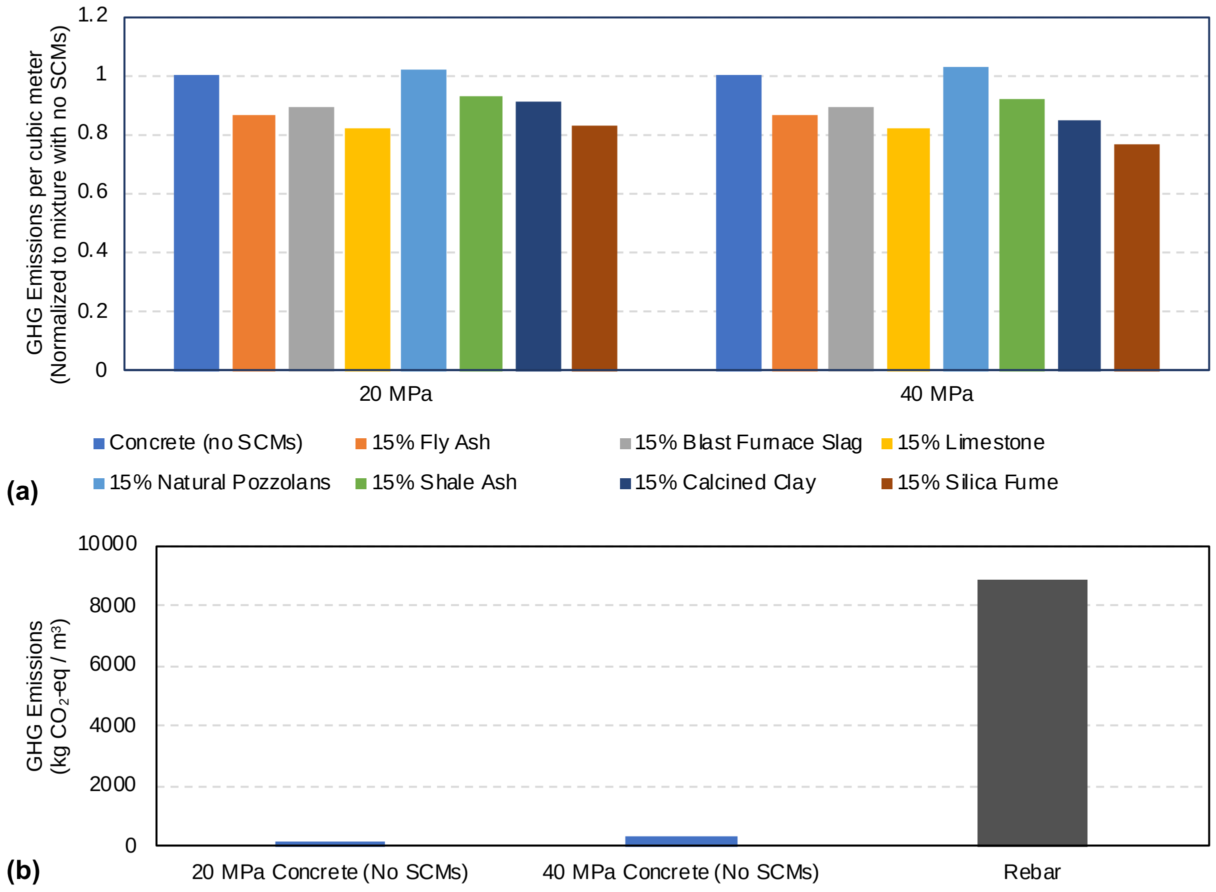


Figure 15. Environmental impacts by volume for materials considered. Panel (a) shows the environmental impact differences noted between concrete mixtures with varying SCMs normalized to mixtures with no SCMs for two strengths. Panel (b) shows GHG emissions per cubic meter concrete mixtures with no SCMs at two strengths and that of steel rebar.

5.2.2.2. Axially Loaded Column – Reinforced Concrete Member

Figure 16 shows the results of how design decisions could begin to influence the GHG emissions for a reinforced concrete column. The results plotted are for the case study discussed in Section 5.2.1.3. As such, the values presented reflect this case study alone, not all columns. However, findings demonstrate the significance of considering both the GHG emissions from steel rebar and from concrete production when trying to mitigate emissions. The results indicate that a larger steel area would increase the GHG emissions in the production of columns. On the other hand, the contribution of concrete strength to the emissions is much smaller as demonstrated by the relatively vertical contour lines (Figure 16). There would be a slight rise in GHG emissions if lower concrete strength is used for columns with equivalent steel area (Figure 16). This trend is due to the need for a larger concrete cross-sectional area (and concurrently the gross cross-sectional area) to withstand the given external loading when concrete strength or steel area is reduced. Findings also suggest that the use of SCMs as a partial replacement of cement would be effective for reducing the impacts, as observed by the reduced GHG emissions dependent on which SCM was used (see Appendix B.1. Supplementary Column Contour Plots).

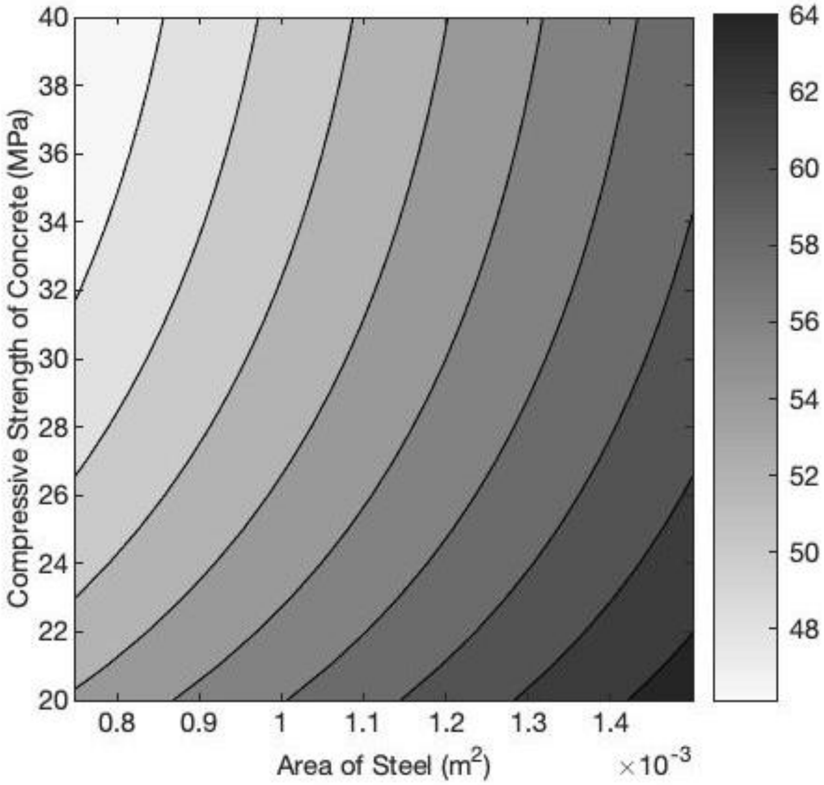


Figure 16. Column contour plots for mixtures containing no SCMs. The gradation scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: this diagram reflects mixtures from [143], [144], [150]; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

5.2.2.3. Beam at the Cracking Stage – Reinforced Concrete Member

The GHG emissions for the example of a beam designed at the initial cracking stage are shown in Figure 17. Again, the contour plot shows the influence of the considered ranges of concrete strength and steel area on emissions for the case study examined (see Section 5.2.1.4). The figure shows a gentle slope of the contour lines (Figure 17) compared to the steep lines obtained by the preceding analysis on column members (Figure 16). While, again, exact values shown in Figure 17 are reflective of the particular case study, the trends suggest factors that could drive the emissions of members designed for the cracking stage. For example, the relatively flat contour lines in Figure 17 indicate that the GHG emissions in the initial carking stage of beam bending are primarily controlled by the compressive strength of concrete more than the area of steel. This differs from the previous section, where the steel area would have more control for column members carrying an axial load. In the cracking stage, the emissions could be primarily reduced by selecting lower cement content (here reflected by the members with lower concrete strength and the use of SCMs—results of using SCMs are shown in Appendix B.2. Supplementary Contour Plots: Beam Designed at the Cracking Stage).

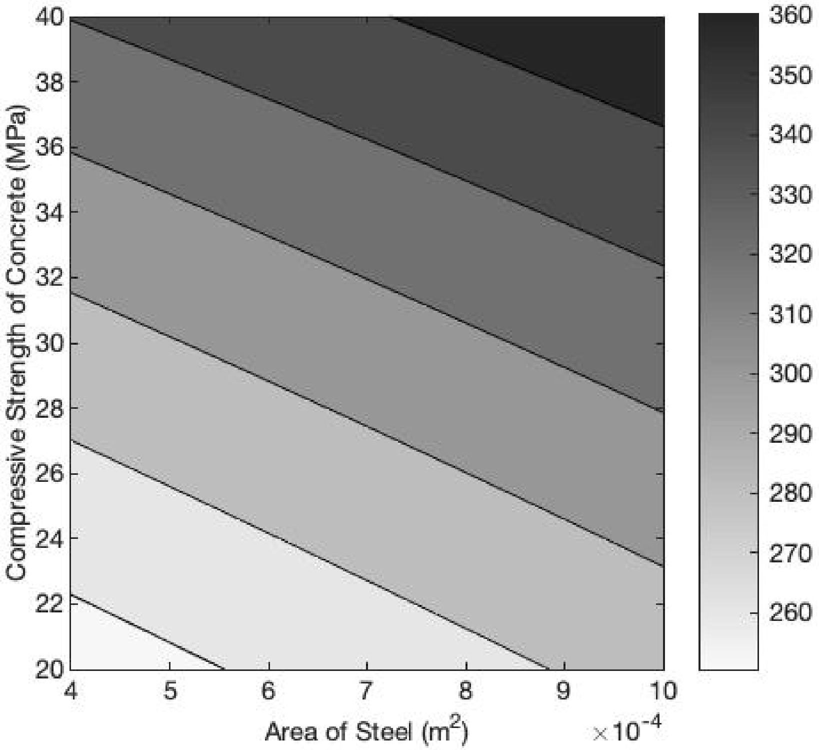


Figure 17. Contour plots of beam members in bending at the cracking stage for mixtures containing no SCMs. The gradation scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: this diagram reflects mixtures from [143], [144], [150]; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

5.2.2.4. Beam at the Yield Stage – Reinforced Concrete Member

The GHG emissions for the example of a beam designed at the initial cracking stage are shown in Figure 18. Note that for the yield stage design, the cross-sectional area of concrete needed is a function of both the concrete strength and the steel area. This is dissimilar from the beam designed in the initial cracking stage, where the area was a function of concrete strength only (Equation 9).

While the figure represents the case study application, the trends present key factors influencing the GHG emissions from beams for this design stage. Results of the GHG emissions of the beam example in the yield stage of bending exhibit an increase of the emissions with the higher binder content, higher concrete strength (Figure 18). Based on the results, the contribution of steel to the system behavior suggests that a notable fraction of emissions could be mitigated through lowering cement content, even if some concrete strength is lost. Modifying the steel area would also contribute to reducing the emissions, but the contribution to change is smaller than that of altering cement content. The higher binder content, higher strength concrete leads to higher GHG emissions when the volume of the material is constant (see Section 5.2.2.1); however, a larger steel area for this member design facilitates a change in volume, which can lower GHG emissions of the member if concrete strength is constant.

Using FA (and other SCMs) as a partial replacement of cement content was effective in mitigating the environmental impacts in all loading stages of beam bending (see Appendix B.3. Supplementary Contour Plots: Beam Designed at the Yield Stage). A 15% FA replacement lowers GHG emissions by ~10% relative to the mixture without FA.

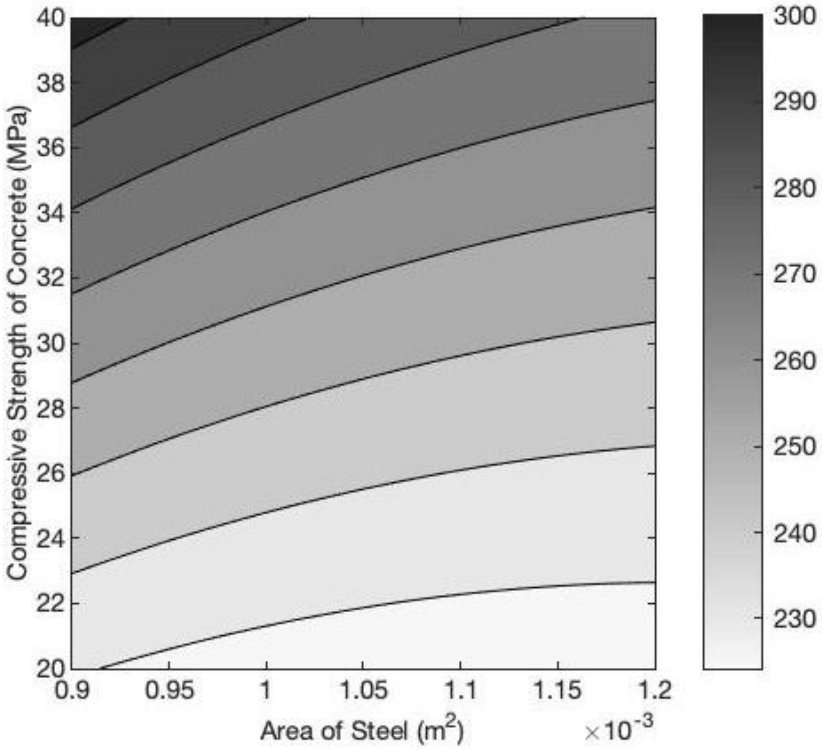


Figure 18. Contour plots of beam members in bending at the yield stage for mixtures containing no SCMs. The gradation scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: this diagram reflects mixtures from [143], [144], [150]; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

5.2.2.5. Beam at the Nominal Stage – Reinforced Concrete Member

The relationship between GHG emissions as a function of concrete strength and steel area in the nominal stage was similar to those of the yield stage. This similarity is due to the comparable weighting of mechanical properties and environmental impacts of steel and concrete in Equation 12 and Equation 14. Due to the analogous trends present between the member designed for the yield stage and that for the nominal stage, a different discussion is not presented, but the plots of the emissions in this stage are provided (Figure 19 and in Appendix B.4. Supplementary Contour Plots: Beam Designed at the Nominal Stage).

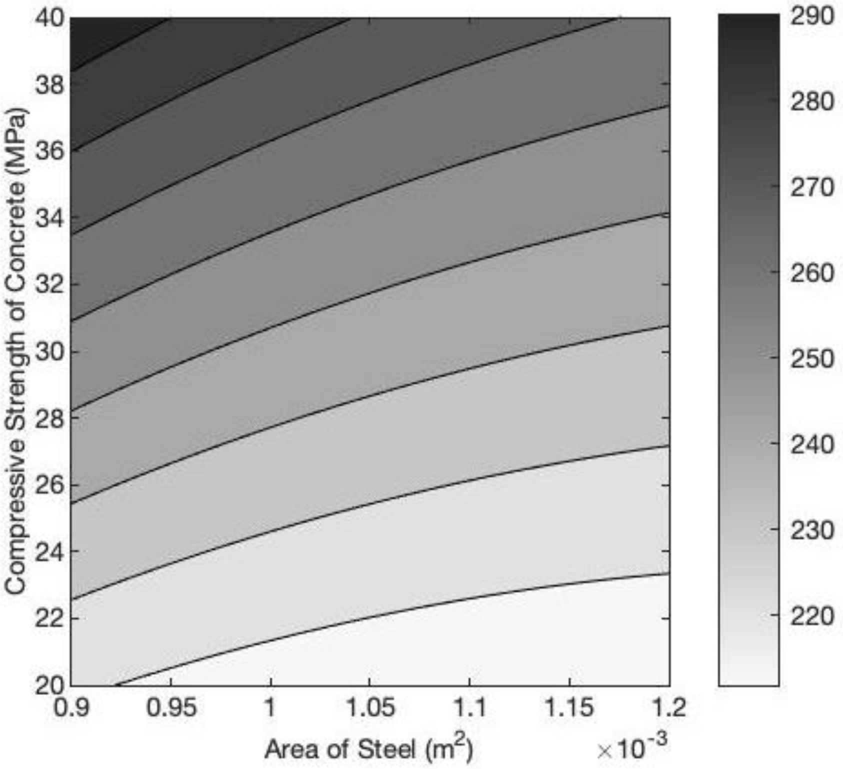


Figure 19. Contour plots of beam members in bending at the nominal stage for mixtures containing no SCMs. The gradation scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: this diagram reflects mixtures from [143], [144], [150]; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

5.2.3. Summary

In this work, equations that relate environmental impacts for reinforced concrete members to the strength of concrete, the quantity of steel reinforcement, and the environmental impacts of each of these two materials were explored. There are several key takeaways from this work:

- The environmental impacts of steel reinforcement can be large and could drive GHG emissions for certain reinforced concrete member designs.
- Concrete compressive strength is not consistently a strong indicator of shifts in reinforced concrete member GHG emissions. It has a stronger effect in designs for which compressive strength is a driving characteristic, e.g., columns.
- The use of SCMs, if they are modeled as having negligible environmental impacts, can be a useful means to reduce the environmental impacts of concrete.

In future work, there are several additional areas of research that should be explored. The sensitivity of trends noted to other case study applications should be investigated. The effects of lateral reinforcement should be addressed. The environmental impacts analyzed should extend beyond GHG emissions from material production. For byproduct SCMs, the use of allocation methods should be explored to address impacts associated with primary processes. Further, the effects of production improvements, such as higher recycled content rebar or use of improved energy resources, should be considered to inform scenarios under which minimal environmental impact can be achieved.

6. Greenhouse gas emissions mitigation strategies and costs in concrete design

The objective of this section is to identify preliminary costs associated with each of the GHG emissions mitigation strategies examined in this report. Incorporating the findings from preceding sections on GHG emissions mitigation strategies into a case study will elucidate how to draw informed comparisons in the design of concrete infrastructure systems. Specifically, this analysis explores simple decision-making tools to permit stakeholders to identify mitigation strategies that have the greatest ability to reduce GHG emissions while being likely to incur the least cost (or save costs) for stages associated with material specification and design. Cost-abatement curves for each GHG emission are presented for different mitigation strategies.

