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LETTER

# The role of cement service-life on the efficient use of resources

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## Abstract

The high demand for cement-based materials to support building and infrastructure systems is of growing concern as the production of cement leads to significant greenhouse gas (GHG) emissions and notable resource demand. While improved efficiency of cement use has been proposed as a means to mitigate these burdens, the effects of increasing longevity of cement in-use remains a poorly studied area. This work quantitatively explores the implications of using cement for a longer in-use residence times. Specifically, this work uses dynamic material flow analysis models to quantify the in-use stock of cement in the United States from 1900 to 2015. With these models, the implications of increasing or decreasing mean longevity of in-use cement on required cement production, demand for batching water, aggregates, and energy for cement-based materials, and GHG emissions are quantified. This work shows that a 50% increase in cement longevity could have led to a 14% reduction in material resource demand and GHG emissions from concrete production in the United States, equivalent to 0.28 to 0.83 Gt of batching water, 2.9 to 7.6 Gt of aggregates, 1E + 06 to 2.3E + 06 TJ of energy, and 0.4 to 0.7 Gt of $CO_2$-eq emissions. This percent reduction exceeds goals for reducing GHG emissions through alternative energy resources, suggesting improving durability and longevity of in-use cement stock could be a critical means to mitigating environmental impacts.

## 1. Introduction

Construction materials typically have low environmental impact per cubic meter, but there is vast global consumption of these materials and demand has been rapidly increasing over the past three decades [1]. The production of cement and concrete is among the most substantial and difficult to decarbonize processes [2]. Annually, concrete production is responsible for over 8% of anthropogenic greenhouse gas (GHG) emissions [3], ~9% of industrial water withdrawals [4], and 2%–3% of anthropogenic energy demand [3]. Further, many construction materials, like concrete, are used once and then disposed of, leading to significant accumulation of construction and demolition wastes in landfills: in the United States alone, this waste is an estimated 325 million tons annually [5].

Concrete is composed of hydraulic cement (primarily made of clinker, a kilned and quenched material, and mineral admixtures), water, aggregates, and additional admixtures, which vary depending on application. While by volume, aggregates constitute the majority of concrete, the cement binder leads to approximately 90% of GHG emission associated with concrete production [6]. The efficient use of cement in concrete and the efficient use of concrete in applications have been highlighted as necessary means to mitigate GHG emissions [7]. It is critical that such goals for material efficiency, which capture factors that would influence resource scarcity, be considered concurrently with environmental impact assessment [8–10]. This concept is particularly relevant for cement-based materials for which upfront environmental impacts from cement production are often addressed separately from performance (e.g. [7]).

In the life cycle of cement-based materials, such as concrete, there are several critical levers that influence environmental burdens including: resources utilized for production, energy- and process-derived emissions during manufacturing, effects of design and construction decisions, the role of use-phase sinks or burdens, and end-of-life impacts. Due to the high impacts of the energy- and process-derived emissions from cement production, the partial replacement of cement has been a heavily examined area of study for mitigating environmental impacts. Work in this area has included assessment of using new and conventional mineral admixtures to mitigate environmental burdens of concrete production (e.g. [11–14]). Assessments are so robust in this domain that use of mineral admixtures to reduce GHG emissions has been incorporated into roadmaps for the cement and concrete industries [7, 15]. Slightly less well examined is the potential mitigation of environmental impacts from the use of alternative cements, such as alkali-activated materials (e.g. [16]) or cement systems with different mineral composition to conventional cements [17]. Yet, the use of these materials has not been consistently codified, and for some, further material characterization is still needed [18, 19].

Not well quantified are the effects of elongating functional life to offset the necessity to produce more cement-based materials. Material longevity (i.e. how long it remains in service) is often a function of multiple components or interaction effects. Focusing on a particular application or point in time can lead to inefficient use of concrete (e.g. [20]) when viewed over the life cycle of an application or when considered from a systems dynamics perspective. Further, removing infrastructure from service and replacing it with new infrastructure systems can have a notable effect on the environment.

