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Reducing greenhouse gas emissions for prescribed concrete compressive strength

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HIGHLIGHTS

- Equations are developed for green engineering of concrete with specified strength.
- Higher compressive strength typically results in higher GHG emissions in concrete.
- Optimal use of SCMs to reduce GHG emissions varies depending on their properties.

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ABSTRACT

Often, when proportioning "green" concrete mixtures, the use of Supplementary Cementitious Materials (SCMs) is deemed to be favorable. While appearing more in the literature, it is still not commonplace that design strength is considered in assessments of environmental impacts. When mechanical or material properties are incorporated into environmental impact assessments, comparisons are drawn based on the property attainable for any given mixture, most commonly, compressive strength. However, in structural applications, compressive strength is typically specified in the design and there are currently no means for specifying the best concrete constituents for a set compressive strength to reduce greenhouse gas emissions from production. In this research, concrete mixture proportioning based on water-to-binder content and supplementary material-to-Ordinary Portland Cement ratios are examined. For these parameters, mathematical models are developed to perform optimization of GHG emissions for four groups of concrete (those containing varying levels of fly ash, ground granulated blast furnace slag, natural pozzolans, and limestone filler as a means to reduce Ordinary Portland Cement content). For the particular binary blended binders examined in this work, optimal ratios of supplementary material use were highly dependent on the type of alternative material and were consistently below the highest replacement level considered. The equations developed will facilitate the green engineering of concrete when a specified strength is required.

1. Introduction

Growing urban populations and the demand for infrastructure are resulting in a growth of cement consumption globally [1,2]. The production of hydraulic cement has seen a steep incline within the past two decades with global production from 1950 to 2000 growing by 1.5 gigatonnes (Gt) and production in the subsequent 15 years, 2001–2015, growing by over 5 times the rate seen in the previous 5 decades with an increase in production of 2.4 Gt [3,4]. This high cement production produces notable greenhouse gas (GHG) emissions, estimated at 8.6% of total anthropogenic GHG emissions in 2012 [5]. This growing demand for a material that is resulting in substantial GHG emissions highlights the need to develop means to produce a structural material that can meet the needs of society while limiting its burden on the environment.

While there are many ways to reduce the emissions associated with the production of concrete, including use of more efficient equipment, alternative fuels, and carbon capture and storage (e.g., [6,7]), one of the most prevalent means to reduce emissions is to reduce the demand for Ordinary Portland Cement (OPC). OPC is one the most prevalent binders in concrete and current production methods involve using high levels of clinker, a kilned and quenched material, that requires high energy input during production, resulting in GHG emissions, as well as produces material-derived CO_2 emissions through processes such as the chemical

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Nomenclature

b	binder content by weight (kg/m^3)
c	ordinary Portland Cement content by weight (kg/m^3)
f_c	compressive strength of concrete (MPa)
FA	fly ash
i	volumetric environmental impact (environmental impact/m^3)
$GGBS$	ground granulated blast furnace slag
$k_{1,2}$	constants which depend on the concrete materials used
$k_{3,A}$	constants which depend on cement manufacturing
$k_{4,B,D}$	constants which depend on materials and processing used
k_C	constants which depend on the manufacturing of supplementary cementitious materials
L	limestone
NP	natural pozzolans
OPC	ordinary Portland Cement
s	supplementary cementitious material or filler content by weight (kg/m^3)
w	water content by weight (kg/m^3)
α, $\beta_{1,2}$, $\gamma_{1,2}$, $\xi_{1,2}$	empirically derived parameters to relate constants $k_{1,2}$ to ratio of supplementary cementitious materials or filler to Ordinary Portland Cement content

reaction in which limestone is converted to lime. One way to reduce the quantity of OPC necessary is increased use of Supplementary Cementitious Materials (SCMs) or increased use of well-dispersed inert fillers (e.g., [8]). SCMs can include a wide range of materials including natural pozzolans (e.g., diatomite), thermally treated clays (e.g., calcined clay), and industrial byproducts (e.g., fly ash from coal combustion and slag from metal refinement). These materials not only offer potential benefits in terms of reducing GHG emissions from the production of concrete, but also offer benefits to certain material and durability properties [9–11]. However, while the environmental impacts of inclusion of SCMs in concrete has been examined, how to use them most efficiently while meeting material property requirements has not been well studied.

