SUSTAINABILITY OF CONCRETE IN THE PACIFIC NORTHWEST

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INTRODUCTION

Buildings are being constructed at a rapid pace, and structural engineers are looking for ways to design more sustainable buildings so that the built environment has less of an impact on the natural environment. The Intergovernmental Panel on Climate Change sites a warming of 1.5-2.0ºC by 2050 as the point at which the effects of climate change will become irreversible [1]. In response to this phenomenon, a series of initiatives were established by the Architecture and Engineering industries to prevent that warming of 1.5-2.0ºC. Among these efforts are initiatives such as the Carbon Leadership Forum (CLF), Structural Engineers 2050 Commitment Program (SE 2050) and Architecture 2030. The CLF is an interdisciplinary organization working to reduce embodied carbon in building materials and construction [2]. In 2019, the CLF challenged structural engineers to work towards a global vision of Zero Carbon buildings by 2050. SE 2050 is a response to this challenge, and aims to educate structural engineers on sustainable structural design and construction, develop and deploy an embodied carbon tracking program, and report on the current embodied carbon impacts of various structural systems [3]. SE 2050 is modeled after Architecture 2030, which was established by the American Institute of Architecture (AIA) to achieve reduction targets for embodied carbon emissions. The Architecture 2030 challenge aims to reduce embodied carbon emissions from all new buildings, infrastructure, and associated materials by 45% in 2025, by 65% in 2030, and to be zero by 2040 [4]. If this 2030 milestone is not met, it is unlikely that the 2050 target will be achievable.

The embodied carbon of building structures, substructures, and enclosures are responsible for 11% of global greenhouse gas emissions [4]. Structural materials, like concrete, account for at least 50% of the carbon emitted in production, delivery, and installation of materials for new constructions [5]. Cement is a primary component of concrete, and its production alone accounts for about 5% of all global greenhouse gas emissions [6]. Reducing the CO_2 emitted by the production of cement will help in reaching the 2050 target goal. This reduction can be done various ways: by changing fuel to one with a lower carbon content during the calcination process, by adding a chemical absorption process that would capture CO_2, changing the clinker manufacturing process to be more efficient, or lastly, to add supplementary cementitious materials (SCMs) to the cement [7]. The latter is the most practical and economic method, and is one that structural engineers can address. Global warming potential (GWP) is a measure of the amount of CO_2 emitted by a particular concrete mix. By specifying concrete mixes with lower GWPs for use in building structures, substructures and enclosures, structural engineers can reduce the carbon emissions of buildings. In addition, one of the stipulations to obtain the LEED v4 MR Credit Building Product Disclosure and Optimization is if the concrete mix designs have a lower GWP than the National Ready-Mix Concrete Association (NRMCA) benchmark [8].

PROJECT OBJECTIVES

In this paper, a cradle-to-gate life cycle analysis (LCA) is used to explore the impact that SCMs have on the GWP of concrete in Seattle. The objectives of this project are to: (1) demonstrate that the use of supplementary cementitious material in concrete mixes reduces the GWP of concrete, (2) comparing the GWP of the NRMCA Pacific Northwest regional benchmark mix designs with commonly used mix designs in Seattle, and (3) quantify how different supplementary cementitious materials can have an impact on concrete's GWP.

BACKGROUND

Many studies have examined the positive environmental benefits of replacing cement with SCMs like slag, fly ash and silica fume. Souto-Martinez et al. (2018) used an LCA to quantify and compare the cradle to gate CO_2 emissions of concrete with the total amount of CO_2 that can be sequestered from exposed concrete building elements. This study demonstrated that the use of SCMs did lead to lower CO_2 emissions and suggested that the CO_2 sequestered throughout the lifetime of an exposed concrete member should be considered when estimating the CO_2 emissions of a concrete mix [9]. However, Souto-Martinez et al. (2018) analyzed mixes that were designed for the study, and do not necessarily reflect the mixes that are being used in the industry.

Yang et al. (2014) quantified the effectiveness of SCMs in reducing CO_2 emissions from OPC concrete. The study performed life cycle inventory (LCI) from cradle to preconstruction for laboratory concrete mixes as well as plant mixes. The results indicated that CO_2 intensity ($kg/m^3 * MPa^{-1}$) decreased as the substitution level of SCMs increased until the substitution level was 15-20%, at which point the rate of decrease in the CO_2 intensity slowed. These results established that using SCMs can reduce the CO_2 emitted from the production of concrete [7]. It demonstrates that the use of SCMs in concrete can make the concrete more sustainable, but it does not address whether or not this is being done in practice.