6.1. Introduction

A major shortcoming in the development of green transportation infrastructure systems is the disjoint perspective on the design, use, and end-of-life of their components. The state-of-practice focuses on individual components at single points in time but often overlooks how multiple components interact and how material longevity can affect environmental and monetary costs. This convention can lead to inefficient use of materials in transportation systems (e.g., [172]). As such, there is an urgent need to improve design and selection tools to facilitate the efficient use of cement and concrete. By reducing the demand for these materials through informed design, reductions in burdens on the environment can be achieved. However, means to achieve such reductions must be examined within the context of their economic feasibility.

This work will assess the monetary costs of reducing environmental impacts from materials demand in concrete infrastructure. Through a cost analysis of each of the GHG emissions mitigation methods considered in the other components of this work, this study will provide initial quantification of economic benefits and deterrents from: (1) using varying concrete mixture proportions, including higher levels of SCMs; (2) using varying concrete strength, SCM content, and reinforcement ratios of simply designed reinforced concrete members; and (3) improving material longevity to reduce replacement of pavement overlay.

6.2. Methods

To perform cost assessments, values of each constituent in the assessed systems were approximated. According to USGS 2016 data, the unit values of Portland cement and sand/gravel were approximated as \$93.37 per metric ton (based on [173]) and \$12.77 per metric ton (based on [174]), respectively. Fly ash was estimated at \$76.10 per metric ton from [175] (published in 2017), which is approximately 18% less than the cost of cement. Steel costs were considered in the examination of the reinforced concrete members using cost values based on a report from the Organization for Economic Cooperation and Development (OECD) [176]. The price of steel rebar was approximated as 4380.30 (US\$/m^3), as a result of the 2016 average unit cost of steel, 558 (US\$/metric ton), multiplied by the density of steel, 7.850 (metric ton/m^3). Costs used per metric ton of material are shown in Table 10.

Table 10. Unit prices of material constituents

Unit Price	Cement	Fly Ash	Aggregate	Rebar
USD$/metric ton	93.37	76.10	12.77	558.00

In addition to these constituent costs, an approximate cost of acquiring and batching the concrete constituents was determined through the use of costs quoted by Central Concrete in the San Francisco Bay Area for the production of 9 known concrete mixtures in 2015 [177]. Using the mixture proportions and costs for these mixtures, the costs for concrete constituents, using values listed in Table 10 were assessed. The difference between quoted retail values and the material costs were assumed to be additional direct and indirect costs incurred by ready mixed concrete producers as well as their profit. In this case, that average value was $114 per cubic meter of concrete.

6.2.1. Varying mixture constituents

To draw cost comparisons based on varying concrete mixture proportions, the three mixtures used in the pavement overlay, discussed further in Section 6.2.3, were modeled. These mixtures were based on designs used in a pavement overlay system recently placed in California [178]. For this system, a concrete mixture using conventional Portland cement, with no specified additional use of mineral admixtures, was specified (labeled as PCC for this work). An adaptation of this mixture was considered in which fly ash was modeled as replacing 15% of the Portland cement (labeled as PC/FA). While not used in the final project, a roller-compacted concrete mixture had been specified in an early design iteration; this roller-compacted concrete mixture was also used for comparison (labeled as RCC). The mixture proportions examined are shown in Table 11.

Table 11. Mixture proportions (in kg/m^3)

	water	Portland cement	fly ash	coarse aggregate	fine aggregate	GWP*	Total GWP**
PCC	175	390	-	915	892	335	10.9 E+05
PC/FA	175	332	58.5	915	892	286	9.28 E+05
RCC	137	267	-	806	1200	230	7.49 E+05

* units in kg CO_2-eq / m^3; ** units in kg CO_2-eq / slab, where each slab was modeled as having a volume of 3234 m^3

6.2.2. Design of reinforced concrete members

This work examines how material-related costs would vary as a result of design decisions for reinforced concrete (RC) members, focusing on the effects of changing concrete strength and reinforcement ratio. These findings are discussed in the context of the changes to GHG emissions from material production as a function of the same design alterations. Here, the potential GHG emissions and costs related to material production are examined in four case study applications: (1) an RC column member under axial loading; (2) an RC beam member in bending at the cracking stage of the moment-curvature relationship; (3) an RC beam member in bending at the yield stage of the moment-curvature relationship; and (4) an RC beam member in bending at the nominal stage of the moment-curvature relationship. The same case designs as presented in the accompanying report on the influence of RC member design on GHG emissions were used here. For this cost-based analysis, the only mineral admixture considered was fly ash at a 15% replacement of Portland cement.

To draw a finite number of comparisons, a baseline design and 8 permutations were selected from the ranges presented as case-study designs (Table 12). These mixtures are not representative of actual designs, but rather are used as indicative of the design methods that can be used. The baseline for each RC member design was modeled as the median concrete strength (~30 MPa) and steel area (varies by case study). The eight design alternatives included variations of concrete compressive strength (lower, ~20 MPa, and higher, ~40 MPa), steel area (low and high – varied based on designs), and mixtures (Portland cement as the only binder and 15% replacement by fly ash). The range for the concrete compressive strength was 20 - 40 MPa for all members, while the steel area ranged from 0.00075 - 0.0015 m^2 for the column, 0.0004 - 0.001 m^2 for the beam at the initial cracking stage of bending, and 0.0009 - 0.0012 m^2 for the other two stages. The concrete mixture proportions were based on the inputs used in the accompanying section on the influence of RC member design on GHG emissions, namely, from implementing experimental values measured by Oner *et al.* [151] for the production of a cubic meter of concrete. Estimates for the emissions and costs assumed that the RC members undergo axial loading of 1,500 kN on the square column, flexure of 30.63 kN.m in the initial cracking stage of rectangular beam, and 183.75 kN.m in the yield and nominal stages. Design codes were followed for members assessed, and to determine environmental impacts gross and concrete areas of the members were calculated accordingly based on the material properties of the RC member to make sure the member is theoretically capable of carrying the load (Table C-1). Lengths of 3 m and 7 m were used for the column and beams for these examples, respectively. Only longitudinal reinforcement was considered in this analysis.

Table 12. Concrete mixture proportion and the compressive strength of the baseline and eight alternative RC members

Label	**Description**	**Constituents (kg/m^3)**				**f_c (MPa)**
		Water	Cement	Fly Ash	Aggregate	
PC30	PC, average f_c and A_s (baseline)	232	350	-	1721	33
PC40-L	PC, high f_c, low A_s	239	400	-	1652	38
PC40-H	PC, high f_c, high A_s					
PC20-L	PC, low f_c, low A_s	218	245	-	1849	21
PC20-H	PC, low f_c, high A_s					
PC/FA40-L	PC/FA, high f_c, low A_s	237	320	50	1660	37
PC/FA40-H	PC/FA, high f_c, high A_s					
PC/FA20-L	PC/FA, low f_c, low A_s	216	200	30	1851	20
PC/FA20-H	PC/FA, low f_c, high A_s					

The GHG emissions and costs for each design alternative were depicted using cost-abatement plots with the potential GHG emissions reduction, relative to the baseline, on the x-axis and costs on the y-axis relative to the baseline mixture (i.e., the emissions and costs of the baseline mixture are set zero). If cost estimates are lower than the baseline, the alternative design is shown as negative on the y-axis; if there is a reduction of GHG emissions relative to the baseline, it is shown as positive on the x-axis. Therefore, both the emissions and cost-reducing alternatives are depicted in the fourth quadrant, emissions-reducing but cost increasing in the first, cost-saving but the emissions increasing in the third, and both the emissions and cost increasing options in the second quadrant of the plot.

6.2.3. Pavement overlay

To calculate costs for each of the permutations in the designed pavement overlay, the quantity of material ordered for the construction, calculated by the unit weights from the mixture proportions and by the quantity bid, 3234 m^3, was used to approximate the practical expenses in terms of USD$. Note: all comparisons are drawn in today's dollars, there is no consideration for inflation, cost of material or acquisition increases, or other factors that could affect prices in the future.

Like the cumulative GHG emissions shown in previous components of this work, the cost associated with each of the mixtures also accumulates over time based on the need to replace the pavements upon reaching end-of-life. With respect to calculating the cumulative costs, the number of construction occurrences (*N*) in Table 13 is multiplied by the material price for a single construction. Using the relationship, the cumulative material costs of the nine pavement scenarios are assessed. To quantify the cost-saving potentials of the mixture alternatives to the baseline mixture (PCC 45yrs), the cumulative material costs of the nine cases are compared at 50, 100, 150, 200 years. The overall effectiveness of the eight alternatives relative to the baseline (PCC 45yrs) was evaluated based on their potential to mitigate GHG emissions and to reduce material expenses using cost-abatement plots.

Table 13. The number of road constructions required at the end of each service period (50, 100, 150, and 200 years), N, for the three life spans considered

		Service Period Scenarios			
		50 years	100 years	150 years	200 years
Pavement life spans	45 years	2	3	4	5
	55 years	1	2	3	4
	75 years	1	2	2	3

6.3. Results for the comparison of varying concrete mixtures

6.3.1. Cost comparisons

The estimated unit prices of PCC, PC/FA, and RCC are presented in Table 14 based on the 2016 California costs of the concrete constituents and weighted by the mixture proportions in Table 11.

Table 14. The cost per ton of the three concrete mixtures used in the roadway case study

	PCC	PC/FA	RCC
Unit value ($/t)	59.48	58.16	50.77

Of the mixtures compared in this work, the PCC was estimated as the most expensive at $59.48 per metric ton, followed by PC/FA ($58.16 per metric ton), and the least expensive was the RCC at $50.77 per metric ton. The PCC had the highest unit cost as a function of the relatively high Portland cement content. Similarly, the lowest unit price by RCC is attributable to the smallest amount of cement in the mixture.

6.4. Results for the comparison of reinforced concrete members

6.4.1. Cost-abatement plots of a reinforced concrete column

The effectiveness of using each one of the eight alternative designs of RC columns to reduce GHG emissions and production costs relative to the baseline is shown in Figure 20. The results of this comparison show that PC/FA40-L, PC40-L, and PC/FA20-L could potentially reduce the GHG emissions of the baseline mixture. Among those, the PC/FA40L and PC40-L would also reduce costs. These two designs have a combination of low steel area and high concrete strength, which can lead to a reduction in GHG emissions by 14 to 21% and a reduction in costs by approximately 20% from the baseline. Between the two mixtures, PC/FA40-L had the more desirable effects on GHG emissions (a 21% reduction) and costs (a 22% reduction), due to the benefits from using fly ash.

While the combination of high concrete strength and low steel area shows the potential to reduce GHG emissions and costs, the opposite combination (low concrete strength with high steel area, shown in the left two bars, PC20-H and PC/FA20-H, in Figure 20) tends to increase both factors. These trends are related to the volume of concrete or steel required, and the unit volume prices of the materials for the properties selected. For example, the concrete volume could be reduced if higher concrete strength is used for the given loading. Additionally, the high environmental impacts and price of steel compared to concrete (by a factor of 26 - 40 and 75 - 98 on environmental impacts and costs, respectively, per volume) contributes to both the emissions and costs addition. However, those trends would not always hold and depend on the mixture proportions and material properties of concrete and steel as well as loading configuration. For example, while fly ash contributes to reduced GHG emissions for the PC/FA20-L mixture relative to the baseline as well, the costs would increase by 19%. All members with higher concrete strength (40 MPa) showed cost savings potential relative to the baseline, a function of the lower concrete volume. However, only two of the design alternatives potentially reduced the GHG emissions among those 40 MPa members in Figure 20.

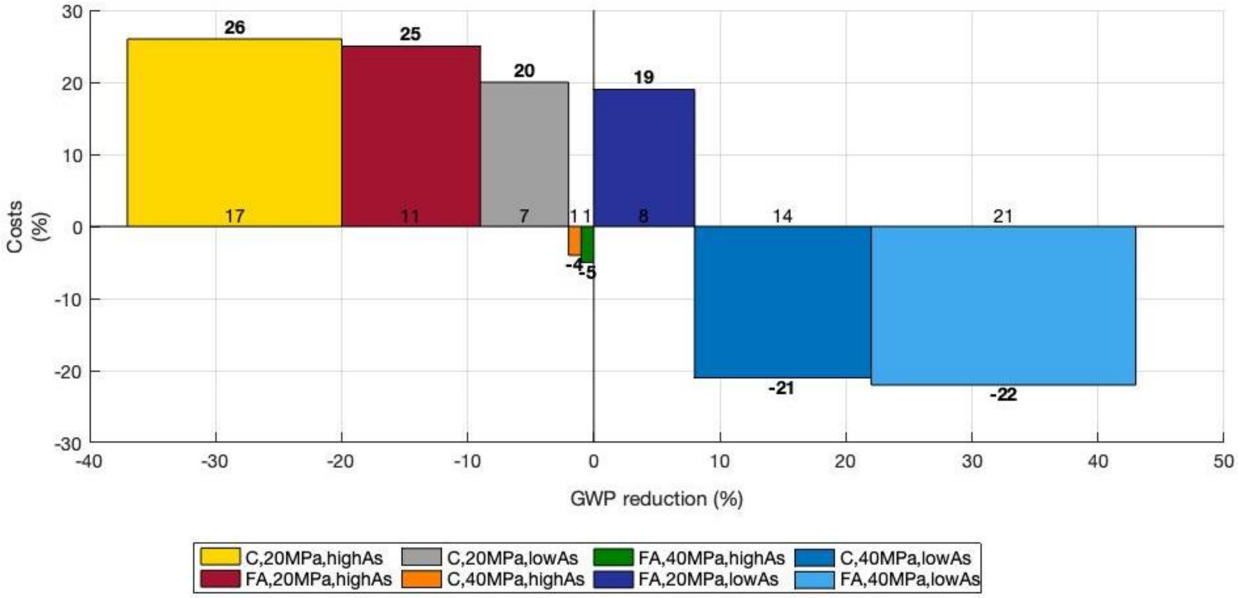


Figure 20. RC column production costs and GHG emissions of the design alternatives relative to the baseline (PC30) designed for axial loading

6.4.2 Cost-abatement plots of a reinforced concrete beam at the cracking stage of beam flexure

For RC beams studied at the initial cracking stage, 5 designs (PC/FA40-L, PC/FA20-L, PC20-L, PC/FA20H, and PC20-H in Figure 21) show the potential reduction of GHG emissions against the baseline. For 4 of those 5 designs, the members have lower concrete strength than the baseline, which implies the potential that reducing the strength may contribute to the mitigation of the GHG emissions for beams in bending designed at this stage (note: this is the inverse of the trend found for the column case study). Among the alternatives that led to a reduction in GHG emissions, PC/FA40-L, PC/FA20-L, and PC20-L would also have potential cost savings. These alternatives all used a smaller amount of steel than the baseline. In contrast, members using more steel than the baseline (PC40-H, PC20-H, PC/FA40-H, and PC/FA20-H) have higher estimated production costs, suggesting the amount of steel is a controlling factor in the production costs in this study. As expected, alternatives with high strength, which was modeled for these examples as having higher binder content, and high steel area (such as PC40-H and PC/FA40-H) showed an increase in both the emissions and the production costs.

PC/FA40-L which uses 15 % fly ash mixed concrete with higher concrete strength and a smaller amount of longitudinal steel than the baseline, presented the best performance. This mixture exhibited the largest potential reduction for both factors, lowering GHG emissions by 30% and costs by 7% relative to the baseline design.

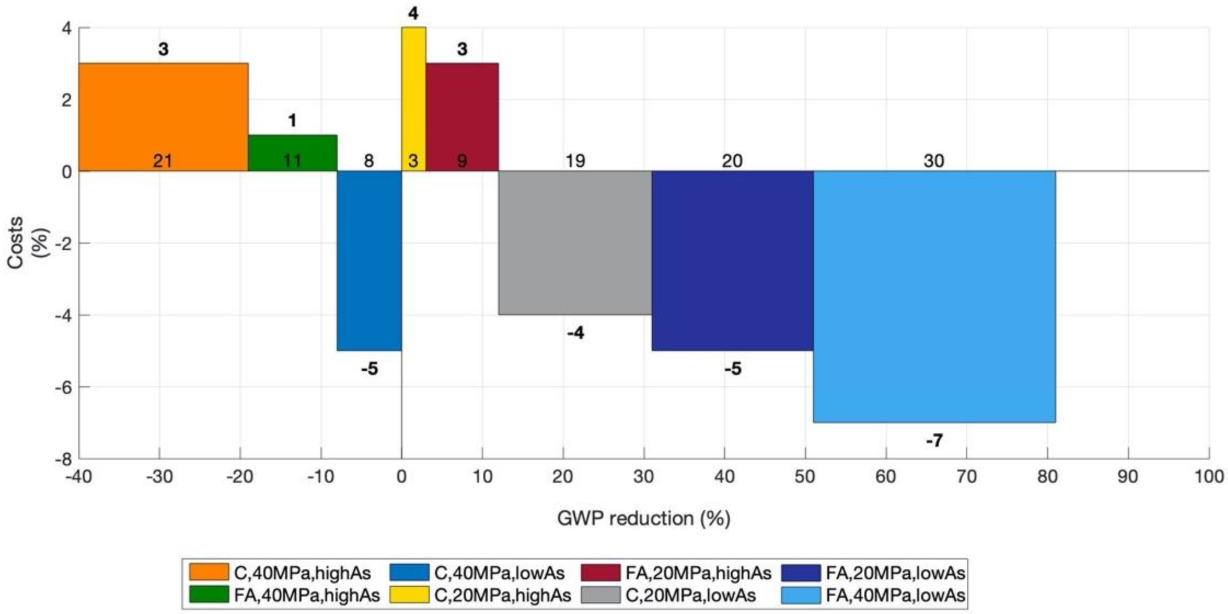


Figure 21. Production costs and GHG emissions (marked as a percent change in global warming potential (GWP)) of the RC flexure beam alternatives at the initial cracking stage relative to the baseline (PC30). x-axis values labeled for each bar reflect percent reduction associated with each alternative; y-axis values labeled for each bar reflect percent change in costs for each alternative

6.4.3 Cost-abatement plots of a reinforced concrete beam at the yield stage of beam flexure

Shifts in GHG emissions and costs from the eight alternative designs relative to the baseline for a beam in bending designed at the yield stage are shown in Figure 22. Results indicate that GHG emissions would be reduced if the baseline design is replaced by PC/FA40-H or each of the four members with lower concrete strength. This trend is similar to the preceding analysis of a beam at the cracking stage in which a reduction of concrete strength contributes to a reduction in GHG emissions. However, PC/FA20-L and PC20-L show an increase in costs by 5 - 6%. The three other designs, PC/FA40-H, PC/FA40-L, and PC20-H, on the other hand, are estimated to reduce the production costs by 1 - 6% in addition to the 13 - 21% GHG emissions reduction. Among those options, the combination of fly ash and high steel area produced the best performances (PC/FA40-H and PC/FA20-H), with the higher strength concrete contributing to the best combination of effects. It is notable that for this stage of beam design, a higher area of steel led to a reduction in costs. This behavior opposes the trend of the cracking stage, showing that material selection to reduce costs should be determined by the targeted load stage.

