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Concrete mixture proportioning for desired strength and reduced global warming potential

Sabbie A. Miller [a,*], Paulo J.M. Monteiro [b], Claudia P. Ostertag [b], Arpad Horvath [b]

[a] Department of Civil and Environmental Engineering, University of California, Davis, United States
[b] Department of Civil and Environmental Engineering, University of California, Berkeley, United States

HIGHLIGHTS

- A method for obtaining optimal water-to-binder ratio for concrete mixes is presented.
- Analyses are based on compressive strength and global warming potential of concrete.
- Optimal water-to-binder ratios occur at high strengths.
- At common compressive strengths, optimality is not achieved.
- In some cases, use of cement as the sole binder is the most sustainable solution.

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ABSTRACT

In this research, formulae for predicting compressive strength and global warming potential (GWP) per cubic meter of concrete are proposed. These equations allow for prediction of properties based on the water-to-binder ratio for concrete mixtures containing cement as the only binder, as well as for concretes containing Class F fly ash (FA) and ground granulated blast furnace slag (GGBS) as partial cement replacement. To meet multi-criteria demands of mechanical properties and lower GWP, a method for obtaining the optimal water-to-binder ratio, for given replacement level, is presented. In this research, optimization is based on a direct ratio of GWP to compressive strength, but the methodology has the potential to be extended to other environmental impact categories and material property relationships. For the classes of concrete examined, the analyses showed that high levels of cement replacement with GGBS may provide the best, hence resulting in the lowest, ratio of GWP to compressive strength for the mixtures examined. Additionally for the classes of concrete examined, the results showed that optimal water-to-binder ratios for the best ratio of GWP to compressive strength occurred at relatively high strengths (∼50–70 MPa). Yet, the majority of concrete used in countries such as the U.S. is lower strength concrete (<∼35 MPa). For the mixtures examined, it was shown that the concrete mixtures of low compressive strength (i.e., high water-to-binder ratios) containing only cement as the binder provided a lower ratio of GWP to compressive strength than some of the mixtures containing large quantities of replacement binder suggesting replacement of cement as a binder may not always be the most sustainable solution for low strength concretes.

1. Introduction

Recently, there have been considerable efforts in developing methods to reduce the greenhouse gas emissions associated with concrete production. These efforts have been in response to large increases in cement consumption over the past 50 years, with exponential increases in certain nations with developing economies [1]. While the increase in cement consumption is a logical result of the need for a binder in concrete, the high levels of greenhouse gas emissions associated with cement production from both the calcination process and the combustion of fuel for its production have been of concern [2]. The combination of greenhouse gas emissions and consumption levels of cement for use in concrete are responsible for approximately 8% of annual anthropogenic greenhouse gas emissions based on an analysis of data from 2005 [3].

* Corresponding author.
E-mail address: sabmil@ucdavis.edu (S.A. Miller).

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Nomenclature

b	binder content by weight (kg/m^3)
c	Portland Cement content by weight (kg/m^3)
FA	fly ash
f_c	compressive strength of concrete (MPa)
$GGBS$	ground granulated blast furnace slag
GWP	global warming potential (kg CO_2-eq)
i	volumetric environmental impact (environmental impact/m^3)
$k_{1,2}$	constants which depend on the concrete materials used
k_3	constant which depends on cement manufacturing
k_4	constant which depends on materials and processing used
k_5	constant which is a function of k_3, water content by weight (w), and the replacement ratio of supplementary cementitious materials to cement content
N_{axial}	normalized comparison equation for environmental impacts and strength in axial compression
PC	Portland Cement
s	supplementary cementitious material content (kg/m^3)
χ_{axial}	comparison equation for environmental impacts and strength in axial compression
w	water content by weight (kg/m^3)

Many methods for reducing the greenhouse gas emissions associated with the production of cement and concrete have been proposed, such as improved efficiency of manufacture methods and carbon capture and storage [4]. One of the more heavily researched areas for improving the greenhouse gas emissions profile for concrete production is to reduce the use of Portland cement (PC), which has high associated emissions, through the use of alternative binders [5]. In this popular area of research, the use of byproducts from other manufacturing and energy production methods, such as fly ash (FA) and ground granulated blast furnace slag (GGBS), as cement replacement have been heavily examined. Their influence on the mechanical properties and durability of concrete has been studied in detail (e.g., [6–10], among many others).