The Structural Engineers Association of Washington (SEAW) performed a study (Fischer and Slivers 2017) with the goal of understanding the environmental footprint of continuously approved concrete mix designs used in Seattle and how they compare with the NRMCA benchmarks. Continuously approved mixes meet the requirements of Seattle Building Code 1905.1.11. Their use speeds up the approval of concrete mixes on a project by project basis by waiving plant inspections from the building official. The study found that Seattle's continuously approved mixes met and were below the NRMCA benchmarks [10]. Since this study, more ready-mix concrete suppliers have established more Environmental Production Declarations (EPDs), which use different impact sources than this study originally used.

The Structural Engineers Association of Northern California (SEAoNC) conducted a study on the embodied carbon impacts of California concrete mix designs (2019). The sustainable design committee collected concrete mixes used in California and performed a life-cycle assessment to quantify the environmental impacts of the mixes. With the results of this life-cycle analysis, the industry average in California was compared to the NRMCA national averages. This study found that some mixes being used in California have less than half of the GWP of the national average [11]. The research presented in this paper follows a procedure similar to that taken by the (SEAoNC).

METHODS

Data for the study

The data for this research was obtained from concrete suppliers in Seattle. It consists of 121 mix designs of continuously approved concrete mixes in Seattle. Typically, an inspection is required during the mixing of concrete in every project. A continuously approved concrete mix meets the requirements of the Seattle Building Code section 1905.1.11 [12]. To meet this code, the mix proportions must be selected in accordance with ACI 318, Section 5.3 (ACI 2019), [13] the mixes must be frequently used, and there must be a good consistency history with the concrete producer. It is advantageous to specify continuously approved mix designs because it can speed up the construction process by eliminating the need for an inspection during mixing. Also included in the data is the percentage of the total 2017 concrete production that came from each of the mix designs. The results of the LCA of the continuously approved mix designs are compared to the NRMCA Pacific Northwest regional industry benchmarks. The NRMCA is an industry advocate for ready mixed concrete and works in partnership with state associations on its regulation. The NRMCA benchmarks represent the industry averages, for the country as a whole, and by region.

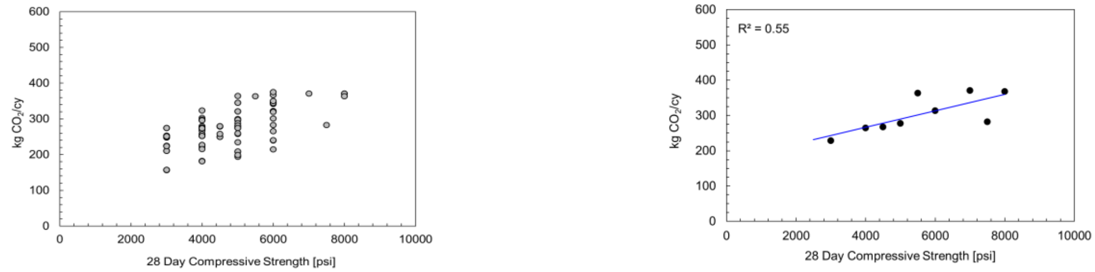
Analysis methodology

The mix designs were evaluated for sustainability using the Athena Impact Estimator [14]. This is a software tool designed to evaluate the environmental impacts of assemblies and/or buildings based on internationally recognized LCA methodology [15], ISO 14040 [16] and ISO 14044 [17]. Athena Impact Estimator considers the environmental impacts of material manufacturing (including resource extraction), related transportation, on-site construction, regional variation in energy use and transportation, building type and lifespan, maintenance, demolition and disposal. While the Athena Impact Estimator will conduct an LCA from cradle-to-grave, this work will only examine the cradle-to-gate environmental impacts. This is the product phase, and it includes raw material supply, transportation, and manufacturing. The environmental impact that is examined is the GWP of each concrete mix design. The GWP is measured in $kgCO_2$/cy of material. In addition to each mix design, the NRMCA industry benchmark mixes were run through the Athena Impact Estimator so that the comparison between the continuously approved mix designs and the benchmarks utilized the same impact sources.