For concrete, typical environmental impact assessments have the goal of assessing burdens or valuing improvements to the impacts associated with production of a constant volume or constant mass of concrete (e.g. [21–23]). However, the role of different phases of a structural material's life cycle can outweigh upfront environmental impacts from production. For example, material losses during construction due to waste [24], the role of loads and boundary conditions on the volume of material needed considering material properties [25], and the durability of a material, which would influence both maintenance and replacement [27], have the potential to overshadow benefits gained through manufacturing conditions. Some recent work to bridge these concepts focuses on assessment of mechanical properties concurrently with environmental impacts (e.g. [25, 26–31]). Case studies suggest that materials and designs selected can lead to a reduction in environmental impacts during a material's use phase, but such designs could lead to increased impacts during the material sourcing and production phases [32]. For example, high performance concrete mixtures, such as those engineered with fiber reinforcement, can reduce the quantity of steel rebar necessary in structures and have been shown to possess improved durability properties [33], but their production can have higher environmental impacts than production of conventional concrete [34]. However, it is also possible to improve certain durability traits by utilizing certain mineral admixtures [35], which could reduce environmental impacts from cement-based material production. Factors such as these make it critical to understand how material in-use longevity can play a role in resource demand and environmental impacts.

The uptake of $CO_2$ during cement utilization as well as the potential to mitigate resource demand and uptake $CO_2$ from crushed concrete at its end-of-life should be taken into consideration when analyzing cement-based materials. Concrete can be crushed and used as aggregate, noting such use of recycled aggregate can affect material properties [36]. This practice can act as form of resource recovery and, due to the ability for conventional hydrated cement to absorb $CO_2$ through carbonation, both increased in-use service and exposure of crushed concrete at end-of-life can contribute to $CO_2$ uptake [37].

This work offers a systematic quantification of the influence of cement-based material longevity on GHG emissions and resource demand. The effects of longevity are considered in the context of environmental impacts from production, use, and end-of-life. In doing so, this work offers a foundational understanding of a heretofore poorly examined environmental burden mitigation strategy for the cement and concrete industries.

## 2. Methods

### 2.1. Modeling in-use cement stock and increased longevity of in-use cement

This work focuses on the cement production and use in the United States to exemplify the effects of increasing in-service longevity of cement. Data for annual cement production were based on historic data from the United States Geological Survey (USGS) from 1900 to 2015 [38]. To capture the amount of cement in use each year, the dynamic in-use stock model by Kapur *et al* [39] was utilized considering the fractions of cement to each of 8 application categories presented by the authors: (i) residential buildings; (ii) public buildings; (iii) commercial buildings; (iv) streets and highways; (v) water and waste management; (vi) farms; (vii) utilities; and (viii) other. The percent use increase in stock from cement production by category was assumed to be consistent from year to year, and the lognormal distributions for in-use periods were implemented. For simplicity, in the presentation of results for this work, public and commercial buildings are discussed together as 'non-residential buildings' and cement use in farms, utilities, and other applications are discussed together as 'other' uses. The distributions for in-residence times were applied both as an indicator of the amount of in-use cement stock in building and infrastructure applications for the United States annually and to assess the amount of cement removed from use each year. Removal of cement-based materials was considered as a removal from primary-life, including factors such as dismantling and crushing.

To determine the effects of increased longevity of cement in-use periods on reducing potential demand for new cement production, an increase in the mean service life of each of the eight categories for cement use was modeled separately; the standard deviations were maintained. Five percent increases in mean in-service life were considered: 10%, 20%, 30%, 40%, and 50%. As a point of comparison, the effects of truncating the in-use service life by reducing the mean by 10%, 20%, 30%, 40%, and 50% were also modeled. The study period of 1900–2015 was selected as opposed to projecting cement demand to minimize uncertainty in assumptions necessary to project future cement requirements. This work assumes that increased (or reduced) service life of cement would directly influence the demand for new cement production; that is, an elongation of in-use cement was modeled as directly offsetting cement produced. In reality, several factors could influence the applicability of this assumption; however, this work aims to capture the effects of increasing time to material obsolescence.

### 2.2. Use of other resources to produce concrete

It is often assumed that locally sourced materials have inherently lower environmental impact due to reduced transportation [40]. While cement is monitored because it is a traded commodity [41, 42], water and aggregate resources are often locally sourced, which results in less robust records of consumption. The typically local nature of resource acquisition for these constituents has raised concern of resource scarcity in regions with high levels of infrastructure development and limited local materials [3, 43].

