Embodied Carbon Impacts of California Concrete Mix Designs

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Abstract

According to the World Business Council for Sustainable Development, “concrete is the most widely used material on earth, apart from water, with nearly three tons used annually for each man, woman, and child.” There are four basic components common to all concrete: Portland cement, water, coarse aggregate, and fine aggregate. Additionally, ingredients may be added to the concrete mix to improve both the fresh and hardened properties, including supplementary cementitious materials and/or chemical admixtures. Despite the relatively few ingredients that go into a concrete mix, the proportions of these ingredients can vary significantly. This variability leads to significant differences in the carbon emissions associated with any given concrete mix. Added over the many cubic yards of concrete used in all building projects, seemingly small changes in the concrete mix design can effectively reduce the embodied carbon inherent in the construction of the built environment.

The SEAOC Sustainable Design Committee (SDC) has collected over 300 concrete mixes used in California projects the last few years, and performed a Life-Cycle Assessment (LCA) on the mixes to quantify their environmental impacts. Using the data from the mix designs collected, the committee has determined where the industry average is in California, how this average compares to the NRMCA national average, and has explored what major factors affect the environmental performance of concrete materials. Note the NRMCA national averages were published in 2016, and they summarize the environmental impacts of concrete mix designs collected from 90 different concrete suppliers and 2,800 plants across the U.S.

The SEAOC SDC has determined which components in a mix design most greatly impact the environmental performance and explores cost comparisons between typical concrete mixes and low carbon (cement) mixes. The forthcoming low carbon concrete code, that may soon be adopted in the Bay Area, is also discussed. Lastly, the committee makes recommendations to all structural engineers on how to specify more sustainable concrete and encourages them to build with lower carbon footprints.

Acknowledgments

We would like to acknowledge Lisa Podesto and Cary Rapoport, members of the SEAOC SDC, who helped collect mix designs and all of the other SEAOC members who submitted mix designs. We would also like to thank Nicole Wang from SOM for creating the Google Form that was used to collect all of the mix design data and Ana Moura-Cook from Arup for formulating the charts from the raw data.

Introduction

In 2018, the SEAONC SDC started collecting California concrete mix designs, for projects constructed within the last 5 years. The committee asked for limited project information and categorized the mix designs based on the concrete's use (ie vertical applications (walls and columns), horizontal applications (slabs and beams), and foundations). The committee then ran an LCA on the 170 mixes collected and analyzed the data. The study only looked at the Global Warming Potential (GWP) of these mixes and the results were presented at the 2018 SEI Structures Congress in a session titled "Specifying Sustainable Concrete". Since then, this study has become a state-wide effort utilizing the SEAOC SDC and the local member organizations (MO) to collect more mix designs and perform further analysis on the data collected.

The SDC local MO's solicited their membership for mix designs and as of June 2019, the committee has received just over 300 mix designs. The Athena Impact Estimator was used to perform the LCA on the mix designs. Within the Impact Estimator, the regional selection chosen was Los Angeles and the Extra Basic Materials function was used to determine the mix design's GWP per cubic yard of concrete. Only the life-cycle phases A1-A3 (ie "cradle-to-gate") were considered to match which phases the NRMCA national average accounts for.

The mix design GWP data has been analyzed various ways and the results are presented in the following charts. The mix design's specified strength versus its tested strength, whether a 28-day or 56-day strength is specified, and costs associated with low carbon mixes, is also presented. Finally, recommendations for structural engineers are summarized and the importance of specifying low carbon concrete is highlighted.

Data Analysis

There was a total data count of 312 mix designs analyzed. A majority (~75%) of the mix designs came from projects constructed in the Bay Area and most (~70%) of the mix designs have compressive strengths between 4000-6000 psi. The low number of data points for the design strengths above 6000 psi and below 4000 psi does impact the trends that can be determined from the data.

Below, various relationships are charted with their respective analyses using boxplot charts. Boxplots summarize the data using five numbers: the 25th percentile (first quartile), the 50th percentile (the median), the 75th percentile (third quartile), and the top and bottom of the data range. The data has been analyzed by the SEAOC SDC.

Figure 1a and 1b provide a look at the overall trends within the data. It can be seen that the California mixes had less cement and GWP than the NRMCA national data on average. The data follows the same general trend as the NRMCA average, with more cement and GWP with increasing concrete strength. Mixes with 3000 and 4000 psi compressive strengths nationally were near the upper quartile of the California mixes in the dataset. Higher strength mixes in the dataset had less GWP and cement than the national average. The variability within the mixes was significant. 3000 psi concrete had the least variability, with the highest GWP mix having twice the impact as the lowest GWP mix across the 44 3000 psi mixes collected. Mixes with a compressive strength of 4000 psi were the most common in the data set with 86 mixes collected. These mixes also had the highest variability in GWP, with the most impactful mix having 3.4 times the GWP as the least impactful mix.