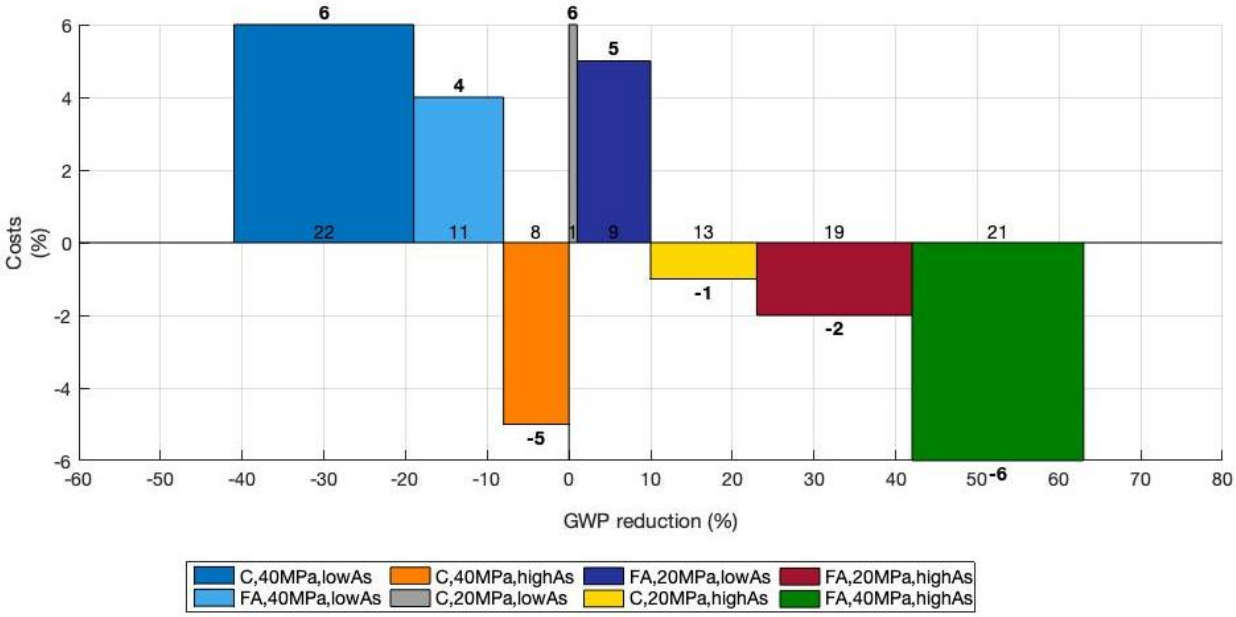


Figure 22. Production costs and GHG emissions (marked as a percent change in global warming potential (GWP)) of the RC flexure beam alternatives at the yielding stage relative to the baseline (PC30). x-axis values labeled for each bar reflect percent reduction associated with each alternative; y-axis values labeled for each bar reflect percent change in costs for each alternative

6.4.4 Cost-abatement plots of a reinforced concrete beam at the nominal stage of beam flexure

In addition to the yield stage, the potential GHG emissions and costs arising from the production of the RC member designed for the nominal stage of beam bending were examined (Figure 23). Results of the analysis for the nominal stage show a similar trend to the yield stage. These similarities are driven by analogous loading and dimensional configurations.

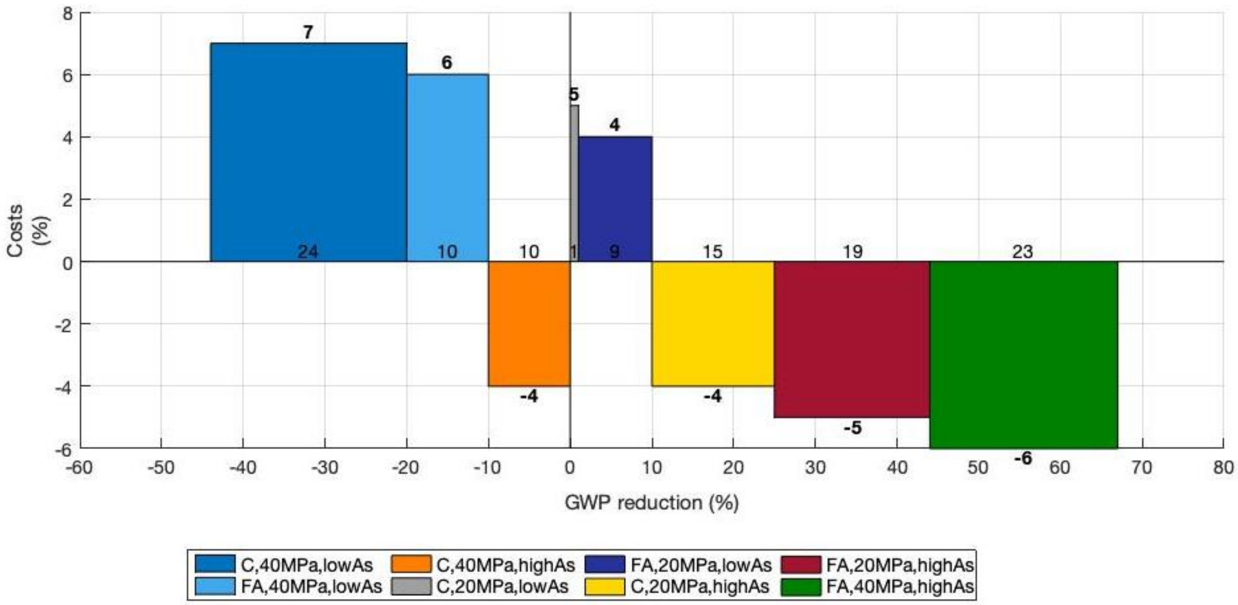


Figure 23. Production costs and GHG emissions (marked as a percent change in global warming potential (GWP)) of the RC flexure beam alternatives at the nominal stage relative to the baseline (PC30). x-axis values labeled for each bar reflect percent reduction associated with each alternative; y-axis values labeled for each bar reflect percent change in costs for each alternative

6.5. Results for the case study on pavement overlay longevity

6.5.1. Cost comparisons

The results of this analysis suggest that costs can be considerably reduced by selecting the mixture alternatives such as RCC or PC/FA instead of the baseline mixture, PCC, which uses the greatest amount of cement for the mixtures analyzed. The cumulative material costs of the nine pavement scenarios are presented in Figure 24. As seen from the figure, the most cost-saving alternatives vary by the length of desired service periods. The cost-saving potentials of the mixture alternatives, relative to the baseline mixture (PCC 45yrs) compared at 50, 100, 150, 200 years are shown in Figure 25. As can be seen, if the mixture containing 15% fly ash replacement of PC, PC/FA, is used over PCC, the cost would be reduced by 0.5% for the same service life period. A much larger reduction can be achieved by RCC, namely 5% of PCC. The cost savings of RCC over PCC is expected to be $56,000 in today's dollars for the 50-year service period (for the case of mixtures with a 45-year life span). In the 100-year service period, the cost savings by RCC could reach $84,000, and the savings for 150 years is anticipated to be $113,000, again both in today's dollars.

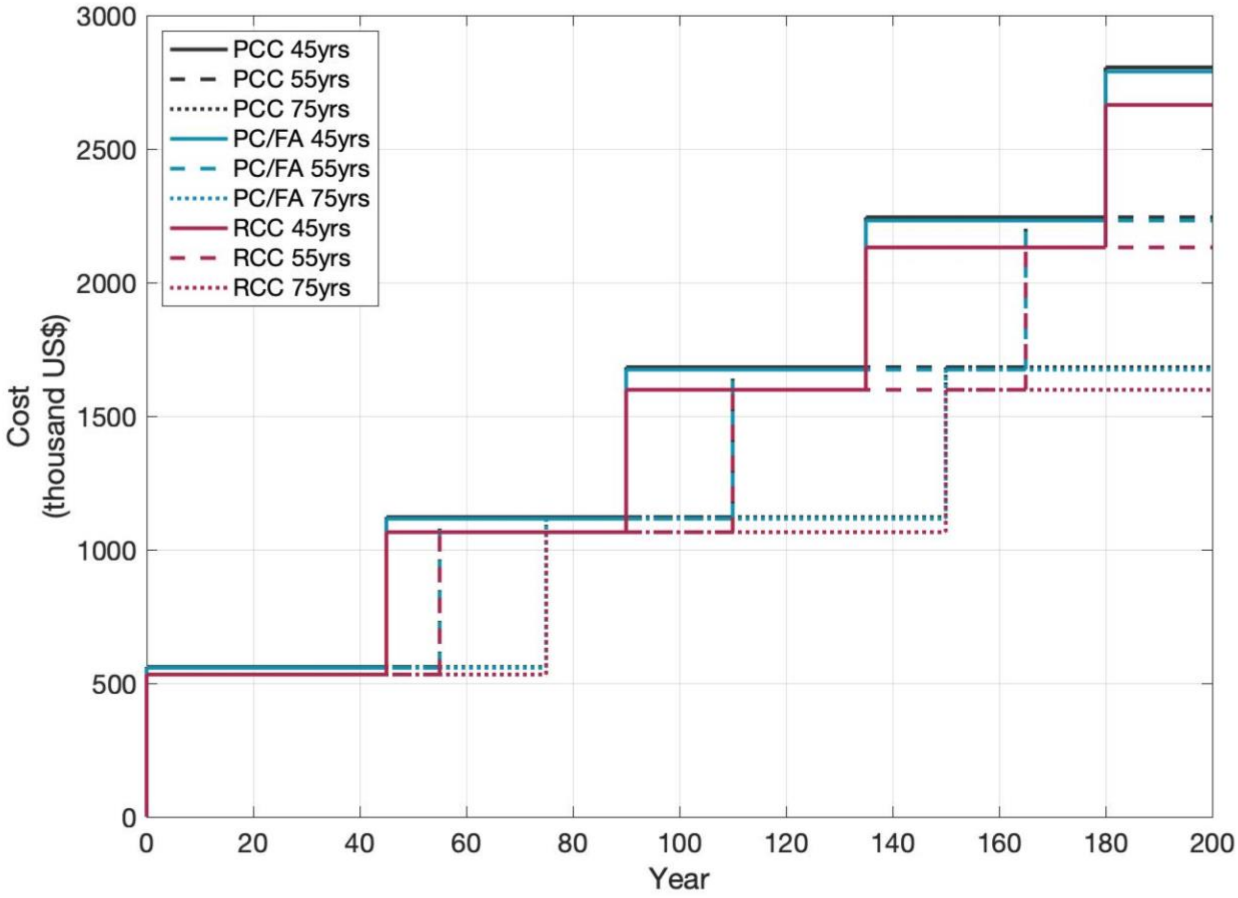


Figure 24. The costs to produce PCC, RCC, and PC/FA mixtures for the designed pavement overlay (illustrated as black, blue, and red lines, respectively). Varying line expressions are used depending on the years of anticipated lifespan prior to replacement.

Increasing the viable life of a pavement mixture could be a means for mitigating the material costs (all of which are presented here in today's dollars). A 55-year life span could cut expenses from the baseline 45-year service life overlay (with the same mixture) by half, which is equivalent to saving $533,000 to $561,000 in the 50- and 100-year service periods. The mixtures can be further economized by selecting the favorable mixture proportions in addition to designing for longer life pavements. Notably, the use of RCC with a design life of 55 years or 75 years is expected to reduce the material costs up to $589,000 to $617,000 (37% to 52%) of the baseline mixture, 'PCC 45yrs'. However, it should be noted here that the savings potential of the 75-year design would not exceed that of the 55-year design for a 100-year service period regardless of material selection.

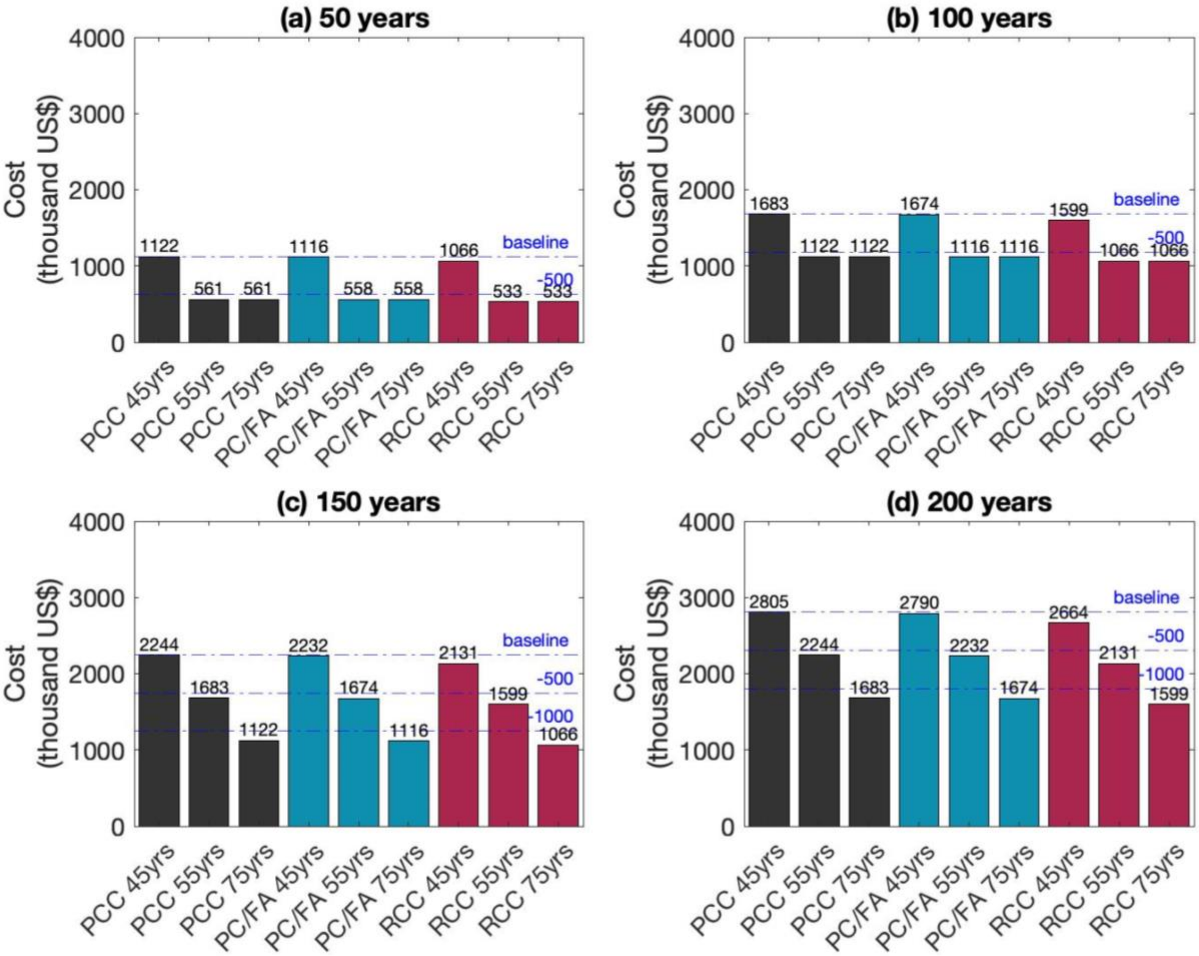


Figure 25. Costs for each PCC, PC/FA, and RCC considering 45, 55, and 75 functional lives for the pavement overlays at each of four potential service-lives of the road system, namely, 50, 100, 150, and 200 years of required service.

This similarity is between service periods is a function of the same reason as was noted for GHG emissions. The 75-year service life design, though, could remarkably cut down on the material expenses if targeting 150-year service. The costs in this scenario would be half of those for the 45-year service life (with the same mixture). This shift is equivalent to $1,065,000 to $1,122,000. Whereas design for a 55-year viable life would be beneficial to any of the 45-year service life calculations including the baseline, but by a smaller amount, namely by 25% ($532,000 to 561,000). If the most cost-saving alternative, 'RCC 75yrs', is compared to the baseline 'PCC 45yrs' at the 150-year time period, the savings are expected to be $1,178,000 (52% of baseline). The 75-year design is also attractive as there would be no additional expenses in the 50 years, between 100 to 150-year required service periods, thus suggesting higher functioning service life can benefit late-stage elongation of required service periods.

6.5.2. Cost abatement plots

The overall effectiveness of the eight alternatives relative to the baseline (PCC 45yrs) was evaluated based on their potential to mitigate GHG emissions and to reduce material expenses. The expected reduction quantities of the eight alternatives are compared in Figure 26 for different service life scenarios, by setting the emissions and cost of the baseline mixture as 0. All eight alternatives showed desirable mitigation potential for both GHG emissions (reduction values shown as bar width on the x-axis) and material expenses (savings shown as negative values in the y-axis) relative to the baseline. A bar on the right is a more effective alternative on the graphs. The plots also illustrate that each alternative scenario considered leads to GHG emissions mitigation as well as cost-reduction for the cases examined. This trend is due to the proportional relationship between the amount of cement and the per-volume GHG emissions or the per-volume costs (see GHG emissions mitigation section and Table 14).