To determine the effects of increased longevity of cement in-use periods on other resources, demands for batching water and aggregates were approximated. In the United States, approximately 92.3% of cement produced is used in concrete [44]. To facilitate calculations, this work assumes the remaining 7.7% of cement is used in mortar, a common assumption (e.g. [45]). The production of concrete and mortar was used to estimate required batching water and aggregates. To perform this assessment, the relative demand for water and aggregates for a given volume of cement in a cubic meter of concrete were based on data from the Portland Cement Association (PCA) [46] and in a cubic meter of mortar demand was based on data from the PCA as well as United States materials standards [47, 48]. For the models developed, mineral admixture content in the cementitious materials were based on the national consumption reported by the World Business Council for Sustainable Development's Cement Sustainability Initiative [49]. A synopsis of the ranges for mixture proportions to perform this analysis is presented in the supplementary material (available online at stacks.iop.org/ERL/15/024004/mmedia).

### 2.3. Quantification of greenhouse gas emissions and energy demand

Beyond reducing material demand, the extension of service-life of cement-based materials has the potential to contribute to reductions in GHG emissions and energy demand by lowering the need to produce new materials. To quantify GHG emissions and embodied energy from the production of concrete and mortar in the United States since 1900, a representative model capturing impacts from cradle-to-gate production of cement-based materials with region-specific inputs was used (from [6]). This model quantifies the effects on GHG emissions, including $CO_2$, $CH_4$, and $N_2O$ emissions (using 100 year global warming potentials), and energy from the production and acquisition of each of the main constituents in cement-based materials including factors from associated energy, transportation, and processing. For the production of cement, this includes electricity and thermal energy required in raw material acquisition, pre-grinding and homogenization, kilning, cooling, and blending of cement, as appropriate, as well as emissions from calcination (the conversion of $CaCO_3 \rightarrow CaO + CO_2$ in the kiln) and transportation. For the mineral admixtures, this assessment method includes collection and transportation. For aggregates, this assessment method includes emissions from energy for acquisition and sieving of aggregates as well as transportation. National average data were used for kiln efficiency and energy mixes (based on [6]). Aggregates were assumed to be transported 75 km by diesel truck; mineral admixtures and cement were assumed to be transported 150 km by diesel truck. Variation in production methods annually was not incorporated into this analysis. Time-dependent effects of global warming potentials are not taken into account, but the majority of emissions from cement and concrete emissions are $CO_2$ emissions, so effects of this exclusion are considered minimal. Emissions and embodied energy inputs used are stipulated in the supplementary material.

In addition to GHG emissions from material production, the influence of emissions during use and demolition were considered. While the effects of maintenance were excluded from this assessment, the $CO_2$ uptake from carbonation was incorporated. Carbonation of concrete is a function of several parameters, including available CaO content, exposure of concrete to $CO_2$, and duration of exposure [37, 45, 50]. For this work, a range of $CO_2$ uptake from carbonation was considered to be 30%–80% of the original $CO_2$ emissions from the calcination process (approximated to encapsulate potential uptake during use and end-of-life). Additionally, emissions and energy associated with demolition equipment were modeled to capture these

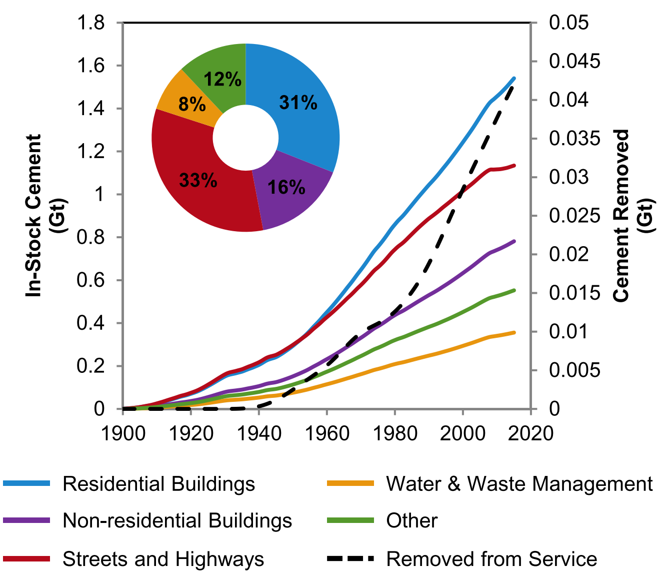


**Figure 1.** Estimated in-stock use of cement by sector. The pie chart indicates the cement consumption by sector over 1900–2015, the line diagram indicates the cement currently being used by sector and the cement removed from service.

end-of-life impacts from concrete structures (modeled upon removal from primary use). Values for these emissions and energy requirements were based on [51].