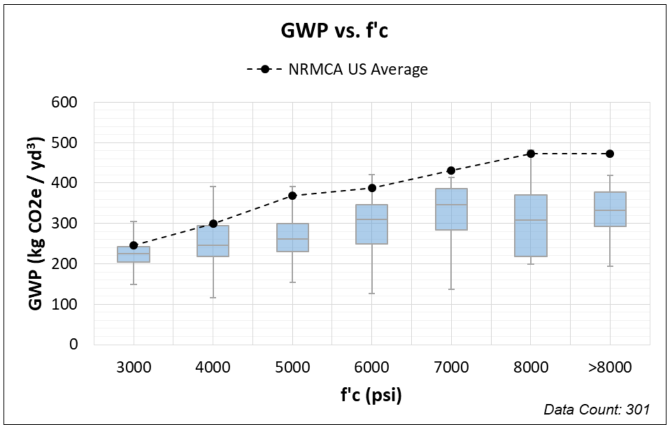

Figure 1a

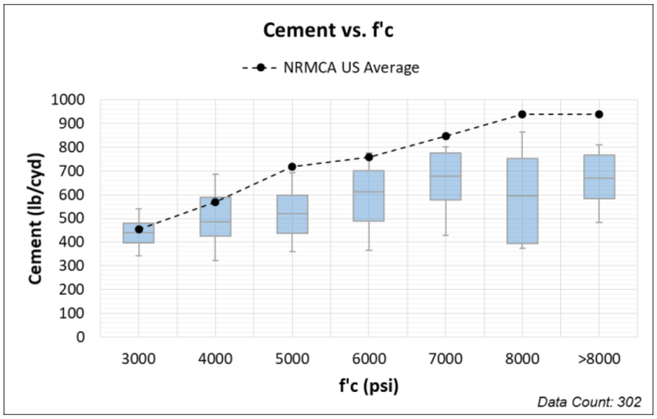

Figure 1b

Breaking out the concrete strength vs GWP by structural element helps to determine if higher carbon emissions are linked to concrete mixes for certain building components. Figure 2a compares the average global warming for each use type. Figures 2b, 2c, and 2d show the variability of the data through box plots for foundations, horizontal superstructure (slabs and beams), and vertical superstructure (walls and columns), respectively. Shotcrete variability was not included due to the low number of mix designs collected.

Of the mix designs collected for this study, shotcrete and horizontal superstructure uses had higher average GWP and less variability than foundations and vertical superstructure.

This result is not outside expectations. The horizontal superstructure elements within concrete structures are generally the most demanding elements when it comes to performance and speed of construction. There is a preference for high early strength, particularly in post-tensioned slabs, and where contractors are re-shoring slabs from levels below. Other concerns include high shear demands near columns, long term creep performance, and shrinkage cracking. None of these factors prevent the use of cement replacements, and in fact high SCM mixes can outperform standard mixes in many of these respects. However, these performance considerations may be leading engineers and contractors to stick with more standard mixes that have worked in the past, leading to less variability and higher cement content than other use categories. Similarly, shotcrete has a higher proportion of cement in the mix due its own performance requirements, including placement and workability.