RESULTS

Of the mix designs that were used for this study, 23 did not use any SCMs, while the remaining 98 mix designs used at least one SCM. Of the mix designs that use SCMs, 95% used slag, indicating that slag is the primary SCM used in Seattle. Figures 1 and 2 plot the relationship between GWP and use of SCMs.

The results of the analyses show that the GWP of the concrete mixes increased with increasing compressive strength (Figure 1). Figure 1 shows this trend, which is likely due to an increased quantity of cement in mixes of higher strength. Figure 1 also shows that there is a large scatter in the data at compressive strengths below 6000 psi.



(a) **(b)**

Figure 1. Global Warming Potential of Continuously-Approved Mix Designs in Seattle for (a) Individual Seattle Mix Designs and (b) Average Seattle Mix Designs with Regression Line

The scatter in the data can also be seen in Figure 2, which plots the percentage of the total mix GWP that is contributed to either slag or cement. The red dots represent the percentage of a mix design's GWP that can be attributed to cement. The blue dots represent the percentage of a mix's GWP that is attributed to slag.

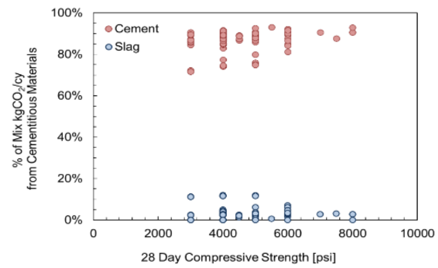
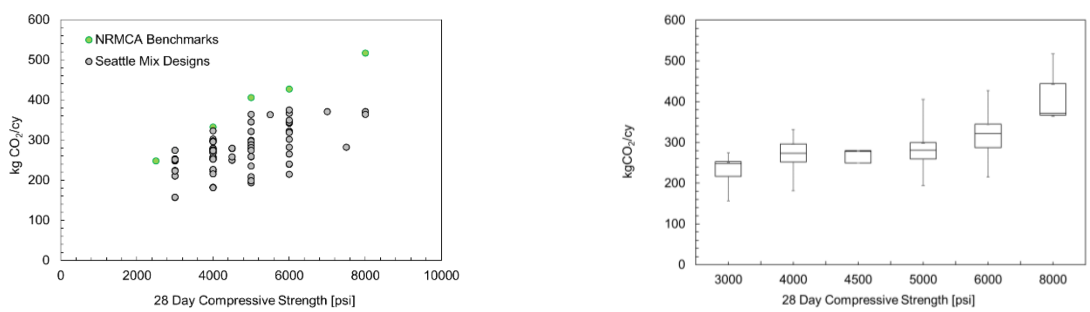


Figure 2. Percentage of GWP of a Mix Design Attributable to Cement or Slag

Figure 2 illustrates that cement accounts for at least 71.7% of the GWP of each mix design. Whereas, slag accounts for at most 12.1% of the GWP of each mix design. At a compressive strength of 6000 psi or lower, there is more variation in the percentage of GWP that cementitious material contributes to each mix design. At compressive strengths higher than 6000 psi, there is less data, and less variation in the percentage of GWP that cementitious material contributes to a mix design.

Figures 1 and 2 show that there is more data for slag being used in low compressive strength concrete mixes (below 6000 psi) than there is in high compressive strength mixes, and that GWP decreases with the compressive strength of a concrete mix design. This is consistent with existing research and demonstrates that the use of SCMs in concrete mixes reduces the GWP of concrete.



(a) **(b)**

Figure 3. GWP of (a) Individual Continuously-Approved Mixes in Seattle with NRMCA Benchmarks and (b) Summary of Continuously-Approved Mixes in Seattle

When the results of the analyses are compared against the NRMCA benchmarks (Figure 3a), the analyses shows that 98% of Seattle mix designs of a given compressive strength have a lower GWP than their corresponding NRMCA benchmark. This indicates that the continuously-approved concrete mix designs within the City of Seattle are mainly falling below the NRMCA benchmarks and is an indicator for how sustainable Seattle's concrete is.