While not part of this study, improved longevity of cement-based materials in-use would also be anticipated to reduce demand for the production of reinforcing steel. Depending on the recycled content of steel and production methods, it could have substantial GHG emissions associated with its production [2, 52]. With reinforcing steel being over 6% of the steel market [53], the reduction in demand for this material could further contribute to mitigation of GHG emissions.

## 3. Results

### 3.1. In-stock cement and cement removed from service

The quantity of in-service cement annually from 1900 to 2015 steadily increased for the United States despite the relatively mature economy (see figure 1). Approximately 5.5 Gt of cement was produced in the 115-year study period. Of that 5.5 Gt, a bit under 4.4 Gt of cement was in-use as of 2015. The long service period of buildings over the past 115 years has resulted in a 6% increase in fraction of in-use cement stock relative to the percent cement added to this use category. In juxtaposition, the relatively short service period of streets and highways has resulted in a 7% decrease in relative fraction of cement in-use stock. Approximately 1.2 Gt of cement has been removed from service across applications. This equates to 21% of the cement produced and has contributed to 3–7 million $m^3$ of concrete removed. The annual rate of cement removal is growing as concrete infrastructure and buildings age in the United States, a phenomenon that would be anticipated in the coming decades for the nations that have had significant infrastructure expansion more recently.

### 3.2. Effects of concrete longevity on cement demand

The potential effects of increasing or decreasing longevity of cement in-use periods on offseting cement production are substantial (see figure 2). If mean longevity of cement use was 50% greater, a 14% reduction in cement production could have been possible. The majority of this potential reduction would have been achieved through the elongation of the service period for streets and highways, which contributed to approximately half of the potential cement production reduction. This high relative contribution is a function of the shorter mean service period for cement in streets and highways than the other sectors, approximately 45 years relative to buildings at 70–90 years. Similarly, the benefits of increased in-residence times are non-linear and decrease as longevity is increased: 28% of the potential reduction of cement production occurs at a 10% increase in longevity, with lower relative change with further increases in longevity.

Decreased in-use service periods had a greater potential effect on cement production. A 50% decrease in mean service life would have resulted in a 19% increase in cement demand. While there was a stark contribution of the effects of increased longevity on streets and highways, decreased longevity of cement in-use period led to similar growth in demand for cement in residential buildings as in streets and highways, approximately 6% from each sector. This potential shift in cement demand is of critical importance in countries that are seeing removal of

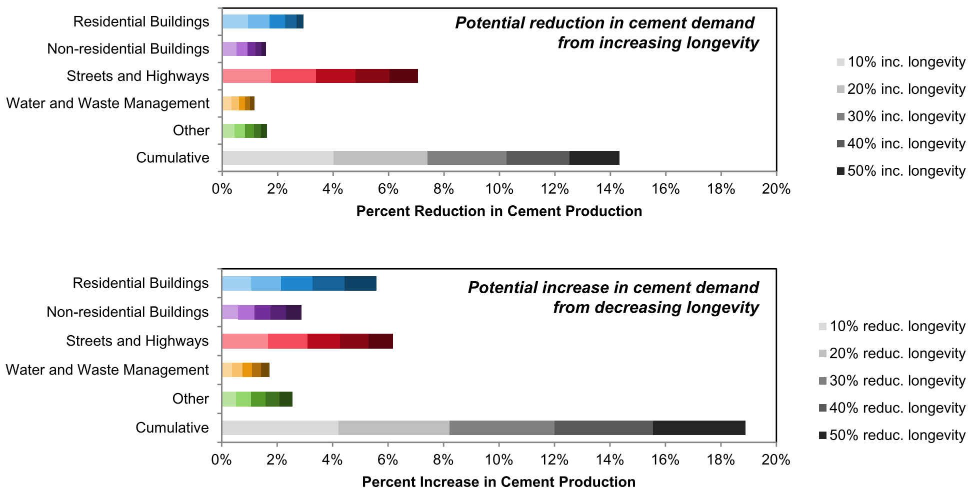


**Figure 2.** Potential quantity of cement demand reduction from extension of service-life. Charts indicate the quantity of cement reduction for each of 5 potential increases in longevity and the effects on cement demand were service-life to have been shorter than it was during 1900–2015.

cement-based material systems before their original intended end-of-service. This type of early removal of concrete structures would also be pertinent to situations in which less durable materials were utilized. Notably, for nations that have significantly lower in-use periods for cement than the United States, such as China [54, 55], the benefits of elongating in-use stock of cement would be expected to be much greater, as indicated by the notable benefits of increasing longevity in the shorter lived streets and highways in the United States.