The results of these comparisons indicate that mixture RCC designed for 55- or 75-year service lives are the most desirable alternatives, displaying the greatest cost savings as well as the highest reduction of GHG emissions in the 50- and 100-year modeled service periods. The savings of those mixtures are notable compared to the baseline mixture, potentially reaching \$589,000 and 1423 tons CO_2-eq in 50 years and \$617,000 and 1760 tons CO_2-eq in 100 years (Figure 26; costs in today's dollars). Large savings can be also expected by implementing the PC/FA 55-year design, the PC/FA 75-year design, the PCC 55-year design, or the PCC 75-year design (Figure 26). Some savings are expected for the mixtures with 45-year life span designs; however, the reduction potentials are not as high as the other alternatives (Figure 26). If 150 years of service life are required, the priority alternatives to use are shown in Figure 26c. Here, selecting a design that specifies a concrete mixture life span of 75 years becomes superior to the other cases regardless of the mixture constituents. The best alternative would be 'RCC 75yrs' followed by 'PC/FA 75yrs' and 'PCC 75yrs' Figure 26c. Regardless of the length of a service period, 'RCC 75yrs' was considered the most effective alternative to replace the baseline mixture for mitigating GHG emissions and reducing the material costs.

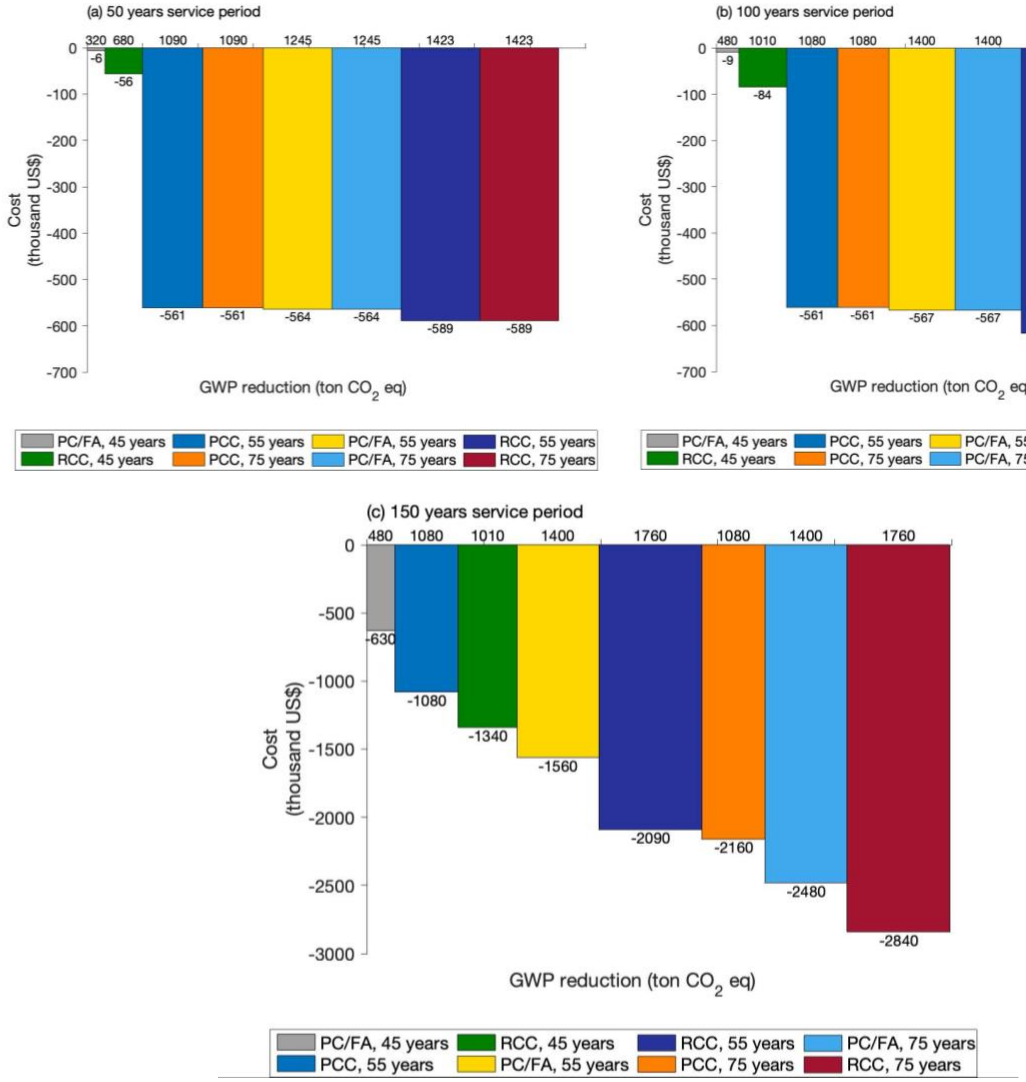


Figure 26. Cost GHG emissions-abatement plot of the eight mixture-life span cases relative to the baseline mixture (PCC 45yrs), in (a) a 50-year service period, (b) a 100-year service period, and (c) a 150-year service period; (costs are in today's dollars)

6.6. Findings and limitations

This section showed the relationship between costs and GHG emissions mitigation efforts outlined in previous sections. Additionally, a simplified case study was presented for a pavement overlay designed for California. Findings showed that there is potential to both save on material costs and reduce GHG emissions through material selection and design. It is important to note that consideration of material durability was outside the scope of this project, but more realistic comparisons could be drawn with the inclusion of durability parameters and exposure conditions when assessing the implications of material selection on system longevity. Here, a simplified example of how longevity could influence emissions is presented; this simplified approach is considered with exaggerated timelines due to limitations in the scope of this work with regard to modeling requisite maintenance and replacement schemes. In future work, more robust modeling efforts should be coupled with the environmental impact approach presented herein to inform mechanisms to drive down both costs and GHG emissions.

7. Summary and future work

This work presented methods to incorporate environmental impacts, specifically GHG emissions, into the design of concrete materials, members, and systems. These methods are applied to data from the literature to provide examples and context for their use. These methods are a first step in facilitating engineering of concrete and concrete systems to lower environmental burdens while meeting performance needs. More work must be conducted in this area to bridge more complex aspects of concrete engineering and environmental impact assessment methods.

References

[1] A. P. Gursel, E. Masanet, A. Horvath, and A. Stadel, “Life-cycle inventory analysis of concrete production: A critical review,” *Cem. Concr. Compos.*, vol. 51, no. 0, pp. 38–48, 2014, doi: http://dx.doi.org/10.1016/j.cemconcomp.2014.03.005.

[2] WBCSD, I. E. A, and O. and T. W. B. C. for S. Development, “Cement technology roadmap 2009,” 2009.

[3] E. Benhelal, G. Zahedi, E. Shamsaei, and A. Bahadori, “Global strategies and potentials to curb CO2 emissions in cement industry,” *J. Clean. Prod.*, vol. 51, no. 0, pp. 142–161, 2013, doi: http://dx.doi.org/10.1016/j.jclepro.2012.10.049.

[4] S. A. Miller, M. D. Lepech, and S. L. Billington, “Evaluation of Functional Units Including Time-Dependent Properties for Environmental Impact Modeling of Biobased Composites,” *J. Biobased Mater. Bioenergy*, vol. 7, pp. 1–12, 2013, doi: 10.1166/jbmb.2013.1388.

[5] S. A. Miller, M. D. Lepech, and S. L. Billington, “Static versus time-dependent material selection charts and application in wood flour composites,” *J. Biobased Mater. Bioenergy*, vol. 9, no. 2, 2015, doi: 10.1166/jbmb.2015.1517273.

[6] M. D. Lepech, M. Geiker, and H. Stang, “Probabilistic design and management of environmentally sustainable repair and rehabilitation of reinforced concrete structures,” *Cem. Concr. Compos.*, vol. 47, no. 0, pp. 19–31, 2014, doi: 10.1016/j.cemconcomp.2013.10.009.

[7] H. G. van Oss, “Minerals Yearbook: Cement 2012,” United States Geological Survey, Reston, VA, 2015.

[8] Caltrans, “Fly Ash: Current and Future Supply. A Joint Effort Between Concrete Task Group of the Caltrans Rock Products Committee and Industry,” 2016.

[9] H. G. van Oss and U. S. G. Survey, “Mineral Commodity Summaries: Cement,” US Geological Survey, 2016.

[10] State of California Department of Finance, “Projections: Population Projections (Baseline 2016),” 2017. [Online]. Available: www.dof.ca.gov/Forecasting/Demographics/Projections.

[11] W. McDonough and M. Braungart, *Cradle to cradle: remaking the way we make things*. New York: North Point Press, 2002.

[12] M. D. Bovea and V. Pérez-Belis, “A taxonomy of ecodesign tools for integrating environmental requirements into the product design process,” *J. Clean. Prod.*, vol. 20, no. 1, pp. 61–71, 2012, doi: http://dx.doi.org/10.1016/j.jclepro.2011.07.012.

[13] P. T. Anastas and J. C. Warner, *Green Chemistry: Theory and Practice*. Oxford, England: Green chemistry: Theory and practice, 1998.

[14] P. T. Anastas and J. B. Zimmerman, “Peer reviewed: Design through the 12 principles of green engineering,” *Environ. Sci. Technol.*, vol. 37, no. 5, pp. 94A-101A, 2003, doi: 10.1021/es032373g.

[15] C. Hendrickson, A. Horvath, S. Joshi, and L. Lave, “Peer reviewed: Economic input–output models for environmental life-cycle assessment,” *Environ. Sci. Technol.*, vol. 32, no. 7, pp. 184A-191A, 1998, doi: 10.1021/es983471i.

[16] P. Brunner and H. Rechberger, “Practical handbook of material flow analysis,” *Int. J. Life Cycle Assess.*, vol. 9, no. 5, pp. 337–338, 2004, doi: 10.1007/bf02979426.

[17] M. E. Boesch and S. Hellweg, “Identifying Improvement Potentials in Cement Production with Life Cycle Assessment,” *Environ. Sci. Technol.*, vol. 44, no. 23, pp. 9143–9149, 2010, doi: 10.1021/es100771k.

[18] NRMCA, “Environmental Product Declaration: NRMCA Member Industry-wide EPD for Ready Mixed Concrete,” National Ready Mixed Concrete Association, Silver Spring, MD, 2014.

[19] M. D. Lepech, V. C. Li, R. E. Robertson, and G. A. Keoleian, “Design of green engineered cementitious composites for improved sustainability,” *ACI Mater. J.*, vol. 105, no. 6, pp. 567–575, 2008.

[20] S. A. Miller, M. D. Lepech, and S. L. Billington, “Application of multi-criteria material selection techniques to constituent refinement in biobased composites,” *Mater. Des.*, vol. 52, 2013, doi: 10.1016/j.matdes.2013.06.046.

[21] D. N. Huntzinger and T. D. Eatmon, “A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies,” *J. Clean. Prod.*, vol. 17, no. 7, pp. 668–675, 2009, doi: http://dx.doi.org/10.1016/j.jclepro.2008.04.007.

[22] S. A. Miller, “The role of cement service-life on the efficient use of resources,” *Environ. Res. Lett.*, vol. 15, no. 2, 2020, doi: 10.1088/1748-9326/ab639d.

[23] C. Formoso, L. Soibelman, C. De Cesare, and E. Isatto, “Material waste in building industry: main causes and prevention,” *J. Constr. Eng. Manag.*, vol. 128, no. 4, pp. 316–325, 2002, doi: doi:10.1061/(ASCE)0733-9364(2002)128:4(316).

[24] P. Billon, J.-C. Galloo, and Lafarge, “Ductal®: A Material at the Heart of Sustainable Construction,” Lafarge, 2010.

[25] G. Habert, C. Billard, P. Rossi, C. Chen, and N. Roussel, “Cement production technology improvement compared to factor 4 objectives,” *Cem. Concr. Res.*, vol. 40, no. 5, pp. 820–826, 2010, doi: http://dx.doi.org/10.1016/j.cemconres.2009.09.031.

[26] D. M. Flower and J. Sanjayan, “Green house gas emissions due to concrete manufacture,” *Int. J. Life Cycle Assess.*, vol. 12, no. 5, pp. 282–288, 2007, doi: 10.1065/lca2007.05.327.

[27] B. L. Damineli, F. M. Kemeid, P. S. Aguiar, and V. M. John, “Measuring the eco-efficiency of cement use,” *Cem. Concr. Compos.*, vol. 32, no. 8, pp. 555–562, 2010, doi: 10.1016/j.cemconcomp.2010.07.009.

[28] G. Habert and N. Roussel, “Study of two concrete mix-design strategies to reach carbon mitigation objectives,” *Cem. Concr. Compos.*, vol. 31, no. 6, pp. 397–402, 2009, doi: http://dx.doi.org/10.1016/j.cemconcomp.2009.04.001.

[29] A. P. Fantilli and B. Chiaia, “Eco-mechanical performances of cement-based materials: An application to self-consolidating concrete,” *Constr. Build. Mater.*, vol. 40, no. 0, pp. 189–196, 2013, doi: http://dx.doi.org/10.1016/j.conbuildmat.2012.09.075.

[30] K. Sakai and J. K. Buffenbarger, “Concrete Sustainability Forum VI,” *Concr. Int.*, vol. 36, no. 3.

[31] K. Scrivener, V. M. John, E. M. Gartner, and U. N. E. Programme, “Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO2 Cement-based Materials Industry,” United Nations Environment Programme, Paris, France, 2017.

[32] IEA, “Technology Roadmap: Low-Carbon Transition in the Cement Industry,” Paris, France, 2018.

[33] P. J. M. Monteiro, S. A. Miller, and A. Horvath, “Towards sustainable concrete,” *Nat. Mater.*

[34] M. W. Doyle and D. G. Havlick, “Infrastructure and the environment,” *Annu. Rev. Environ. Resour.*, vol. 34, no. 1, pp. 349–373, 2009, doi: doi:10.1146/annurev.environ.022108.180216.

[35] A. Kapur, G. Keoleian, A. Kendall, and S. E. Kesler, “Dynamic modeling of in-use cement stocks in the United States,” *J. Ind. Ecol.*, vol. 12, no. 4, pp. 539–556, 2008, doi: 10.1111/j.1530-9290.2008.00055.x.

[36] S. Hellweg and L. Milà i Canals, “Emerging approaches, challenges and opportunities in life cycle assessment,” *Science (80-.).*, vol. 344, no. 6188, pp. 1109–1113, 2014, doi: 10.1126/science.1248361.

[37] ISO, “14040: Environmental Management – Life Cycle Assessment – Principles and Framework.” International Organization for Standardization, Geneva, Switzerland, 1997.

[38] ISO, “14041: Environmental Management – Life Cycle Assessment – Goal and Scope Definition and Inventory Analysis.” International Organization for Standardization, Geneva, Switzerland, 1998.

[39] ISO, “14042: Environmental management — Life cycle assessment — Life cycle impact assessment.” International Organization for Standardization, Geneva, Switzerland, 2000.

[40] ISO, “14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines.” International Organization for Standardization, Geneva, Switzerland, 2006.

[41] G. A. Keoleian and D. V Spitzley, “Life Cycle Based Sustainability Metrics,” in *Sustainability Science and Engineering: Defining Principles*, vol. 1, M. Abraham, Ed. Elsevier, 2006.

[42] SAIC and E. P. Agency, “Life Cycle Assessment: Principles and Practice,” National Risk Management Research Laboratory, Environmental Protection Agency, Reston, VA, 2006.

[43] P. S. Vieira and A. Horvath, “Assessing the end-of-life impacts of buildings,” *Environ. Sci. Technol.*, vol. 42, no. 13, pp. 4663–4669, 2008, doi: 10.1021/es071345l.

[44] C. Chen, G. Habert, Y. Bouzidi, A. Jullien, and A. Ventura, “LCA allocation procedure used as an incitative method for waste recycling: An application to mineral additions in concrete,” *Resour. Conserv. Recycl.*, vol. 54, no. 12, pp. 1231–1240, 2010, doi: http://dx.doi.org/10.1016/j.resconrec.2010.04.001.

[45] A. Horvath, “Green Buildings Seminar: How much do we know about green buildings?,” University of California, Berkeley, Berkeley, CA, 2015.

[46] R. M. Andrew, “Global CO2 emissions from cement production, 1928–2018,” *Earth Syst. Sci. Data*, vol. 11, no. 4, pp. 1675–1710, Nov. 2019, doi: 10.5194/essd-11-1675-2019.

[47] W. Shen, L. Cao, Q. Li, W. Zhang, G. Wang, and C. Li, “Quantifying CO2 emissions from China’s cement industry,” *Renew. Sustain. Energy Rev.*, vol. 50, pp. 1004–1012, 2015, doi: https://doi.org/10.1016/j.rser.2015.05.031.

[48] S. A. Miller, A. Horvath, and P. J. M. Monteiro, “Readily implementable techniques can cut annual CO2 emissions from the production of concrete by over 20%,” *Environ. Res. Lett.*

[49] J. M. Paris, J. G. Roessler, C. C. Ferraro, H. D. DeFord, and T. G. Townsend, “A review of waste products utilized as supplements to Portland cement in concrete,” *J. Clean. Prod.*, vol. 121, pp. 1–18, 2016, doi: https://doi.org/10.1016/j.jclepro.2016.02.013.

[50] P. K. Mehta and P. J. M. Monteiro, *Concrete: microstructure, properties, and materials*, 3rd ed. New York: McGraw-Hill, 2006.

[51] F. Krausmann *et al.*, “Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use,” *Proc. Natl. Acad. Sci.*, vol. 114, no. 8, p. 1880, 2017, doi: 10.1073/pnas.1613773114.

[52] D. Ioannidou, G. Meylan, G. Sonnemann, and G. Habert, “Is gravel becoming scarce? Evaluating the local criticality of construction aggregates,” *Resour. Conserv. Recycl.*, vol. 126, pp. 25–33, 2017, doi: 10.1016/j.resconrec.2017.07.016.