Figures 1 and 3a show the scatter of data for GWP when concrete compressive strength is below 6000 psi. Figure 3b demonstrates that variability within the data in a box and whisker plot. Figure 3b emphasizes that on average, the concrete mix designs produced in Seattle have a lower GWP than the NRMCA benchmarks. At each compressive strength, up to the 75th percentile of GWPs in concrete mix designs are still well below the NRMCA benchmarks. Figures 3a and b demonstrate that the City of Seattle is meeting the NRMCA benchmarks established for the U.S.

Table 1. Percent Difference in GWP of Seattle Mixes with No SCMs or With Slag from NRMCA Benchmarks

Compressive Strength [psi]	NRMCA Benchmark [GWP, kg CO_2/cy]	No SCM		Slag	
		Average GWP	% Difference from Benchmark	Average GWP	% Difference from Benchmark
2500	248	--	--	--	--
3000	274	299.61	+5.39%	213.92	-24.63%
4000	332	282.61	-16.07%	254.32	-35.50%
5000	406	274.48	-38.65%	280.72	-36.49%
6000	427	338.97	-28.97%	313.32	-30.71%
8000	517	--	--	370.80	-32.93%

Table 1 summarizes the GWP for the NRMCA benchmarks for each concrete compressive strength, the average GWP for concrete mixes analyzed with and without SCMs, and the percent different between those averages and the NRMCA benchmarks. The first column (left to right) lists the compressive strength. The second column lists the GWP of the NRMCA benchmark mixes. The third and fourth columns show the analysis data from Seattle mixes with no SCMs. Respectively, they list the average GWP and percent difference from the benchmark. The two columns on the right show the average GWPs at each compressive strength and their percent differences from the NRMCA benchmarks for Seattle mixes that utilized slag. The data in Table 1 indicates the percent difference in GWP between Seattle mix designs that utilize either slag or no SCMs and the NRMCA benchmarks. On average, mixes using slag had a 30% lower GWP than their corresponding NRMCA benchmark. In Seattle, mixes with no SCMs had on average, a 22.3% lower GWP than the corresponding benchmark. Slag is the primary SCM used in Seattle. 79% of mix designs contained slag, 2.5% contained fly ash, and less than 1% contained silica fume. Table 1 demonstrates that in Seattle, of the possible SCMs, it is slag specifically, that reduces the GWP of concrete.

SUMMARY AND CONCLUSIONS

This research used continuously-approved concrete mix designs obtained from concrete suppliers in Seattle, and an LCA tool to explore the impact that SCMs have on the GWP of concrete in Seattle. The results are consistent with existing research in demonstrating that the use of SCMs in concrete mixes reduces the GWP of concrete. A comparison of the GWP of the Seattle mix designs with the GWP of the NRMCA benchmark mixes demonstrated that 98% of continuously-approved concrete mixes in Seattle are meeting the NRMCA benchmarks for GWP. In addition, 79% of the Seattle mix designs utilized slag, and on average, these mixes had a GWP 30% lower than the NRMCA benchmark for the same compressive strength.

CONTRIBUTION TO SLAG/CEMENT INDUSTRY

Slag is the most commonly used SCM in the Pacific Northwest. In Seattle alone, 79% of continuously approved concrete mix designs use slag. All continuously approved mix designs in Seattle that utilize slag are below the NRMCA benchmarks, so if an engineer specs a continuously approved concrete mix design in Seattle with slag, they meet one stipulation for a LEED credit for their building. Continuously approved mix designs in Seattle that utilize slag have a GWP on average 30% lower than the NRMCA benchmarks. This research provided a framework that could be used by other major cities to evaluate how sustainable their concrete is and highlight which SCMs are being utilized the most. This framework and other studies such as the one presented in this paper could demonstrate how major cities are taking strides towards more sustainable construction to meet the Architecture 2030 and SE 2050 goals.

CONTRIBUTION TO CONCRETE INDUSTRY

Concrete is not traditionally considered a sustainable building material. However, this study demonstrated that the use of SCMs in concrete is widely accepted in the City of Seattle. The framework developed in this study, and the results of this study demonstrate that with the use of SCMs, commonly utilized concrete mixes can be considered a sustainable building material. Seattle's continuously-approved mix designs fall below the NRMCA benchmarks. Consistent with existing studies, replacing portions of the cement quantities with SCMs reduces the impact of concrete mixes on the environment. Sustainable mix designs are being used in Seattle, a city that has high-rise, mid-rise, and low-rise concrete buildings, thereby promoting the use of sustainable concrete.

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