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Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: can there be too much of a good thing?

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A R T I C L E I N F O

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A B S T R A C T

Among the many possible strategies for reducing anthropogenic greenhouse gas (GHG) emissions is reduction of emissions associated with the production of concrete, which is responsible for 8–9% of global anthropognic GHG emissions. Using supplementary cementitious materials (SCMs) in concrete to offset demand for clinker in cement is a commonly proposed method to cut GHG emissions from concrete production. The most commonly used SCMs are industrial byproducts, such as fly ash and ground granulated blast furnace slag, but the extent to which these SCMs should be used in individual concrete mixtures is not well examined. This research examines the contribution of fly ash and ground granulated blast furnace slag to compressive strength, the role of allocation in the assessment of environmental impacts, and the impacts of transportation. Quantitative analyses are developed using environmental impact assessments and comparisons are drawn based on changes in GHG emissions for concrete production. The findings of this research show that these three factors can outweigh benefits associated with use of SCMs: depending on SCM type and use of allocation or changes in transportation, high levels of SCM replacement do not consistently result in lower GHG emissions for the production of concrete per unit strength. Limited supplies of these popular byproduct SCMs amplifies the necessity to efficiently use these materials. Within the limitations of this study, this work shows strategic use of SCMs to cut GHG emissions based on regional availability and based on application should be a priority.

1. Introduction

Concrete, the most consumed material by humans after water, has recently been under scrutiny for the environmental impacts associated with its production (Monteiro et al., 2017). Globally, approximately 4.1 billion tonnes of hydraulic cement was produced in 2015 (van Oss, 2017); this hydraulic cement production corresponds to approximately 25–30 billion tonnes of concrete. Globally, the impacts associated with concrete production include 2–3% of annual energy demand and 8–9% of anthropogenic CO_2 emissions (Monteiro et al., 2017). These notable impacts are to a great extent a reflection of the large quantity of concrete being produced, rather than impacts associated with per kg production, which is lower than that for steel and most polymers (Ashby, 2009).

Concrete has become established as the most popular man-made material for several reasons; key among which is the availability of the raw materials used in its production. Concrete is composed of several materials including granular rocks, known as aggregates, water, and binder as well as admixtures and fibers as needed. The binder is composed of several constituents including clinker, a kilned and quenched cementitious material, gypsum, limestone, and supplementary cementitious materials (SCMs). In the production of clinker, raw materials are heated to ~1450 °C and limestone in the raw materials undergoes calcination, in which material-derived CO_2 is produced, such that there are both energy-derived and material-derived GHG emissions. Of these constituents in the concrete binder, clinker is currently responsible for 65–85% of the global hydraulic cement mass (GNR, 2014). As concrete is manufactured today, the binder is responsible for the most of the GHG emissions in the production of concrete, with the majority attributable to the clinker (over 90% of the GHG emissions from producing concrete (Miller et al., 2016a)).

The substantial contribution to anthropogenic GHG emissions from the production of concrete with the majority of these emissions from one constituent, Ordinary Portland Cement (OPC), has resulted in impetus to find material alternatives for this binder (WBCSD and IEA, 2009; Miller et al., 2017). Supplementary

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cementitious materials (SCMs) can come from a variety of sources; among the most popular globally are industrial byproducts such as fly ash (FA) from the combustion of coal and slag from the manufacture of alloys, with the most common slag utilized being ground granulated blast furnace slag (GGBS) (GNR, 2014). FA and GGBS have either pozzolanic or pozzolonic and cementitious properties, which allow them to be used to offset demand for higher clinker content OPC while maintaining similar compressive strength at certain replacement levels. Because these SCMs are byproducts from other industries, they are often modeled as having little to no impacts from production and the environmental impacts from processing or refinement and transportation are minimal relative to the impacts from producing clinker-based cement (e.g., some studies with minimal processing and transportation impacts relative to cement include (Celik et al., 2015; Gursel et al., 2016; Kajaste and Hurme, 2016)). As a result, it is becoming commonplace to recommend or favor the increased replacement of high clinker content OPC with SCMs without taking into consideration the most efficient use of these materials (Lemay, 2004).

This research examines the contribution of FA and GGBS, common SCMs, to compressive strength, as well as the role of allocation in the assessment of environmental impacts and the impacts of transportation. The contributions of such study facilitate our understanding of when use of high levels of SCMs is potentially less favorable in the attempt to reduce GHG emissions from concrete production.