[53] F. Collins, “Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint,” *Int. J. Life Cycle Assess.*, vol. 15, no. 6, pp. 549–556, 2010, doi: 10.1007/s11367-010-0191-4.

[54] R. Andersson, K. Fridh, H. Stripple, and M. Häglund, “Calculating CO2 uptake for existing concrete structures during and after service life,” *Environ. Sci. Technol.*, vol. 47, no. 20, pp. 11625–11633, 2013, doi: 10.1021/es401775w.

[55] N. Muller and J. Harnisch, “A Blueprint for a Climate Friendly Cement Industry,” World Wildlife Fund, Gland, Switzerland, 2008.

[56] S. A. Miller, P. J. M. Monteiro, C. P. Ostertag, and A. Horvath, “Comparison indices for design and proportioning of concrete mixtures taking environmental impacts into account,” *Cem. Concr. Compos.*, vol. 68, pp. 131–143, 2016, doi: 10.1016/j.cemconcomp.2016.02.002.

[57] A. P. Gursel, H. Maryman, and C. Ostertag, “A life-cycle approach to environmental, mechanical, and durability properties of ‘green’ concrete mixes with rice husk ash,” *J. Clean. Prod.*, vol. 112, no. Part 1, pp. 823–836, 2016, doi: http://dx.doi.org/10.1016/j.jclepro.2015.06.029.

[58] K. Celik, C. Meral, A. P. Gursel, P. K. Mehta, A. Horvath, and P. J. M. Monteiro, “Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder,” *Cem. Concr. Compos.*, vol. 56, no. 0, pp. 59–72, 2015, doi: 10.1016/j.cemconcomp.2014.11.003.

[59] S. A. Miller, P. J. M. Monteiro, C. P. Ostertag, and A. Horvath, “Concrete mixture proportioning for desired strength and reduced global warming potential,” *Constr. Build. Mater.*, doi: 10.1016/j.conbuildmat.2016.10.081.

[60] Headwaters, “Fly Ash Concrete Modified Strength Projects,” 2013. [Online]. Available: http://www.flyash.com/data/upfiles/resource/CS 14 Fly Ash Concrete Modified Strength Projects.pdf.

[61] T. Egland *et al.*, “Guidelines for Reviewing Concrete Mix Designs in Accordance with the 2010 CBC,” Structural Engineers Association of Northern California, San Francisco, CA, 2013.

[62] S. A. Miller, A. Horvath, P. J. M. Monteiro, and C. P. Ostertag, “Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors,” *Environ. Res. Lett.*, vol. 10, no. 11, 2015, doi: 10.1088/1748-9326/10/11/114017.

[63] J. Li, W. Zhang, K. Xu, and P. J. M. Monteiro, “Fibrillar calcium silicate hydrate seeds from hydrated tricalcium silicate lower cement demand,” *Cem. Concr. Res.*, vol. 137, p. 106195, 2020, doi: https://doi.org/10.1016/j.cemconres.2020.106195.

[64] S. A. Miller, W. V Srubar III, S. L. Billington, and M. D. Lepech, “Integrating durability-based service-life predictions with environmental impact assessments of natural fiber–reinforced composite materials,” *Resour. Conserv. Recycl.*, vol. 99, pp. 72–83, 2015, doi: 10.1016/j.resconrec.2015.04.004.

[65] S. A. Miller, V. M. John, S. A. Pacca, and A. Horvath, “Carbon dioxide reduction potential in the global cement industry by 2050,” *Cem. Concr. Res.*, vol. 114, pp. 115–124, 2018, doi: https://doi.org/10.1016/j.cemconres.2017.08.026.

[66] H. G. van Oss, “Background Facts and Issues Concerning Cement and Cement Data,” Reston, VA, 2005.

[67] IEA, “Tracking Industrial Energy Efficiency and CO2 Emissions,” Paris, France, 2007.

[68] OECD/IEA and WBCSD, “Cement Roadmap,” 2009.

[69] M. Schneider, M. Romer, M. Tschudin, and H. Bolio, “Sustainable cement production—present and future,” *Cem. Concr. Res.*, vol. 41, no. 7, pp. 642–650, 2011, doi: http://dx.doi.org/10.1016/j.cemconres.2011.03.019.

[70] C. Chen, G. Habert, Y. Bouzidi, and A. Jullien, “Environmental impact of cement production: detail of the different processes and cement plant variability evaluation,” *J. Clean. Prod.*, vol. 18, no. 5, pp. 478–485, 2010, doi: http://dx.doi.org/10.1016/j.jclepro.2009.12.014.

[71] A. Josa, A. Aguado, A. Heino, E. Byars, and A. Cardim, “Comparative analysis of available life cycle inventories of cement in the EU,” *Cem. Concr. Res.*, vol. 34, no. 8, pp. 1313–1320, 2004, doi: http://dx.doi.org/10.1016/j.cemconres.2003.12.020.

[72] C. Valderrama, R. Granados, J. L. Cortina, C. M. Gasol, M. Guillem, and A. Josa, “Implementation of best available techniques in cement manufacturing: a life-cycle assessment study,” *J. Clean. Prod.*, vol. 25, no. 0, pp. 60–67, 2012, doi: http://dx.doi.org/10.1016/j.jclepro.2011.11.055.

[73] T. Kelly, “Crushed Cement Concrete Substitution for Construction Aggregates - A Material Flow Analysis,” U.S. Geological Survey, 1998.

[74] P. Van den Heede and N. De Belie, “Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: Literature review and theoretical calculations,” *Cem. Concr. Compos.*, vol. 34, no. 4, pp. 431–442, 2012, doi: http://dx.doi.org/10.1016/j.cemconcomp.2012.01.004.

[75] A. Horvath, “Construction materials and the environment,” *Annu. Rev. Environ. Resour.*, vol. 29, no. 1, pp. 181–204, 2004, doi: doi:10.1146/annurev.energy.29.062403.102215.

[76] P. K. Mehta, “Sustainable cements and concrete for the climate change era - a review,” in *Second International Conference on Sustainable Construction Materials and Technologies*, 2010.

[77] C. Meyer, “The greening of the concrete industry,” *Cem. Concr. Compos.*, vol. 31, no. 8, pp. 601–605, 2009, doi: http://dx.doi.org/10.1016/j.cemconcomp.2008.12.010.

[78] J. L. Provis, “Green concrete or red herring? – future of alkali-activated materials,” *Adv. Appl. Ceram.*, vol. 0, no. 0, p. 1743676114Y.0000000177, doi: doi:10.1179/1743676114Y.0000000177.

[79] R. J. Flatt, N. Roussel, and C. R. Cheeseman, “Concrete: An eco material that needs to be improved,” *J. Eur. Ceram. Soc.*, vol. 32, no. 11, pp. 2787–2798, 2012, doi: http://dx.doi.org/10.1016/j.jeurceramsoc.2011.11.012.

[80] P. Purnell and L. Black, “Embodied carbon dioxide in concrete: Variation with common mix design parameters,” *Cem. Concr. Res.*, vol. 42, no. 6, pp. 874–877, 2012, doi: http://dx.doi.org/10.1016/j.cemconres.2012.02.005.

[81] S. Talukdar, S. T. Islam, and N. Banthia, “Development of a Lightweight Low-Carbon Footprint Concrete Containing Recycled Waste Materials,” *Adv. Civ. Eng.*, vol. 2011, p. 8, 2011, doi: 10.1155/2011/594270.

[82] F. Pelisser, A. Barcelos, D. Santos, M. Peterson, and A. M. Bernardin, “Lightweight concrete production with low Portland cement consumption,” *J. Clean. Prod.*, vol. 23, no. 1, pp. 68–74, 2012, doi: http://dx.doi.org/10.1016/j.jclepro.2011.10.010.

[83] A. R. Jayapalan, B. Y. Lee, and K. E. Kurtis, “Can nanotechnology be ‘green’? Comparing efficacy of nano and microparticles in cementitious materials,” *Cem. Concr. Compos.*, vol. 36, no. 0, pp. 16–24, 2013, doi: http://dx.doi.org/10.1016/j.cemconcomp.2012.11.002.

[84] K. Simonen, M. Huang, V. Rybl, and B. B. Waldman, “Embodied Carbon in the EC3 Tool: Beta Methodology Report, Beta Release,” Vancouver, WA, 2019.

[85] *Assembly Bill No. 262 Buy Clean California*, no. 262. 2017.

[86] M. Robati, T. J. McCarthy, and G. Kokogiannakis, “Incorporating environmental evaluation and thermal properties of concrete mix designs,” *Constr. Build. Mater.*, vol. 128, pp. 422–435, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.10.092.

[87] J. Anderson, A. Rønning, and A. Moncaster, “The reporting of end of life and module D data and scenarios in EPD for building level life cycle assessment,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, p. 012051, Sep. 2019, doi: 10.1088/1755-1315/323/1/012051.

[88] A. P. Gursel and A. Horvath, “GreenConcrete LCA Webtool,” 2012. [Online]. Available: http://greenconcrete.berkeley.edu/concretewebtool.html.

[89] Sphera, “Gabi Solutions,” 2021. .

[90] G. Habert, J. B. d’Espinose de Lacaillerie, and N. Roussel, “An environmental evaluation of geopolymer based concrete production: reviewing current research trends,” *J. Clean. Prod.*, vol. 19, no. 11, pp. 1229–1238, 2011, doi: 10.1016/j.jclepro.2011.03.012.

[91] J. M. O. dos Santos, S. Thyagarajan, E. Keijzer, R. F. Flores, and G. Flintsch, “Comparison of life-cycle assessment tools for road pavement infrastructure,” *Transp. Res. Rec.*, vol. 2646, no. 1, pp. 28–38, Jan. 2017, doi: 10.3141/2646-04.

[92] E. Ekener-Petersen and Å. Moberg, “Potential hotspots identified by social LCA–Part 2: Reflections on a study of a complex product,” *Int. J. Life Cycle Assess.*, vol. 18, no. 1, pp. 144–154, 2013, doi: 10.1007/s11367-012-0443-6.

[93] various authors PRé, “SimaPro Database Manual: Methods Library,” Amersfoort, Netherlands, 2019.

[94] D. L. Vega A., M. A. Gilberto, and J. M. O. dos Santos, “Life cycle assessment of warm mix asphalt with recycled concrete aggregate,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 603, p. 052016, Sep. 2019, doi: 10.1088/1757-899X/603/5/052016.

[95] N. Santero, A. Loijos, M. Akbarian, and J. Ochsendorf, “Methods, impacts, and opportunities in the concrete pavement life cycle,” Cambridge, MA, 2011.

[96] D. Cass and A. Mukherjee, “Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: Case study for pavement operations,” *J. Constr. Eng. Manag.*, vol. 137, no. 11, pp. 1015–1025, Nov. 2011, doi: 10.1061/(ASCE)CO.1943-7862.0000349.

[97] GreenDelta, “openLCA,” 2021. .

[98] A. Passuello *et al.*, “Evaluation of the potential improvement in the environmental footprint of geopolymers using waste-derived activators,” *J. Clean. Prod.*, vol. 166, pp. 680–689, 2017, doi: https://doi.org/10.1016/j.jclepro.2017.08.007.

[99] Y. Hamdar, G. R. Chehab, and I. Srour, “Life-cycle evaluation of pavements: A critical review,” *J. Eng. Sci. Technol. Rev.*, vol. 9, no. 6, pp. 12–26, 2016.

[100] Athena Sustainable Materials Institute, “LCA Data & Software,” 2021. .

[101] Athena Sustainable Materials Institute, “Learn More About How LCA Works,” 2020. [Online]. Available: http://www.athenasmi.org/resources/about-lca/technical-details/. [Accessed: 16-Mar-2020].

[102] J. T. Harvey, J. Lea, A. Saboori, A. A. Butt, and M. Ostovar, “eLCAP: software for environmental life cycle assessment of pavements,” in *LCA 2020*, 2021.

[103] GCCA, “Getting the Numbers Right Project: Emissions Report 2019,” London, UK, 2019.

[104] GCCA, “Internet Manual,” *Global Cement and Concrete Association*, 2020. .

[105] iPoint-systems, “Umberto LCA+,” 2021. .

[106] R. Bajpai, K. Choudhary, A. Srivastava, K. S. Sangwan, and M. Singh, “Environmental impact assessment of fly ash and silica fume based geopolymer concrete,” *J. Clean. Prod.*, vol. 254, p. 120147, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.120147.

[107] A. Buchwald, M. Weil, and K. Dombrowski, “Life cycle analysis incorporated development of geopolymer binder / Ökobilanziell eingebettete entwicklung von geopolymerbindern,” *Restor. Build. Monum.*, vol. 14, no. 4, pp. 271–282, 2008, doi: https://doi.org/10.1515/rbm-2008-6228.

[108] R. Dandautiya and A. P. Singh, “Utilization potential of fly ash and copper tailings in concrete as partial replacement of cement along with life cycle assessment,” *Waste Manag.*, vol. 99, pp. 90–101, 2019, doi: https://doi.org/10.1016/j.wasman.2019.08.036.

[109] M. R. Ghazy, A. M. Abdallah, M. A. Basiouny, and M. A. S. Saad, “Life cycle assessment of flexible pavement construction,” *Curr. J. Appl. Sci. Technol.*, vol. 12, no. 1, pp. 1–17, 2015, doi: 10.9734/BJAST/2016/20620.

[110] One Click LCA Ltd., “One Click LCA,” 2021. .

[111] ZGF, “LCA Calculator Reduces Concrete’s Embodied Carbon,” *ZGF Press Release*, 2019. [Online]. Available: https://www.zgf.com/news_post/lca-calculator-reduces-concretes-embodied-carbon/. [Accessed: 18-Mar-2020].

[112] R. Haynes, “eTool LCA Software Updates - Autumn 2013,” 2013. [Online]. Available: https://support.etoollcd.com/index.php/knowledgebase/etool-lca-software-news/. [Accessed: 15-Mar-2020].

[113] NIST, “BEES Online 2.0,” *National Institute of Standards and Technology*, 2020. [Online]. Available: https://ws680.nist.gov/Bees2. [Accessed: 18-Mar-2020].

[114] T. Kim, S. Lee, C. Chae, H. Jang, and K. Lee, “Development of the CO2 emission evaluation tool for the life cycle assessment of concrete,” *Sustainability*, vol. 9, no. 11, p. 2116, Nov. 2017, doi: 10.3390/su9112116.

[115] M. A. Curran, J. G. Overly, P. Hofstetter, R. Muller, and B. C. Lippiatt, “BEES 2.0: Building for Environmental and Economic Sustainability Peer Review Report,” Gaithersburg, MD, 2002.

[116] B. Lippiatt and S. Ahmad, “Measuring the life-cycle environmental and economic performance of concrete: The BEES approach,” *Int. Work. Sustain. Dev. Concr. Technol.*, Oct. 2011.

[117] M. Reiner and K. Rens, “High-Volume Fly Ash Concrete: Analysis and Application,” *Pract. Period. Struct. Des. Constr.*, vol. 11, no. 1, pp. 58–64, Feb. 2006, doi: 10.1061/(ASCE)1084-0680(2006)11:1(58).

[118] Carbon Leadership Forum, “Initiative: EC3 Tool,” 2021. .

[119] NSF, “Product Category Rule for Environmental Product Declarations: PCR for Concrete,” Ann Arbor, Michigan, 2019.

[120] ClimateEarth, “Free Concrete Selector,” 2018. [Online]. Available: https://www.climateearth.com/concrete-selector-2/. [Accessed: 15-Mar-2020].

[121] A. Jullien, M. Dauvergne, and C. Proust, “Road LCA: the dedicated ECORCE tool and database,” *Int. J. Life Cycle Assess.*, vol. 20, no. 5, pp. 655–670, 2015, doi: 10.1007/s11367-015-0858-y.

[122] ECORCE, “ECO-comparison Road Construction and Maintenance,” *IFSTTAR*, 2014. [Online]. Available: http://ecorcem.ifsttar.fr/. [Accessed: 22-Mar-2020].

[123] P. Purnell, “Material nature versus structural nurture: The embodied carbon of fundamental structural elements,” *Environ. Sci. Technol.*, vol. 46, no. 1, pp. 454–461, 2011, doi: 10.1021/es202190r.

[124] P. Purnell, “Response to the Comment on ,"Material Nature versus Structural Nurture: The Embodied Carbon of Fundamental Structural Elements,",” *Environ. Sci. Technol.*, vol. 46, no. 6, pp. 3597–3598, 2012, doi: 10.1021/es3007595.

[125] R. Sathre *et al.*, “Comment on ‘Material nature versus structural nurture: The embodied carbon of fundamental structural elements,’” *Environ. Sci. Technol.*, vol. 46, no. 6, pp. 3595–3596, 2012, doi: 10.1021/es300276b.

[126] R. Lifset and M. Eckelman, “Material efficiency in a multi-material world,” *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, no. 371, pp. 1–13, 2013.

[127] D. Yeo and R. D. Gabbai, “Sustainable design of reinforced concrete structures through embodied energy optimization,” *Energy Build.*, vol. 43, no. 8, pp. 2028–2033, 2011, doi: http://dx.doi.org/10.1016/j.enbuild.2011.04.014.

[128] J. S. Damtoft, J. Lukasik, D. Herfort, D. Sorrentino, and E. M. Gartner, “Sustainable development and climate change initiatives,” *Cem. Concr. Res.*, vol. 38, no. 2, pp. 115–127, 2008, doi: http://dx.doi.org/10.1016/j.cemconres.2007.09.008.

[129] Z. Cao, L. Shen, A. N. Løvik, D. B. Müller, and G. Liu, “Elaborating the history of our cementing societies: An in-use stock perspective,” *Environ. Sci. Technol.*, vol. 51, no. 19, pp. 11468–11475, 2017, doi: 10.1021/acs.est.7b03077.

[130] A. P. Fantilli, F. Tondolo, B. Chiaia, and G. Habert, “Designing Reinforced Concrete Beams Containing Supplementary Cementitious Materials,” vol. 12, no. 8, p. 1248, 2019.

[131] P. Kourehpaz and S. A. Miller, “Eco-efficient design indices for reinforced concrete members,” *Mater. Struct. Constr.*, vol. 52, no. 5, 2019, doi: 10.1617/s11527-019-1398-x.