### 3.3. Effects of concrete longevity on batching water and aggregate resources

An increase in cement longevity in service could also offset the direct and ancillary material flows to produce the cement-based materials. To exemplify the potential implications of increased longevity on other material resources, relative changes to energy, batching water, and aggregate demand were considered. A 10% increase in cement longevity could have potentially offset 0.08 to 0.23 Gt of batching water and 0.81 to 2.1 Gt of aggregates (see figure 3). A 50% increase in cement longevity in-stock could have contributed to a reduction of 0.28 to 0.83 Gt of batching water and 2.9 to 7.6 Gt of aggregate demand between 1900 and 2015. In regions experiencing or prone to experience resource scarcity associated with these material flows, increasing longevity of in-use periods could be a critical measure to alleviating material demand burdens. While different regions have access to a varying array of energy resources, this work also shows a 10% increase in cement longevity would have reduced energy demand for cement-based material production and removal by 2.8E + 05 to 6.4E + 05 TJ; a 50% increase in longevity would have saved 1E + 06 to 2.3E + 06 TJ.

### 3.4. Effects of concrete longevity on greenhouse gas emissions

Just as with potential reductions in resource demand through increased longevity of cement in-use periods, there is the potential to mitigate environmental burdens from producing cement and cement-based materials. While there are a myriad of environmental impact categories that could be examined, here GHG emissions were assessed. Depending on mixture proportions, GHG emissions from the production of concrete in the United States from 1900 to 2015 were responsible for approximately 2.8 to 4.7 Gt of $CO_2$-eq emissions. A 50% increase in mean in-use stock of cement could have provided a 0.4 to 0.7 Gt reduction in $CO_2$-eq emissions (see figure 4). However, the inverse of this scenario becomes important to consider as well: a 50% reduction in mean in-use stock of cement could have led to a 0.5 to 0.9 Gt increase in $CO_2$-eq emissions. This is equivalent a 14% potential reduction and a 19% potential increase in emissions, respectively. This reduction in GHG emissions is greater than reductions from proposed mitigation strategies of increased energy efficiency, changes in electricity sources, or changes in kiln fuel [7].

### 3.5. Modeling uncertainty

In this work, several modeling assumptions were made to facilitate analysis, which could lead to potential uncertainties. To reduce such uncertainties, variability, such as a range in uptake of $CO_2$ during carbonation as well as the variability in concrete and mortar mixture proportions, were incorporated into the analysis presented. These results do not, however, capture different modeling assumptions pertaining to the relative fraction of use of cement by sector over time, the change in cement-based materials production methods over time, and the use of different distribution types to model in-use periods for cement.

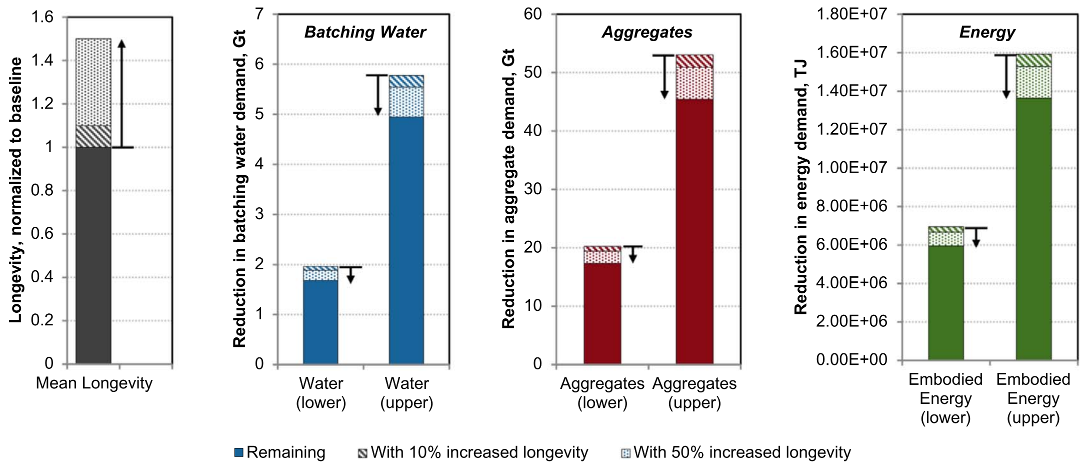


**Figure 3.** Effects of elongation of concrete service life on reductions of other resource demand. The quantity of batching water, aggregate, and energy demand that could have been offset through elongation of concrete service-life are shown with upper and lower ranges reflecting variability in data.