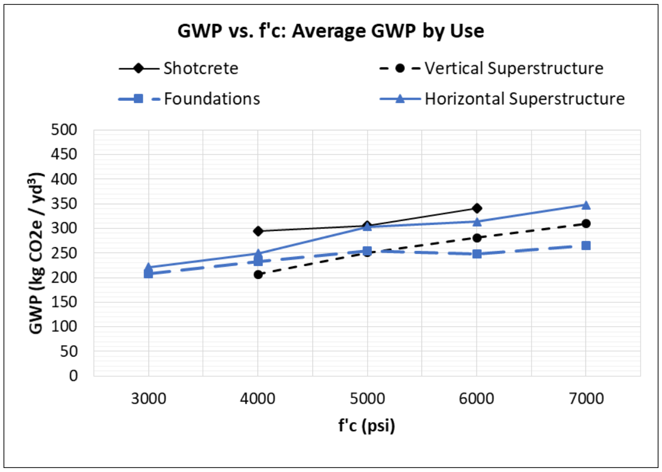

Figure 2a

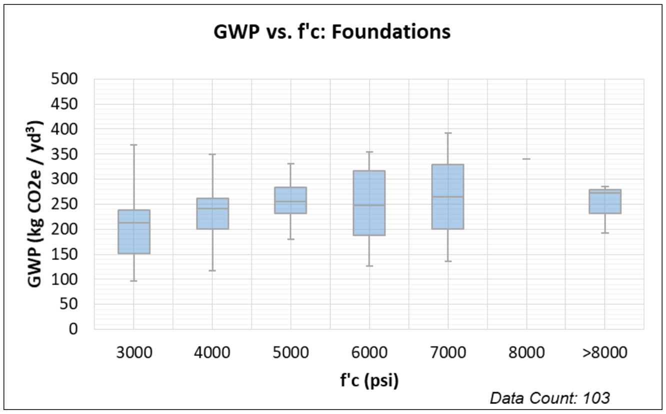

Figure 2b

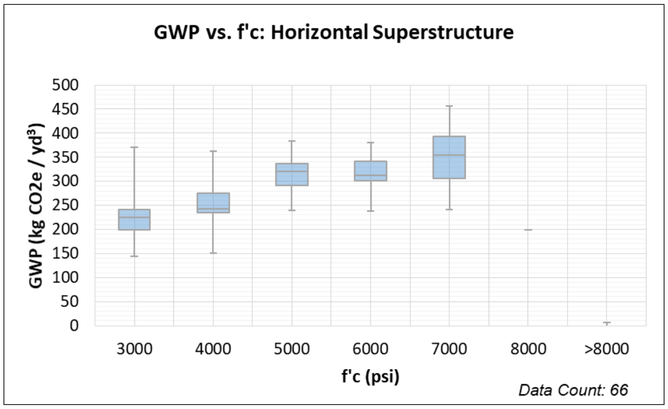

Figure 2c

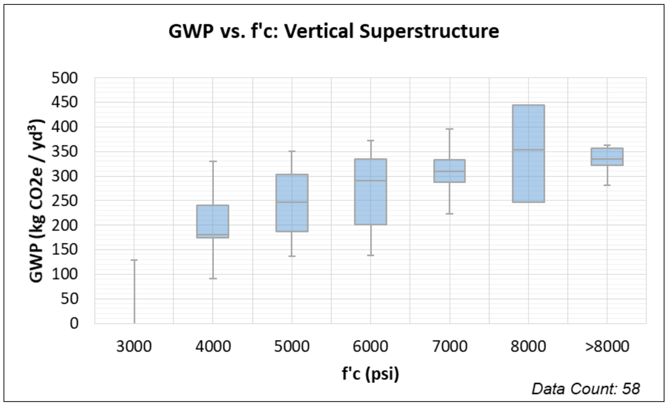

Figure 2d

Cement has by far the highest impact on GWP of all components in a concrete mix. With 1040 lbs. of CO_2e emitted per 1000 lbs. of cement (per Athena LCI data), cement has roughly 80x the impact of aggregates, 70x the impact of fly ash, and 7x the impact of slag on a pound-per-pound basis. Figure 3 shows the reduction in GWP as cement replacement ratio increases within the 4000 psi mixes collected.

The highest cement replacement mix has an impact of 116.5 kg CO_2e at 70% replacement (a mixture of 30% fly ash and 40% slag). Compared to the average GWP of about 350 kg CO_2e for a full cement mix, this is a reduction in GWP of about 67%.

While the result of reduced GWP with increasing cement replacement is expected, it is interesting to note that there is a variability of nearly 30% between the highest and lowest impact mix at common replacement ratios. This indicates that there are significant opportunities to reduce GWP through means other than specifying higher cement replacements.

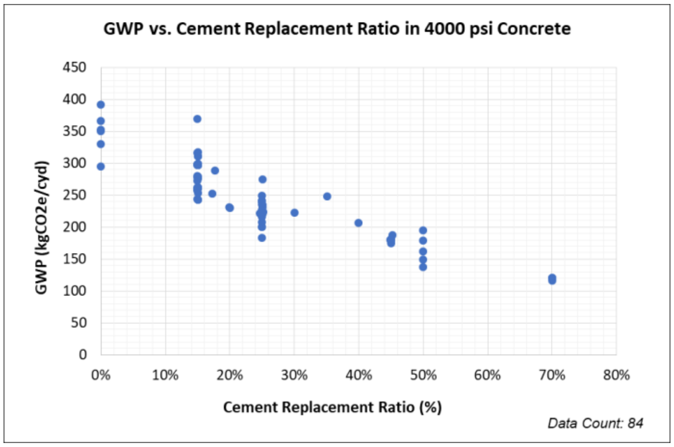

Figure 3

As shown in figure 3, cement replacement ratio is a primary driver of GWP. Figure 4 shows the cement replacement ratio that was included in all of the mix data.