[132] Gordian, “RSMeans,” 2018. [Online]. Available: https://www.rsmeans.com/.

[133] D. R. Gomez *et al.*, “2006 IPCC Guidelines for National Greenhouse Gas Inventories: Chapter 2: Energy: Stationary Combustion,” Intergovernmental Panel on Climate Change, Hayama, Kanagawa, 2007.

[134] T. García-Segura, V. Yepes, and J. Alcalá, “Life cycle greenhouse gas emissions of blended cement concrete including carbonation and durability,” *Int. J. Life Cycle Assess.*, vol. 19, no. 1, pp. 3–12, 2014, doi: 10.1007/s11367-013-0614-0.

[135] M. F. Ashby, “Multi-objective optimization in material design and selection,” *Acta Mater.*, vol. 48, no. 1, pp. 359–369, 2000, doi: https://doi.org/10.1016/S1359-6454(99)00304-3.

[136] S. A. Miller, A. Horvath, P. J. M. Monteiro, and C. P. Ostertag, “Greenhouse gas emissions from concrete can be reduced by using mix proportions, geometric aspects, and age as design factors,” *Environ. Res. Lett.*, vol. 10, no. 11, p. 114017, 2015.

[137] C. T. Mueller, “3D Printed Structures: Challenges and Opportunities,” *Struct. Mag.*, vol. January, pp. 55–56, 2016.

[138] C. Fan and S. A. Miller, “Reducing greenhouse gas emissions for prescribed concrete compressive strength,” *Constr. Build. Mater.*, vol. 167, pp. 918–928, 2018, doi: 10.1016/j.conbuildmat.2018.02.092.

[139] M. Ashby, *Materials Selection in Mechanical Design*, 3rd ed. Oxford, UK: Elsevier Inc., 2005.

[140] C. Bilim, C. D. Atiş, H. Tanyildizi, and O. Karahan, “Predicting the compressive strength of ground granulated blast furnace slag concrete using artificial neural network,” *Adv. Eng. Softw.*, vol. 40, no. 5, pp. 334–340, 2009, doi: http://dx.doi.org/10.1016/j.advengsoft.2008.05.005.

[141] K.-S. Youm, J. Moon, J.-Y. Cho, and J. J. Kim, “Experimental study on strength and durability of lightweight aggregate concrete containing silica fume,” *Constr. Build. Mater.*, vol. 114, pp. 517–527, 2016, doi: https://doi.org/10.1016/j.conbuildmat.2016.03.165.

[142] R. Liu, S. Durham, K. Rens, and A. Ramaswami, “Optimization of Cementitious Material Content for Sustainable Concrete Mixtures,” *J. Mater. Civ. Eng.*, vol. 24, no. 6, pp. 745–753, 2012, doi: doi:10.1061/(ASCE)MT.1943-5533.0000444.

[143] M. S. Meddah, “Durability performance and engineering properties of shale and volcanic ashes concretes,” *Constr. Build. Mater.*, vol. 79, pp. 73–82, 2015.

[144] M. S. Meddah, M. C. Lmbachiya, and R. K. Dhir, “Potential use of binary and composite limestone cements in concrete production,” *Constr. Build. Mater.*, vol. 58, pp. 193–205, 2014, doi: http://dx.doi.org/10.1016/j.conbuildmat.2013.12.012.

[145] S. E. Hedegaard and T. C. Hansen, “Modified water/cement ratio law for compressive strength of fly ash concretes,” *Mater. Struct.*, vol. 25, no. 5, pp. 273–283, 1992, doi: 10.1007/bf02472668.

[146] B. Felekoğlu, S. Türkel, and B. Baradan, “Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete,” *Build. Environ.*, vol. 42, no. 4, pp. 1795–1802, 2007, doi: http://dx.doi.org/10.1016/j.buildenv.2006.01.012.

[147] E. Vejmelková *et al.*, “High performance concrete containing lower slag amount: A complex view of mechanical and durability properties,” *Constr. Build. Mater.*, vol. 23, no. 6, pp. 2237–2245, 2009, doi: http://dx.doi.org/10.1016/j.conbuildmat.2008.11.018.

[148] M. N. Haque and O. Kayali, “Properties of high-strength concrete using a fine fly ash,” *Cem. Concr. Res.*, vol. 28, no. 10, pp. 1445–1452, 1998, doi: http://dx.doi.org/10.1016/S0008-8846(98)00125-2.

[149] K.-R. Wu, B. Chen, W. Yao, and D. Zhang, “Effect of coarse aggregate type on mechanical properties of high-performance concrete,” *Cem. Concr. Res.*, vol. 31, no. 10, pp. 1421–1425, 2001, doi: http://dx.doi.org/10.1016/S0008-8846(01)00588-9.

[150] M. S. Meddah, M. A. Ismail, S. El-Gamal, and H. Fitriani, “Performances evaluation of binary concrete designed with silica fume and metakaolin,” *Constr. Build. Mater.*, vol. 166, pp. 400–412, 2018, doi: https://doi.org/10.1016/j.conbuildmat.2018.01.138.

[151] A. Oner, S. Akyuz, and R. Yildiz, “An experimental study on strength development of concrete containing fly ash and optimum usage of fly ash in concrete,” *Cem. Concr. Res.*, vol. 35, no. 6, pp. 1165–1171, 2005, doi: http://dx.doi.org/10.1016/j.cemconres.2004.09.031.

[152] A. Oner and S. Akyuz, “An experimental study on optimum usage of GGBS for the compressive strength of concrete,” *Cem. Concr. Compos.*, vol. 29, no. 6, pp. 505–514, 2007, doi: http://dx.doi.org/10.1016/j.cemconcomp.2007.01.001.

[153] P. J. M. Monteiro, P. R. L. Helene, and S. H. Kang, “Designing concrete mixtures for strength, elastic modulus and fracture energy,” *Mater. Struct.*, vol. 26, no. 8, pp. 443–452, 1993, doi: 10.1007/bf02472804.

[154] M. J. McCarthy and R. K. Dhir, “Development of high volume fly ash cements for use in concrete construction,” *Fuel*, vol. 84, no. 11, pp. 1423–1432, 2005, doi: http://dx.doi.org/10.1016/j.fuel.2004.08.029.

[155] B. Chen and J. Liu, “Effect of aggregate on the fracture behavior of high strength concrete,” *Constr. Build. Mater.*, vol. 18, no. 8, pp. 585–590, 2004, doi: https://doi.org/10.1016/j.conbuildmat.2004.04.013.

[156] R. A. Einsfeld and M. S. L. Velasco, “Fracture parameters for high-performance concrete,” *Cem. Concr. Res.*, vol. 36, no. 3, pp. 576–583, 2006, doi: http://dx.doi.org/10.1016/j.cemconres.2005.09.004.

[157] P. Zhang, Q. Li, and H. Zhang, “Fracture properties of high-performance concrete containing fly ash,” *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.*, vol. 226, no. 2, pp. 170–176, 2012, doi: 10.1177/1464420711435759.

[158] R. Siddique, “Performance characteristics of high-volume Class F fly ash concrete,” *Cem. Concr. Res.*, vol. 34, no. 3, pp. 487–493, 2004, doi: http://dx.doi.org/10.1016/j.cemconres.2003.09.002.

[159] C. S. Poon, L. Lam, and Y. L. Wong, “A study on high strength concrete prepared with large volumes of low calcium fly ash,” *Cem. Concr. Res.*, vol. 30, no. 3, pp. 447–455, 2000, doi: http://dx.doi.org/10.1016/S0008-8846(99)00271-9.

[160] L. Lam, Y. L. Wong, and C. S. Poon, “Effect of Fly Ash and Silica Fume on Compressive and Fracture Behaviors of Concrete,” *Cem. Concr. Res.*, vol. 28, no. 2, pp. 271–283, 1998, doi: http://dx.doi.org/10.1016/S0008-8846(97)00269-X.

[161] A. A. Ramezanianpour and V. M. Malhotra, “Effect of curing on the compressive strength, resistance to chloride-ion penetration and porosity of concretes incorporating slag, fly ash or silica fume,” *Cem. Concr. Compos.*, vol. 17, no. 2, pp. 125–133, 1995, doi: https://doi.org/10.1016/0958-9465(95)00005-W.

[162] C.-H. Huang, S.-K. Lin, C.-S. Chang, and H.-J. Chen, “Mix proportions and mechanical properties of concrete containing very high-volume of Class F fly ash,” *Constr. Build. Mater.*, vol. 46, pp. 71–78, 2013, doi: https://doi.org/10.1016/j.conbuildmat.2013.04.016.

[163] P. Chindaprasirt, S. Homwuttiwong, and C. Jaturapitakkul, “Strength and water permeability of concrete containing palm oil fuel ash and rice husk–bark ash,” *Constr. Build. Mater.*, vol. 21, no. 7, pp. 1492–1499, 2007, doi: https://doi.org/10.1016/j.conbuildmat.2006.06.015.

[164] A. Behnood and H. Ziari, “Effects of silica fume addition and water to cement ratio on the properties of high-strength concrete after exposure to high temperatures,” *Cem. Concr. Compos.*, vol. 30, no. 2, pp. 106–112, 2008, doi: https://doi.org/10.1016/j.cemconcomp.2007.06.003.

[165] S.-T. Yi, E.-I. Yang, and J.-C. Choi, “Effect of specimen sizes, specimen shapes, and placement directions on compressive strength of concrete,” *Nucl. Eng. Des.*, vol. 236, no. 2, pp. 115–127, 2006, doi: http://dx.doi.org/10.1016/j.nucengdes.2005.08.004.

[166] A. Hasanbeigi, M. Arens, J. C. R. Cardenas, L. Price, and R. Triolo, “Comparison of carbon dioxide emissions intensity of steel production in China, Germany, Mexico, and the United States,” *Resour. Conserv. Recycl.*, vol. 113, pp. 127–139, 2016, doi: https://doi.org/10.1016/j.resconrec.2016.06.008.

[167] A. Hasanbeigi and C. Springer, “Deep Decarbonization Roadmap for the Cement and Concrete Industries in California,” Global Efficiency Intelligence, San Francisco, CA, 2019.

[168] A. C. I, “318-11: Building Code Requirements for Structural Concrete.” American Concrete Institute, Farmington Hills, MI, 2011.

[169] E. Commission, “Joint Research Centre,” 2017. [Online]. Available: http://eplca.jrc.ec.europa.eu/ELCD3/. [Accessed: 01-Apr-2018].

[170] S. A. Miller, “Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: can there be too much of a good thing?,” *J. Clean. Prod.*, vol. 178, 2018, doi: 10.1016/j.jclepro.2018.01.008.

[171] V. M. John, B. L. Damineli, M. Quattrone, and R. G. Pileggi, “Fillers in cementitious materials — Experience, recent advances and future potential,” *Cem. Concr. Res.*, vol. 114, pp. 65–78, 2018, doi: 10.1016/j.cemconres.2017.09.013.

[172] Zhang, H, M. Lepech, G. Keoleian, S. Qian, and V. Li, “Dynamic life-cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration,” *J. Infrastruct. Syst.*, vol. 16, no. 4, pp. 299–309, 2010.

[173] T. Key, “California Non-Fuel Mineral Production 2017,” Sacramento, CA, 2019.

[174] USGS, “Aggregates Data by State, Type, and End Use; 1971–2016,” 2020. .

[175] SR Minerals Inc., “Concept Study: Development of the CS Perlite/Pozzolan Deposit, Esmeralda County, Nevada,” Reno, NV, 2017.

[176] F. Mercier, D. Mabashi, and C. Steidl, “Steel Market Developments, Q4 2018,” 2019.

[177] R. Quintanilla, “Personal Communication: Concrete Mix Pricing.” Granite Rock, Cupertino, CA, 2015.

[178] Clay Socum, “personal communication.” California Nevada Cement Association, 2020.

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

[180] GNR, “Global Cement Database on CO_2 and Energy Information,” 2016. [Online]. Available: http://www.wbcsdcement.org/GNR-2013/index.html. [Accessed: 31-Jan-2016].

[181] Franklin Associates, “Limestone, at mine, 21: Mining, Quarrying, and Oil and Gas Extraction / 2123: Nonmetallic Mineral Mining and Quarrying,” *Federal LCA Commons, National Renewable Energy Laboratory*, 2011. [Online]. Available: https://www.lcacommons.gov/lca-collaboration/National_Renewable_Energy_Laboratory/USLCI/dataset/PROCESS/49e563d8-0cea-3f97-96b8-15787be48b91. [Accessed: 18-May-2020].

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

[183] M. L. Marceau, M. A. Nisbet, M. G. VanGeem, and P. C. Association, “Life Cycle Inventory of Portland Cement Concrete,” Portland Cement Association, Skokie, Illinois, 2007.

[184] SCA, “Slag Cement Association Industry Average EPD for Slag Cement,” Farmington Hills, MI, 2015.

[185] S. A. Miller, S. L. Billington, and M. D. Lepech, “Influence of carbon feedstock on potentially net beneficial environmental impacts of bio-based composites,” *J. Clean. Prod.*, vol. 132, 2016, doi: 10.1016/j.jclepro.2015.11.047.

[186] S. Miller, M. Lepech, and S. Billington, “Mechanical and Environmental Characterization of Bio-Based Composites,” Stanford University, Stanford, CA, 2013.

[187] EFCA, “Environmental Product Declaration: Concrete Admixtures – Plasticizers and Superplasticizers,” European Federation of Concrete Admixtures Association Ltd., Berlin, Germany, 2015.

[188] EFCA, “Environmental Product Declaration: Concrete admixtures – Air entrainers,” Berlin, Germany, 2015.

[189] EFCA, “Environmental Product Declaration: Concrete admixtures – Hardening Accelerators,” Berlin, Germany, 2015.

[190] EFCA, “Environmental Product Declaration: Concrete admixtures – Set Accelerators,” Berlin, Germany, 2015.

[191] EFCA, “Environmental Product Declaration: Concrete admixtures – Water Resisting Admixtures,” Berlin, Germany, 2015.

[192] EFCA, “Environmental Product Declaration: Concrete admixtures – Retarders,” Berlin, Germany, 2015.

[193] K. Kermeli, E. Worrell, and E. Masanet, “Energy Efficiency Improvement and Cost Saving Opportunities for the Concrete Industry,” Berkeley, California, 2011.

[194] L. Michaelis *et al.*, “Climate Change 1995: The IPCC Second Assessment Report: Chapter 21: Mitigation Options in the Transportation Sector,” Intergovernmental Panel on Climate Change, Cambridge, 1995.

[195] ORNL, “Transportation Energy Data Book: Chapter 2: Energy,” Oak Ridge National Lab and U S Department of Energy, 2015.

Data Summary

Products of Research

Concrete mixtures and properties were compiled from the literature, building from a small database constructed by the PI. A method for calculating greenhouse gas (GHG) emissions was used in this work and a small Excel spreadsheet that facilitates those calculations was created.

Data Format and Content

Data are presented in Excel documents:

- Supplementary Data 1: Small database of concrete mixtures
- Supplementary Data 2: GHG emissions calculation method

Data Access and Sharing

The GHG emissions calculation method has been incorporated into a larger environmental impact assessment method that will be published as an open-access concrete impact calculator.

Reuse and Redistribution

Data is currently available upon request from the PI, Sabbie Miller. Users are free to re-use the data with due citation of the work. If the data are modified or re-distributed, this must be stated explicitly and must be done in a manner that does not compromise the integrity of the data.