It has been suggested that within the past few years, there has been an increase in civil engineering use of cement in the United States [54]; however, there have been limited data capturing the changes in the relative fractions of cement use to each of the individual use categories studied in this work. Slightly lower efficiencies in kilns used and higher use of high emitting fuels in the past could have contributed to a higher GHG emissions profile than that modeled in this work, with greater emissions occurring in earlier years when cement production was lower. Finally, as was shown by Kapur *et al* [39], the use of different distributions could affect values of in-use cement stock. The use of gamma distributions or Weibull distributions would have slightly lowered the reduction in material demand from elongating in-use longevity and would have increased the effects of truncating in-use longevity of cement (see the supplementary material).

## 4. Discussion

Noting that advanced cement-based materials with high durability typically have higher environmental impacts to produce [56], the desired service-period and longevity in-use could be a driving factor in understanding if these improved durability properties outweigh benefits from using low environmental impact strategies to produce mixtures. Figure 5 shows a schematic representing this concept with GHG emissions of one cubic meter of concrete analyzed as a function of time, where the materials were assumed to have no impacts from maintenance and are replaced when they have reached a service-limit state. If only GHG emissions from material production are considered, as is common practice in the development of mitigation strategies, a material that has poor longevity could be selected and a more durable material that could facilitate improved longevity of cement in-use may appear undesirable. However, depending on the desired service-life, these materials may switch in terms of their ability to mitigate emissions relative to a baseline scenario. Designers must be mindful that longevity be designed according to desired obsolescence; overdesigned materials and systems that have high production impacts and last longer than the desired service-period would lead to waste of viable products.

Obsolescence of infrastructure systems is typically brought about by changes in demand or functionality [57]. This work is based on the premise that increasing the service-life of cement-based materials could lead to reductions in demand. However, if system obsolescence is deemed early in the use of the materials, benefits might not be accrued and design for improved physical life (i.e. improved durability of materials and systems) would not contribute to reductions in environmental burdens. In long-lived infrastructure, such as that present in developed nations, the physical life of materials is often used as an indicator of service-life [57]. However, in rapidly industrializing nations, such as several in the Global South, obsolescence for structures may be present prior to the physical deterioration of the materials. Further, obsolescence has varying effects on different systems. For housing, there is a decline in expectations of performance with time, unlike other aspects of the built environment [57] and, especially in less densely urbanized areas, there may be less demand for removing structures prior to physical obsolescence to make space for new built systems. However, a loss of performance due to deterioration could lead to changes such as increased heating or cooling loads [58]. For road infrastructure, changes in cement-based material properties, such as surface roughness, can lead to changes in fuel consumption and emissions from vehicle use [59], so while the

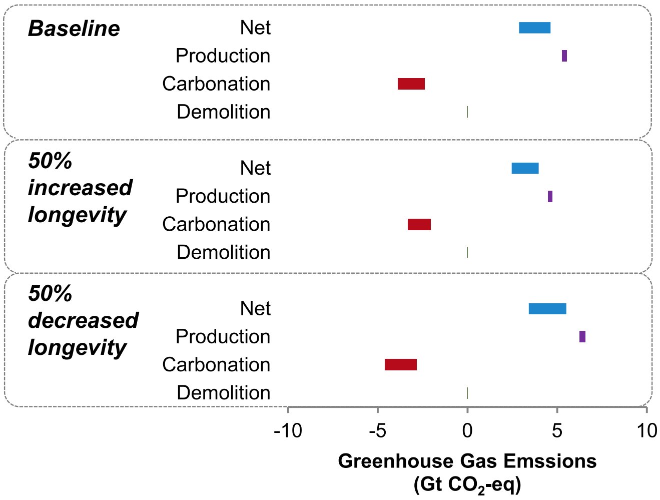


**Figure 4.** Greenhouse gas (GHG) emissions (ranges represent anticipated low and high emissions based on typical United States concrete mixtures) for concrete production from 1900 to 2015 and potential change in GHG emissions with 50% increased and reduced service-life respectively.