2. Background

The efficient use of SCMs can be driven by several broad factors: their availability, their assessed environmental impact, and their contribution to desired material properties. The use of SCMs to reduce GHG emissions from the production of concrete has been substantiated through a great amount of life cycle assessment (LCA) literature. However, there are inconsistencies between methods used in terms of allocation of impacts to byproducts (as shown by (Chen et al., 2010)), inclusion of transportation impacts (e.g., differences between (Damineli et al., 2010; Gursel and Ostertag, 2016), among others), and functional units of comparison (as shown by (Miller et al., 2016b; Gursel et al., 2016; Panesar et al., 2017), which examined the role of different material properties on the volume and environmental impact of concrete production, examined the ratio of environmental impacts to mechanical and durability properties, and examined environmental impacts of concrete based on six functional units, respectively). Further, while most assessments suggest increased SCM use typically reflects a decrease in GHG emissions from concrete production, these studies rarely consider material availability.

While the benefits of trade allow many markets to access a variety of these materials, if the SCMs must be transported a considerable distance, the transportation related emissions could lower net benefits ((Chen et al., 2010; McLellan et al., 2011; Arıoğlu Akan et al., 2017), which note the transportation of concrete constituents and building materials can have a notable impact on GHG emissions). In many regions, even if the SCMs must be transported long distances, they can still have GHG emissions that are lower than the production of a high clinker content OPC (O'Brien et al., 2009); nevertheless, these benefits may be less substantial than anticipated.

Allocation strategies used to assess the environmental impacts of the SCMs that are byproducts of industrial production influence environmental impacts calculated. For example, in a study by Crossin (2015), use of system expansion showed that in constrained markets, the use of GGBS could result in GHG reductions of 1% that would have resulted in over 45% reduction in an unconstrained market. Similarly, Chen et al. (2010) showed how different allocation methods, namely economic-based and mass-based, could influence the GHG emissions associated with the production of FA. In a study by Salas et al. (2016), again use of allocation showed the benefits commonly associated with use of FA and GGBS would be lower than if no allocation methods were used; however, the use of these materials still showed a decrease in environmental impacts analyzed relative to not using these SCMs. Seto et al. (2017) examined the role of several allocation methods, including mass-based, economic-based, and disposal avoidance methods relative to no allocation method and showed increasing FA levels continue to contribute to reduced GHG emissions in the production of concrete, but the extent of this reduction was strongly dependent on the allocation method selected. While there is a lack of consensus on use or type of allocation method, the upstream impacts associated with industrial byproduct SCMs could be a factor in determining their favorability as a GHG emission mitigation method in concrete production.

Despite the influence mechanical properties or durability of concrete can have on the amount of material specified or maintenance and replacement related emissions, the most common means of comparing concrete mixtures is on a volume basis (Gursel et al., 2014). The contribution of SCMs to material properties, such as strength, could influence the quantity of binder or concrete necessary for a particular application and environmental impact of associated concrete production. This concept is further complicated by factors such as: the type of SCM; the SCM chemical composition; the effects on material durability, which can result in certain SCMs being favorable over others to reduce GHG emissions (Panesar et al., 2017); and effects on strength development, as certain SCMs have been shown to change the rate of strength development and as such could result in a less favorable design at an early specified age than at a later age (Arbuckle et al., 2014; Miller et al., 2016a, 2016c). The use of strength and the use of durability properties are becoming more common in comparisons of concrete mixtures (Gursel et al., 2016; Miller et al., 2016b; Panesar et al., 2017).

Currently, there is limited understanding of how these factors in the assessment of the environmental impacts of concrete can collectively contribute to alternative design decisions beyond the premise that more SCMs reduce GHG emissions. The objectives of this research are to examine the roles of changing SCM content in binder, transportation of SCMs, and use of allocation to incorporate upstream impacts in industrial byproduct SCMs, as well as the influence of concrete design age on GHG emissions from production of concrete. In addition, the role of material availability in context of these SCMs is presented, to further address the concept that greater inclusion of SCMs may not consistently be beneficial on a global scale.

3. Materials

In order to understand the role of incorporating more SCMs in concrete as a GHG mitigation strategy, FA (Class F) and GGBS use were assessed. Specifically, 165 mixtures from a publication by Hedegaard and Hansen (1992) were used to consider the role of Class F FA on 28-day and 56-day compressive strength of concrete. These mixtures used Ordinary Portland Cement (OPC), White Cement (WC), Sulphate-resistant Portland Cement (SRPC), and Class F FA in varying proportions ranging from 0% use of FA to a binder containing 91% FA. Because 49 mixtures were tested at a cylinder size of 150 mm $\times$ 300 mm and the remaining mixtures were tested at a cylinder size of 200 mm $\times$ 300 mm, the influence of size differences were adjusted using formulas by Yi et al. (2006). Additionally, 32 mixtures from a publication by Oner and Akyuz (2007) were used to assess use of GGBS with varying proportions