Cement replacement was very common within the mixes submitted - 84% of all mixes specified cement replacement. Fly ash was used in 77% of all mixes while slag was used in 24% of mixes. For mixes that included SCMs, the average cement replacement was 28%. Mixes for compressive strengths from 3000 to 6000 psi all included from 0% to 70% replacement mixes. Excluding the high strength mixes which include few data points, the lower quartile of the mix replacement ranges from 10% to 15%, while the upper quartile ranges from 25% to 35%. Low strength mixes trended towards less replacement.

The widespread adoption of cement replacement is a very positive finding in the data and likely explains the reduced GWP of the California data relative to the NRMCA average. However, there is a good opportunity to reduce the GWP further by increasing the median replacement from the 15%-25% ratio towards the 70% upper range, particularly in low strength mixes which should have more flexibility in mix design.

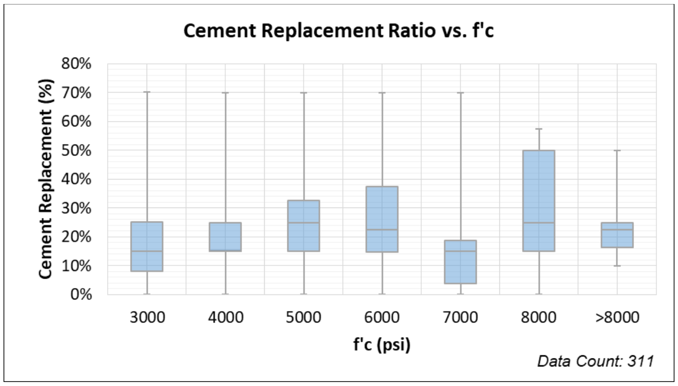

Figure 4

Among the small count of mix designs received with an Environmental Product Declaration (EPD), as noted in Figure 5, we compared the EPD GWP to the GWP calculated as described above. The intention was to check the GWP calculation method with an industry standard. The EPD GWP units are provided in kg CO_2e/m^3 and the GWP calculated with the collected data is in kg CO_2e/yd^3; therefore, the EPD data was divided by 1.308 yd^3/m^3 to compare the data over the 1-1 line. Not considering the outliers above 400 kg CO_2e/m3, it appears the collected GWP values follow a similar trend to those from those mixes with EPDs.

GWP values from EPDs should be more accurate than the GWP estimated for this study due to factors that should be accounted for in the site-specific (aka "product-specific" or "manufacturer-specific") values versus the GWP factors used from Athena Impact Estimator, which are averages for the region. Site-specific EPDs include site-specific energy use of the batch plant, site-specific fuel types and their proportions, and site-specific transportation of materials to the batch plants. Since it was not possible to include these specifics in the data collection, the GWP results from the collected data cannot achieve the same level of accuracy.

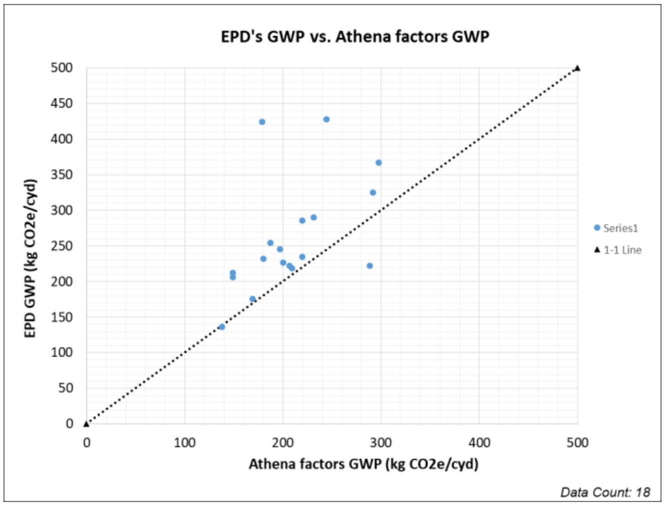

Figure 5

Given the variability of specified design compressive strengths and actual tested strengths, and the fact that a concrete mix's GWP directly correlates to it's cement content, the committee wanted to review the relative strengths of the mixes collected. The results from this analysis can be seen in Figure 7. As suspected, the tested strengths came in almost always higher than the design strengths. While the considerations of statistical analysis of mix designs is outside the bounds of this paper, the committee can't help but wonder if there are ways to better predict the variables that affect in-place strength while also avoiding unnecessary increases in cement content.