Appendix A

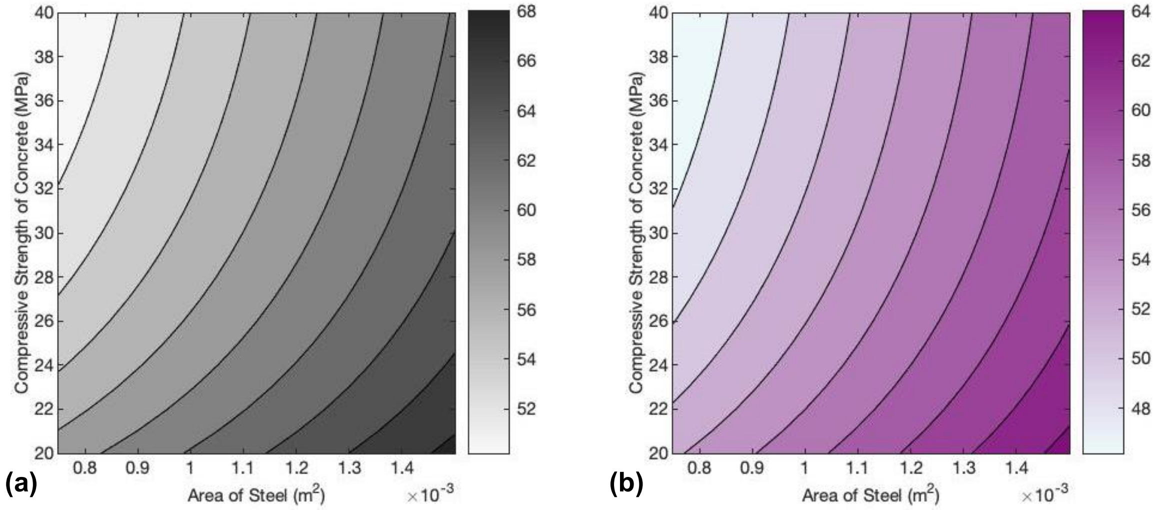
Table A-1. Constituents, processes, and data sources/assumptions for environmental impact model

Constituent	Process	Flow data source & notes
Portland cement	quarry operations, raw meal preparation, finish grinding - wet kiln	[179]
	quarry operations, raw meal preparation, finish grinding - long dry kiln	[179]
	quarry operations, raw meal preparation, finish grinding - preheater kiln	[179]
	quarry operations, raw meal preparation, finish grinding - precalciner/preheater kiln	[179]
	kilning - wet kiln	[180]
	kilning - long dry kiln	[180]
	kilning - preheater kiln	[180]
	kilning - precalciner/preheater kiln	[180]
	calcination emissions	stoichiometry, assuming 65% lime content in clinker & 5% gypsum in cement
Gypsum	quarry operations, preparation	assumed same as limestone filler
Limestone filler	quarry operations, preparation	[181]; conversions from [182]
Natural pozzolans	quarry operations, preparation	assumed same as limestone filler
Fly ash	N/A	[183]
Granulated blast furnace slag	quenching and granulation, dewatering and drying, iron removal, crushing, and grinding	[184]
Rice hull ash	grinding	[57]
Hemp hurd (without photosynthesis)	hackling, scutching	[185] - allocation by weight from [186]
	warm water retting, NaOH treatment	
Calcined clay	grinding, packing, operation, other processes	[65]
	kilning	

Constituent	**Process**	**Flow data source & notes**
Fine Aggregates	quarry operations, preparation	[183]
Coarse Aggregates	quarry operations, preparation	[183]
Plasticizers and Superplasticizers	Raw material supply, transport prior to production gate, and manufacturing	[187]
Air Entrainers	Raw material supply, transport prior to production gate, and manufacturing	[188]
Hardening Accelerators	Raw material supply, transport prior to production gate, and manufacturing	[189]
Set Accelerators	Raw material supply, transport prior to production gate, and manufacturing	[190]
Water Resisting Admixtures	Raw material supply, transport prior to production gate, and manufacturing	[191]
Retarders	Raw material supply, transport prior to production gate, and manufacturing	[192]
	Process	
Batching	Batching (per cubic meter), For water (per kg batching water)	[193]
Transportation	Transportation, truck	[194]
	Transportation, rail	[195]
	Transportation, ship	[195]

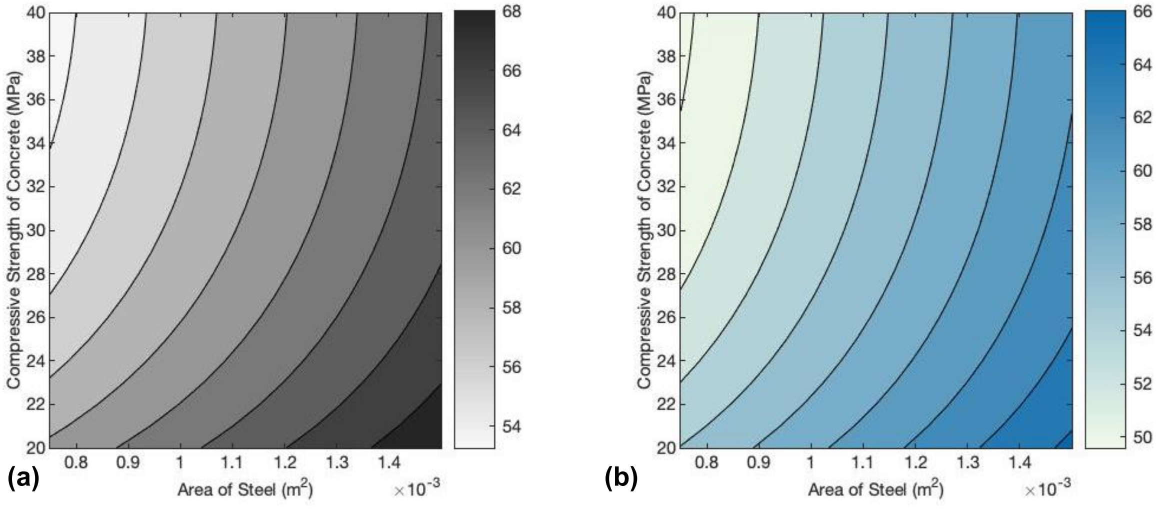
Appendix B

Appendix B.1. Supplementary Column Contour Plots



(a) (b)

Figure B-1. Column contour plots for mixtures containing (a) no SCMs, (b) fly ash at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.



(a) (b)

Figure B-2. Column contour plots for mixtures containing (a) no SCMs, (b) ground granulated blast furnace slag at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

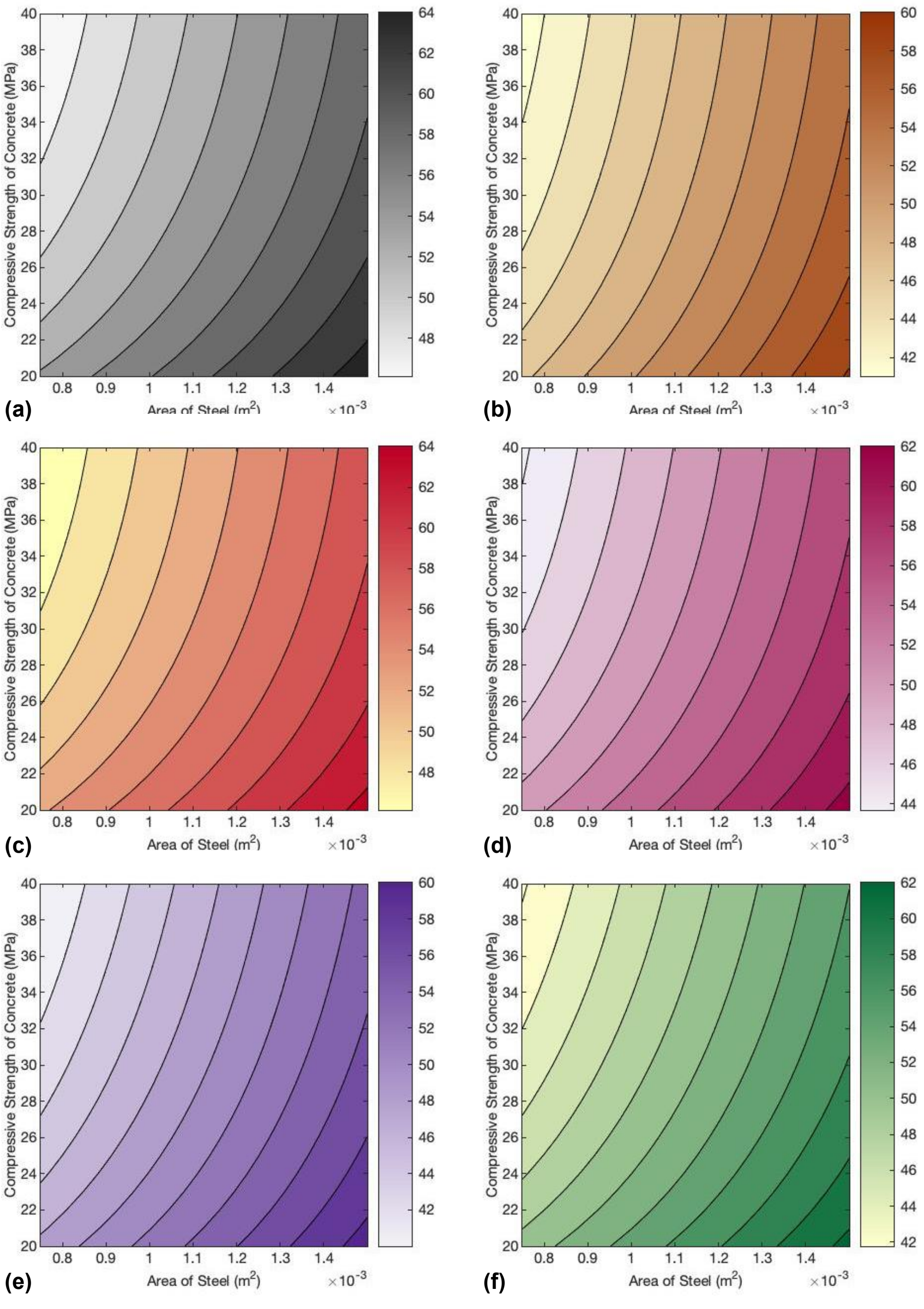


Figure B-3. Column contour plots for mixtures containing (a) no SCMs, (b) limestone filler at 15% replacement of cement, (c) natural pozzolans at 15% replacement of cement, (d) shale ash at 15% replacement of cement, (e) silica fume at 15% replacement of cement, and (f) calcined clay at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain different water content than those with fly ash and blast furnace slag; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not shown.

Appendix B.2. Supplementary Contour Plots: Beam Designed at the Cracking Stage

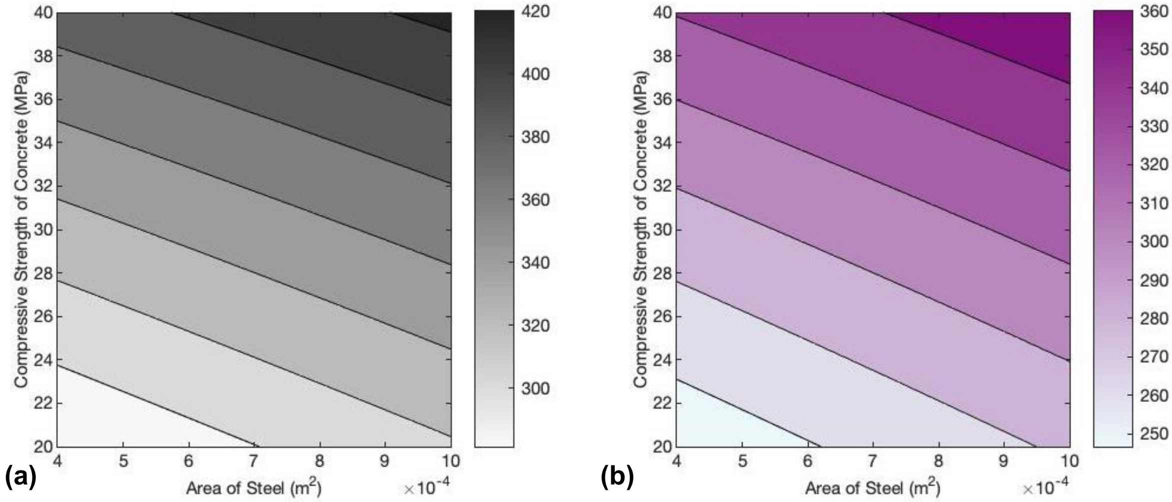


Figure B-4. Contour plots of beam members in bending at the cracking stage for mixtures containing (a) no SCMs, (b) fly ash at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

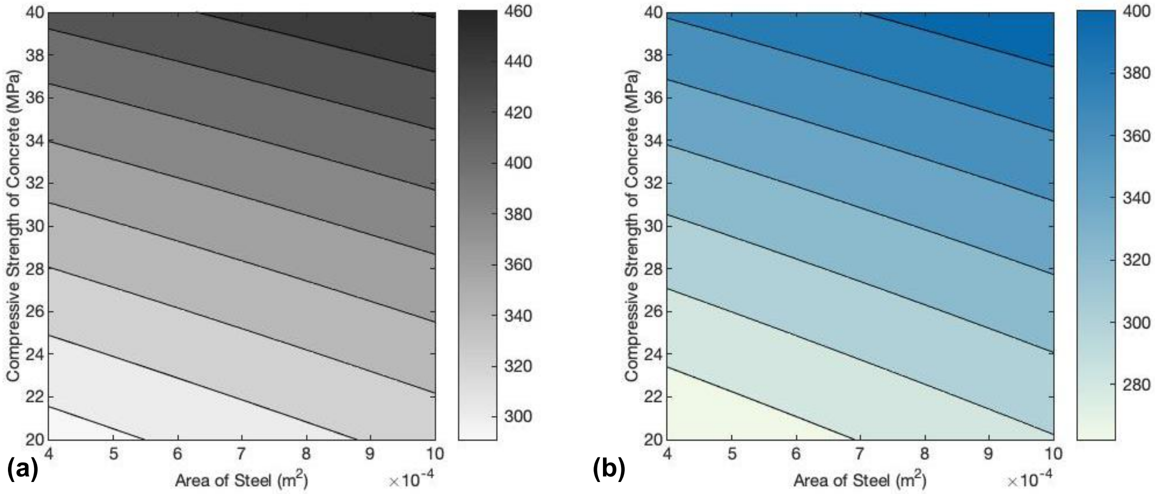


Figure B-5. Contour plots of beam members in bending at the cracking stage for mixtures containing (a) no SCMs, (b) ground granulated blast furnace slag at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

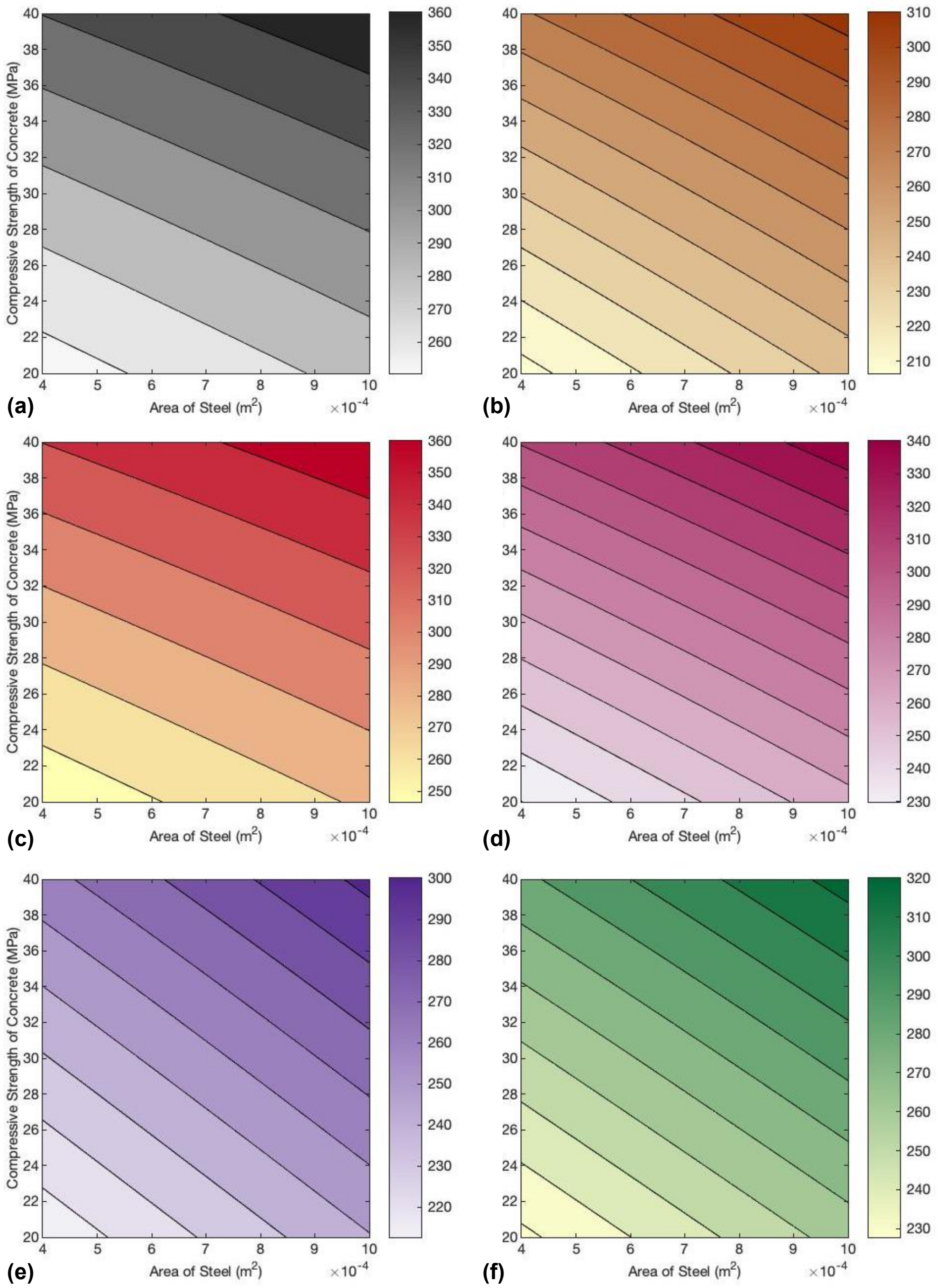


Figure B-6. Contour plots of beam members in bending at the cracking stage for mixtures containing (a) no SCMs, (b) limestone filler at 15% replacement of cement, (c) natural pozzolans at 15% replacement of cement, (d) shale ash at 15% replacement of cement, (e) silica fume at 15% replacement of cement, and (f) calcined clay at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain different water content than those with fly ash and blast furnace slag; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not shown.