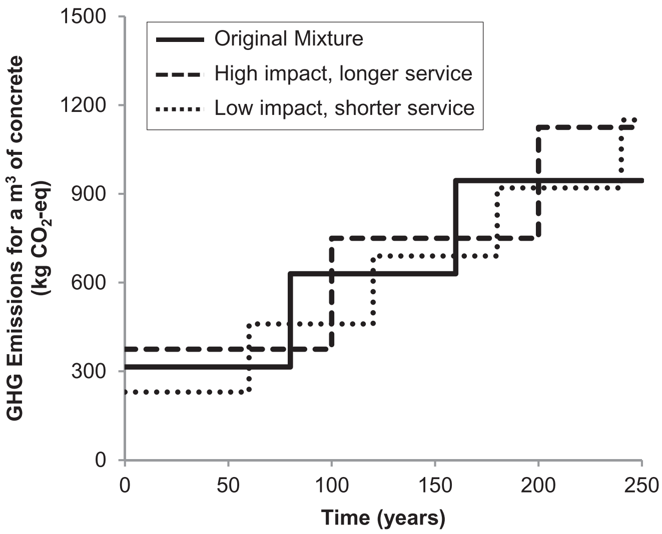


**Figure 5.** Schematic of tradeoffs in upfront environmental impacts from production and longevity in mitigating greenhouse gas (GHG) emissions from concrete. (Note: these diagrams are not representative of actual mixtures or applications).

concrete may still be viable as a bulk material, additional environmental impacts could be incurred.

From an economic perspective, this work focused on cement-based materials use in the United States, where non-metallic mineral manufacturing is responsible for less than 0.5% of the nation's economic gross output (based on 2016 data from [60]). As such, the reduction of cement-based materials production by up to 20% over 100 years, as studied here, would not have a significant effect on the economy. However, in other regions around the world, it is possible that decisions made regarding material production and use could affect economic development. Similarly, GHG emissions are impacting sea level, extreme weather events, and agriculture [61], which have severe economic impacts that far exceed short- or mid-term economic gains of environmentally inferior practices. Factors such as these should be considered in future studies.

While not discussed in this work, there are several additional potential means to benefit concrete infrastructure through material efficiency principals. Improving yield loss during manufacture, where possible (e.g. [62]), and reducing over-ordering of material for construction projects also fall under the category of improving material efficiency measures that could aid in environmental impact mitigation. Further, engineering concrete to provide necessary properties with less material or with less weight can reduce material flows associated with the concrete as well as potentially with structural systems needed to support the concrete. Additionally, frequent replacements or maintenance of material would result in an increased cost, as would many of these other decisions;

however, in infrastructure applications, often the same party is not making decisions at each of these stages.

## 5. Conclusions

The potential implications of extending the longevity of cement in-use periods before removal on offsetting cement and cement-based materials demand was explored in this work. Several key findings from this work included:

- A 50% elongation of in-use periods for cement could have reduced demand by up to 14%, but the same degree of truncation of in-use period would have led to a 19% increase in new cement demand.
- Increasing longevity of cement-based materials in the United States by 50% would have reduced the demand for 0.28 to 0.83 Gt of batching water, 2.9 to 7.6 Gt of aggregates, and 1E + 06 to 2.3E + 06 TJ of energy demand.
- Increasing in-use longevity of cement by 50% could have led to a 0.4 to 0.7 Gt reduction in $CO_2$-eq emissions, which could rival some more commonly considered GHG emissions mitigations strategies.

This work acts as a foundation for additional exploration and investigation in future studies. Future assessments might include the effects of decision-making on when functional obsolescence occurs. However, because this study provides initial insight into using cement for increased service-periods, it acts as foundation for assessment of critical interrelationships between environmental impacts from material production and time-dependent properties. Such interrelationships are essential to understand new cementitious alternatives as they are engineered. Future work could also extend to cement use in other regions. Analyses such as the work presented herein must be explored to instigate effective mitigations for environmental burden and resource scarcity issues surrounding our long-term infrastructure materials.

## Acknowledgments

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## Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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