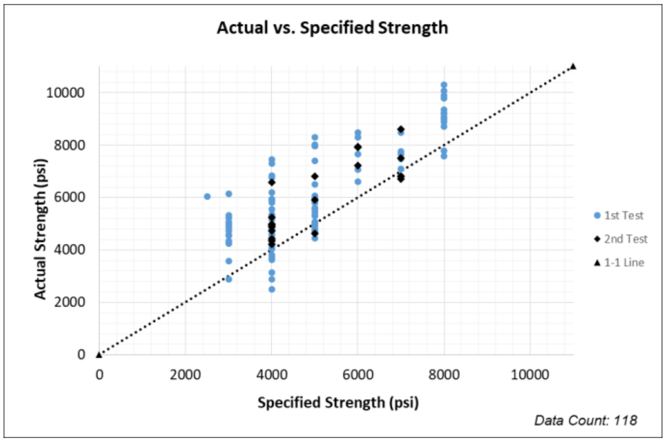

Figure 6

When a 56-day mix is specified, the intent is to allow for strength achievement to occur over a longer period. Just as less-than-28-day mixes usually have more cement to achieve the earlier strength, the 56-day mixes are assumed to have lower cement and, hence, lower overall GWP. As can be deduced from Figure 7, the GWP trend is lower for 56-day specifications for most compressive strengths. For 8000 psi mix designs, the difference is less apparent.

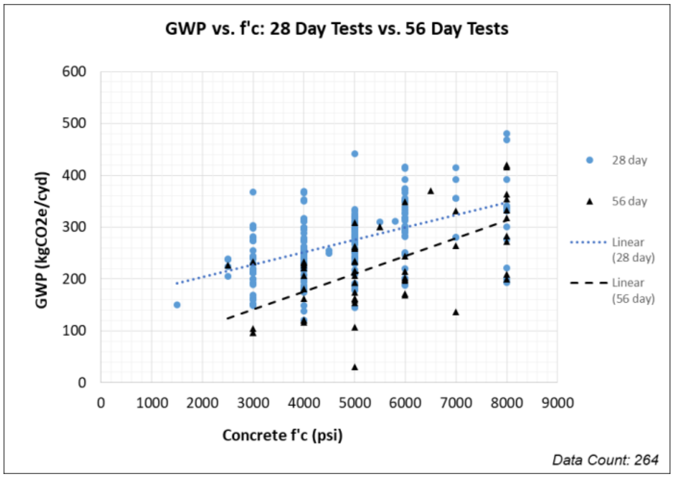

Figure 7

The city of Seattle also collects mix designs from local mix plants as part of a system for continuous approval of commonly used mixes. The SEAW SDC performed an LCA analysis on these concrete mixes, and the results are presented in Figure 8. Compared to the data from California, the GWP in the Seattle mixes is generally higher and has less variability. The reduced variability is due to the prescriptive requirements of these mixes. Higher GWP may be linked to these requirements as well.

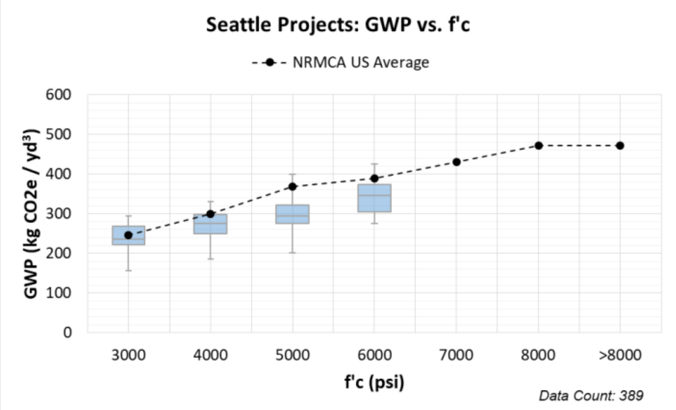

Figure 8

Additional Discussion

Cost Considerations for Low Carbon (Cement) Mixes

Concrete is the most widely used man-made material in the world. The production cost of concrete is the lowest of the main structural materials, when comparing its strength and durability relative to other structural materials (wood, steel, fiber composite, etc.). Given that the environmental impacts of cement are high, as shown in the results of this paper, and that cement is the most costly portion of a concrete mix design, the use of Supplemental Cementitious Material (SCM) has been increasing. The most common SCM used today includes fly ash, slag and silica fume.