More recently, the potential benefits associated with replacing cement in concrete with these alternative binders have been examined through environmental impact assessments. There are many frameworks and design methods that have been developed that can be applied to quantifying and improving the environmental footprint of structural materials. Among these are methods such as 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]. These environmental impact assessments for cement and cement-based materials are often quantified by life-cycle assessments (LCAs), a method to account for material, energy, emissions, and waste flows through the life of a material or product. For cement and concrete, typical LCAs have the goal of valuing improvements or assessing environmental impacts associated with production of a constant volume or constant mass of concrete (e.g., [17–19]). Yet, because 95% of the Portland cement produced is used in concrete [20] and the volume of material needed for an application is subject to its material properties [21], which can influence constituent selection, it is critical to consider concrete material properties in the functional unit of comparison for concrete mixtures.

Some researchers have been examining the relationship between mechanical characteristics and environmental impacts. Flower and Sanjayan [22] developed LCAs for concrete containing cement as the only binder as well as for concrete containing FA and GGBS in the concrete binder. Their analysis focused on cradle-to-gate CO_2 – equivalent emissions, but incorporated the role of compressive strength in different mixture proportions and examined a case study using alternative mixtures. Subsequently, several authors have published environmental impact assessments in addition to examining material properties. Liu et al. [9] examined the influence of different ratios of FA cement replacement on the greenhouse gas emissions and embodied energy for nine concrete mixtures using Economic Input Output LCA for cradle-to-gate and end-of-life impacts. Damineli et al. [23] examined the influence of the quantity of binder needed to provide 1 MPa of strength and the associated CO_2 emissions, assuming only the manufacture of clinker from cement production was a contributor to greenhouse gas emissions. A thorough analysis characterizing the mechanical and durability properties of self-compacting concrete containing binary and ternary blends of FA and limestone with cement was analyzed by Celik et al. [8]. The analysis included a detailed LCA for each of the mixtures considering raw material acquisition, transportation, energy mixes, and manufacture. In an assessment of durability properties and emissions from production, Gursel et al. [24] examined the role of strength development on the quantity of emissions associated with concrete containing binary and ternary blends of rice husk ash and fly ash with cement in concrete relative to strength at different ages. Through examination of design of reinforced structural members and a building design, the role of using different levels of fly ash as substitute binder in concrete and different design ages to reduce greenhouse gas emissions was assessed by Miller et al. [25]. Most often, the use of waste and byproduct materials as binder replacement is considered to have little to no associated environmental impacts, as was the case for these studies. However, researchers are now considering alternative allocation methods for constituents [26,27].

There is increasing interest in the material property assessment and environmental impact assessment for concretes containing waste or byproduct materials as binder replacement for concrete. Yet, there is little work on the development of robust tools for assessing desirability of concrete mixture proportions accounting for mechanical properties and environmental impacts concurrently. The present research attempts to initiate work in meeting that need by combining a classic concrete mixture proportion equation with environmental impact assessments based on constituent contributions to strength and global warming potential (GWP).

The objectives of this research are to develop and expand upon existing concrete mixture proportion equations to allow designers to select desirable concrete constituents or mixture proportions. Methods for selecting optimal constituents to lower associated greenhouse gas emissions are examined within the context of an axially loaded unreinforced concrete member in compression, but the concept can be expanded to other members and applications, with the potential to consider other material properties or concerns.

2. Materials

As discussed previously, concrete mixtures containing waste or byproduct materials such as FA or GGBS are often considered to provide sustainable alternatives to concrete containing PC as the