Appendix B.3. Supplementary Contour Plots: Beam Designed at the Yield Stage

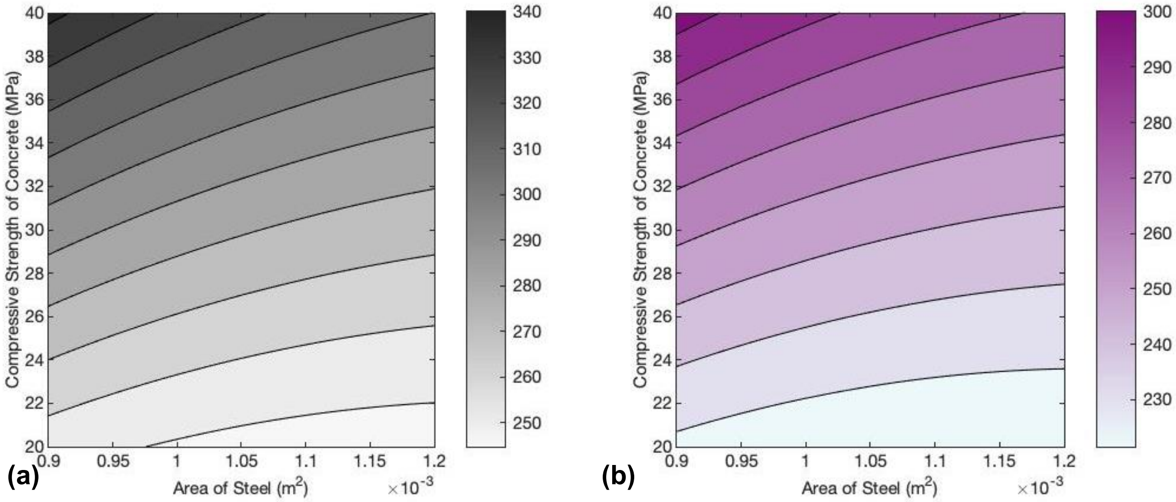


Figure B-7. Contour plots of beam members in bending at the yield stage for mixtures containing (a) no SCMs, (b) fly ash at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

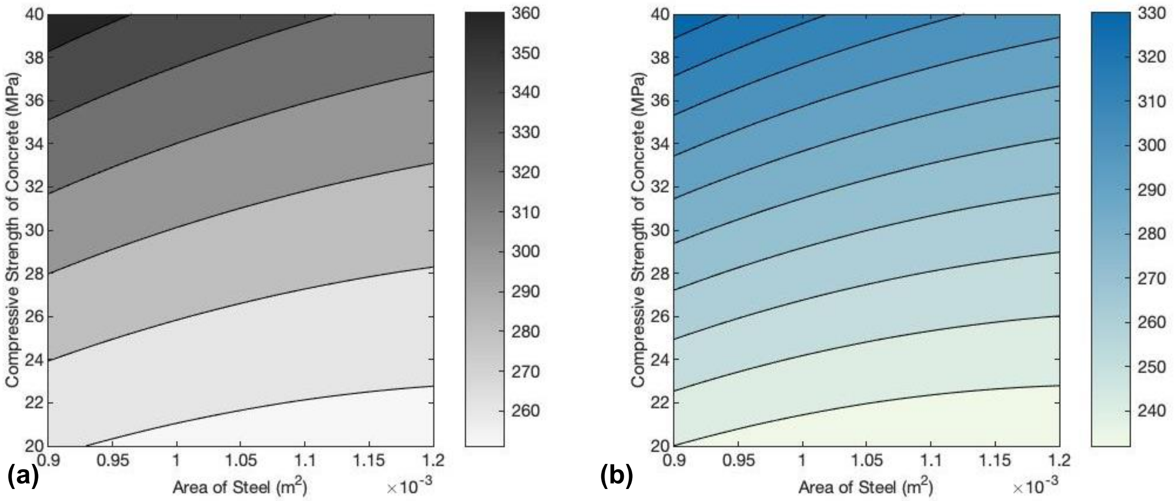


Figure B-8. Contour plots of beam members in bending at the yield stage for mixtures containing (a) no SCMs, (b) ground granulated blast furnace slag at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

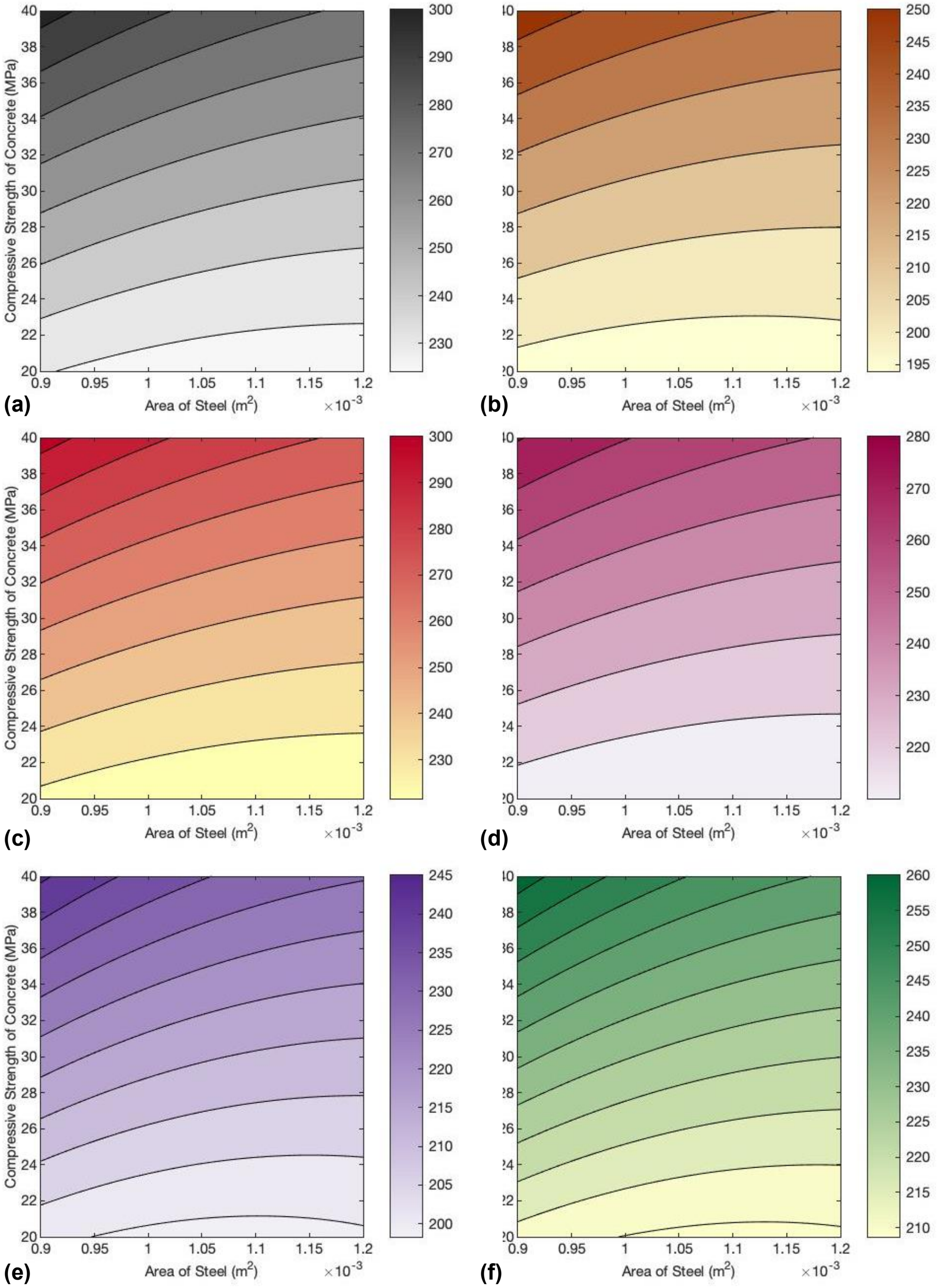


Figure B-9. Contour plots of beam members in bending at the yield stage for mixtures containing (a) no SCMs, (b) limestone filler at 15% replacement of cement, (c) natural pozzolans at 15% replacement of cement, (d) shale ash at 15% replacement of cement, (e) silica fume at 15% replacement of cement, and (f) calcined clay at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain different water content than those with fly ash and blast furnace slag; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not shown.

Appendix B.4. Supplementary Contour Plots: Beam Designed at the Nominal Stage

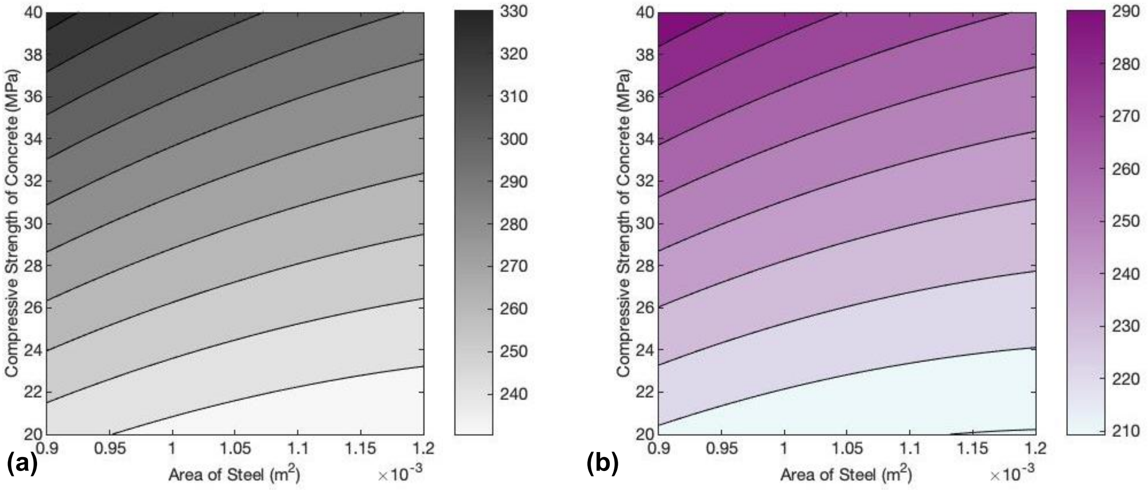


Figure B-10. Contour plots of beam members in bending at the nominal stage for mixtures containing (a) no SCMs, (b) fly ash at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

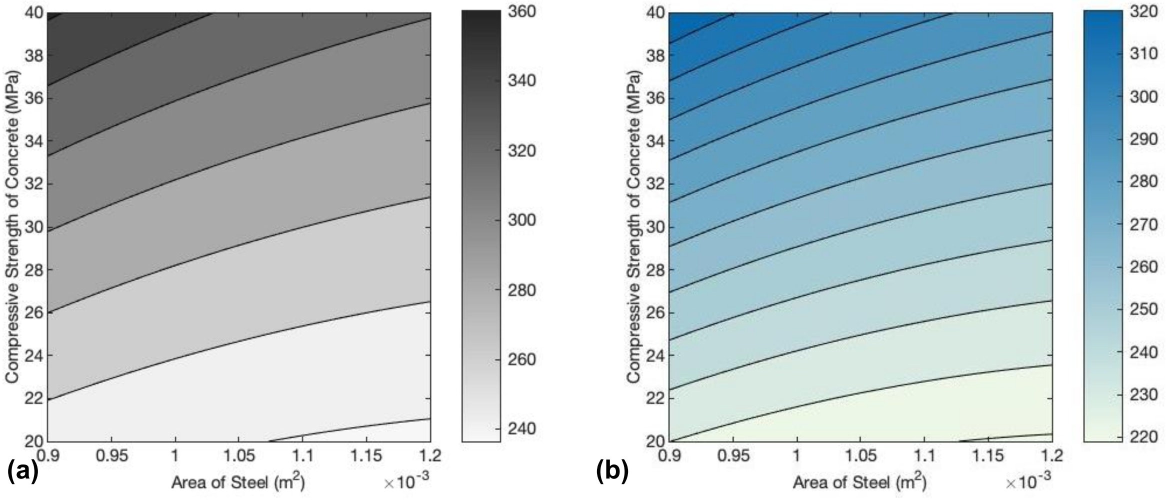


Figure B-11. Contour plots of beam members in bending at the nominal stage for mixtures containing (a) no SCMs, (b) ground granulated blast furnace slag at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain a different water content than those with the other SCMs considered in this work; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not plotted on this diagram.

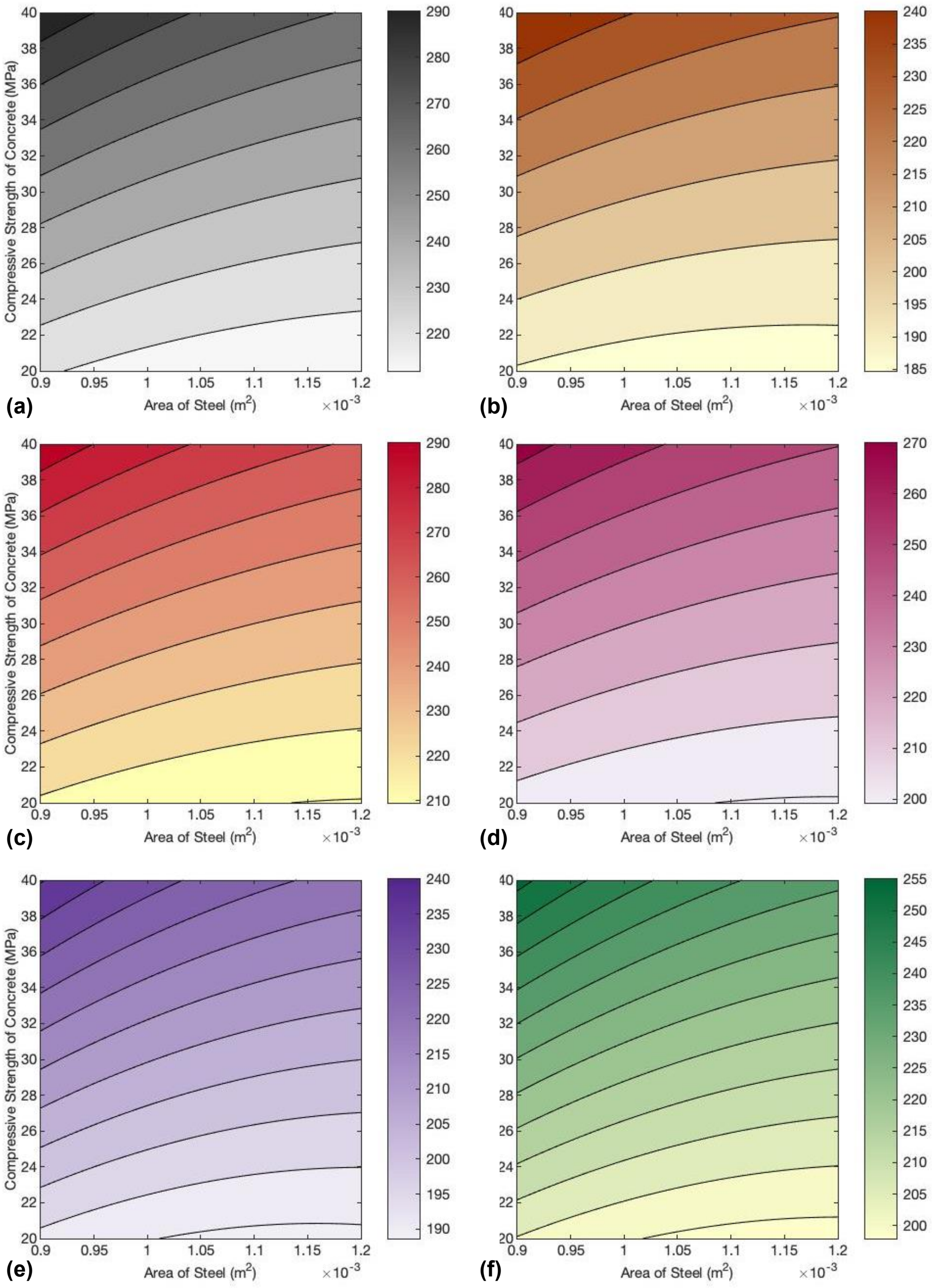


Figure B-12. Contour plots of beam members in bending at the nominal stage for mixtures containing (a) no SCMs, (b) limestone filler at 15% replacement of cement, (c) natural pozzolans at 15% replacement of cement, (d) shale ash at 15% replacement of cement, (e) silica fume at 15% replacement of cement, and (f) calcined clay at 15% replacement of cement. Color scale reflects total GHG emissions in kg CO_2-eq for the designed member. Note: these mixtures contain different water content than those with fly ash and blast furnace slag; due to varying data sources, mixtures that contain a different water content and different associated trends in binder content are not shown

Appendix C

Table C-1. Volume and production costs of concrete and steel of RC column or beam members used in the analysis to estimate the GHG emissions and production costs

		Volume (m^3)		Costs ($)			
		Concrete	Steel	Batching	Concrete*	Steel	Total
Column	PC30	0.1027	0.0034	11.71	17.32	14.89	32.21
	PC40-L	0.0889	0.0023	10.13	15.33	10.07	25.40
	PC40-H	0.0653	0.0045	7.44	11.26	19.71	30.97
	PC20-L	0.1778	0.0023	20.27	28.53	10.07	38.61
	PC20-H	0.1305	0.0045	14.88	20.94	19.71	40.65
	PC/FA40-L	0.0889	0.0023	10.13	15.01	10.07	25.09
	PC/FA40-H	0.0653	0.0045	7.44	11.03	19.71	30.74
	PC/FA20-L	0.1778	0.0023	20.27	28.20	10.07	38.27
	PC/FA20-H	0.1305	0.0045	14.88	20.70	19.71	40.41
Beam-cracking	PC30	1.1091	0.0049	126.44	187.06	21.46	208.52
	PC40-L	1.0719	0.0028	122.20	184.84	12.26	197.11
	PC40-H	1.0677	0.0070	121.72	184.12	30.66	214.78
	PC20-L	1.1691	0.0028	133.28	187.63	12.26	199.89
	PC20-H	1.1649	0.0070	132.80	186.95	30.66	217.61
	PC/FA40-L	1.0719	0.0028	122.20	181.02	12.26	193.29
	PC/FA40-H	1.0677	0.0070	121.72	180.31	30.66	210.98
	PC/FA20-L	1.1691	0.0028	133.28	185.41	12.26	197.68
	PC/FA20-H	1.1649	0.0070	132.80	184.75	30.66	215.41
Beam-yield	PC30	0.7795	0.0073	88.86	131.47	31.98	163.44
	PC40-L	0.8426	0.0063	96.06	145.30	27.60	172.90
	PC40-H	0.6914	0.0084	78.82	119.23	36.79	156.02
	PC20-L	0.9059	0.0063	103.27	145.39	27.60	172.98
	PC20-H	0.7759	0.0084	88.45	124.52	36.79	161.32
	PC/FA40-L	0.8426	0.0063	96.06	142.30	27.60	169.90
	PC/FA40-H	0.6914	0.0084	78.82	116.76	36.79	153.56
	PC/FA20-L	0.9059	0.0063	103.27	143.67	27.60	171.27
	PC/FA20-H	0.7759	0.0084	88.45	123.05	36.79	159.85
Beam-nominal	PC30	0.742	0.0073	84.55	125.09	31.98	157.07
	PC40-L	0.818	0.0063	93.29	141.11	27.60	168.71
	PC40-H	0.659	0.0084	75.14	113.66	36.79	150.45
	PC20-L	0.857	0.0063	97.73	137.59	27.60	165.18
	PC20-H	0.711	0.0084	81.07	114.12	36.79	150.92
	PC/FA40-L	0.818	0.0063	93.29	138.20	27.60	165.79
	PC/FA40-H	0.659	0.0084	75.14	111.31	36.79	148.10
	PC/FA20-L	0.857	0.0063	97.73	135.96	27.60	163.56
	PC/FA20-H	0.711	0.0084	81.07	112.78	36.79	149.57

* includes the batching cost