2. Background

The use of SCMs and other means to develop "green" concretes have been thoroughly examined in the literature. Among the most prevalent means of evaluation is the use of life cycle assessment (LCA) methodology to quantify relative environmental impacts associated with concrete production and the influence of changing mixture proportions [12]. Many such studies have examined the role of improved equipment efficiency, use of alternative fuels, and increased use of industrial byproducts, for example fly ash and blast furnace slag, among others, to reduce clinker content in cement or to reduce use of clinker-intensive cement (e.g., [6,13–15]). Research has expanded further to assess individual mixtures based on production in a certain location to assess benefits or drawbacks to concrete constituent selection when trying to reduce environmental impacts (e.g., [16–20]). Due to the prevalence of industrial byproducts as a means to reduce the demand for clinker in concrete, the role of allocation of environmental impacts from initial production has also been a growing field. Rather than modeling these byproducts as having no associated impact from production, but only refinement, when required, and transportation prior to use, the impacts from production are considered at a certain degree using allocation methods (e.g., [21–23]).

Most commonly the investigation of life cycle impacts is based on a constant volume or mass of material produced (either concrete or cement) (e.g., [12]). However, as has been discussed by several authors, the role of material properties or longevity in an application will directly influence the volume of material or maintenance and replacement necessary (e.g., [24–26]). Recent efforts to change the units of comparison used in the assessment of concrete have attempted to overcome these factors. The most common methods implemented are comparisons using application of case studies (e.g., [16,27]) and using either emissions or binder per cubic meter of concrete as a fraction relative to compressive strength achieved (e.g., [28–30]). More recently, the contributions of concrete design and durability have started to be included in comparisons of mixtures (e.g., [31,32]). While these methods mark an improvement to common volume- or mass-based comparisons, they have the potential to counter design specifications; for example, it is possible that these new comparison techniques could suggest a very low strength or very high strength concrete that would be undesirable from a structural engineering or construction viewpoint. As such, there is a gap in understanding how concrete mixtures should be best proportioned to reduce environmental impacts while meeting specific design requirements.

The objective of this research is to develop a set of mathematical equations that facilitate finding a minimum environmental impact (i), in this case GHG emissions, for a specified constant compressive strength of concrete (f_c) and to dictate the necessary concrete mixture proportions, as are given in this work in terms of water-to-binder (w/b) and supplementary material to OPC (s/c) ratios, to get an optimized environmental impact.

3. Materials

To investigate applicability of equations developed for a variety of concrete mixtures, four groups of concrete mixtures containing different SCMs or fillers were examined. For this research, binary blends were considered to reduce complexity of equations developed; however, principles can be extended to other SCMs and blended binders. Specifically, this research considers concrete mixtures containing Ordinary Portland Cement (OPC) with natural pozzolans (NP), limestone fillers, ground granulated blast furnace slag (GGBS), or Class F fly ash (FA). While there are many viable SCMs that could have been considered, to present the methods discussed in this research, this subset of SCMs facilitates the visualization of the work presented. To facilitate equation development, 20 concrete mixtures with NP contents ranging from 0 to 0.82 NP:OPC, 25 mixtures with limestone ranging from 0 to 0.82 L:OPC, 32 mixtures with GGBS ranging from 0 to 1.57 GGBS:OPC, and 28 mixtures with FA ranging from 0 to 0.58 FA:OPC were used. Data for mixture proportions and compressive strength were from Meddah [33], Meddah et al. [34], Oner and Akyuz [35], and Oner et al. [36]. Equations developed by Yi et al. [37] were used to account for variations in specimen dimensions. Table 1 shows the nomenclature used for mixtures assessed in this project. Each group of concrete mixtures examined in this research was considered using 28-day compressive strength data with varying w/b and s/c ratios; mixture proportions and properties used can be found in the Appendix. Limited data sources were used to provide visualization of methods while improving uniformity in data. However, for any set of comparable data, the methods developed in this research could be applied.