Fly ash is produced as a byproduct of coal combustion in electric power generating plants and is currently the most widely used by-product in concrete. The ash fraction of coal varies (typically 5-15%) depending on coal type and source. The ash is collected as either bottom ash, fly ash, or boiler slag depending on the type of coal combustion technology used; approximately 80% of the ash produced in pulverized coal boilers, for example, leaves the furnace as fly ash, while cyclone and stoker-fired boilers will release only 10 to 30% of the ash as fly ash (Woodyard, 2004). Electrostatic precipitators typically are used to collect the fly ash that is available for use in concrete. The amount of fly ash that can be added to concrete varies depending on the application. While fly ash rates of 50% to 80% of the total cementitious materials have been reported, the typical range is 15% to 25%. Higher rates of addition depend on the type of fly ash and compatibility with other materials in the concrete, and therefore may not be widely applicable (Woodyard, 2004).

Blast furnace slag is a by-product of steel making, specifically the production of molten iron resulting in the fusion of limestone and other fluxes with the ash from coke and silica and aluminum from iron ore (see ACI 233, 1995). Processed granulated blast furnace slag is a glassy, granular material formed when the molten slag is immersed in water. This product is then ground and used as a mineral admixture (partial replacement for Portland cement) in concrete. Slag cement is used in concrete at rates of 20 to 80% of the total cementitious material depending on the application (Woodyard, 2004).

Silica fume is a byproduct of the reduction of high-quality quartz with coke or coal and wood chips in an electric arc furnace, during the production of silicon metal or ferrosilicon alloys (ACI 234, 1996). The fume, condensed from the exhaust gases, contains superfine spherical silicon dioxide particles, typically 100 times smaller than average cement particles. Silica fume is used in concrete at rates of 5 to 10% of the total cementitious material, and is used in applications where a high degree of impermeability is needed and in high-strength concrete (Woodyard, 2004). As silica fume is less commonly used in concrete mixes, the following discussion focuses on fly ash and slag SCMs.

Fly ash and slag can both be used to develop a concrete mix that reduces the cement content in concrete. However, each mix – slag or fly ash – needs to be developed specifically and individually to meet the project performance requirements. Similarly, from a construction perspective both mixes can be constructed with, but they behave somewhat differently. As such, if a contractor is used to working with a mix with fly ash, there needs to be a learning curve and bit of a working time to get used to the slag mix. The structural engineer is encouraged to have early discussions with the contractor to determine the finishing and availability impacts that work best for the local market to assure a cost effective design.

From a cost perspective, fly ash and slag are comparable. Fly ash, being a byproduct of the coal combustion industry, is predicted to have decreasing availability as energy producers recognize the market and regulatory forces driving to more renewable sources of energy production. As seen below in Figure 9, for the west coast of the US, facilities producing fly ash will reduce from 14 to 5 locations. The distance to transport the material is certainly a consideration when evaluating the type of SCM to use.

Figure 9

Additionally, fly ash availability tends to be lower during the early spring when coal power plant demand is low and plants are shut down for maintenance.

The amount of slag cement for a specific project depends on several factors including application, early and later age strength requirements, durability requirements and ambient temperature to name a few. Most general or structural concrete applications (flatwork, paving, foundations, walls, columns, floors, etc.) typically use between 25 and 50% slag cement. Optimum slag cement percentage for maximum strength development is generally between 40 and 50 percent. A specification based on concrete strength at 28-days may be able to use less total cementitious material (Portland + slag cement) than a similar plain Portland mixture if mixture strength is optimized. If durability parameters are specified (e.g. permeability, sulfate resistance, alkali-silica reaction (ASR) resistance) up to 70 percent slag cement may be required.

Slag cement improves many of the strength and durability properties of hardened concrete. Slag cement is a hydraulic binder that, like Portland cement, reacts with water to form cementitious material calcium-silicate hydrate (CSH). It also, similar to a pozzolan, consumes by-product calcium hydroxide from the hydration of Portland cement to form additional CSH. The resulting cement paste is stronger and denser, which creates concrete that has smaller pores and lower concrete permeability. As market demand for SCM continues to grow, and fly ash availability decreases, the cost of slag will likely come down.

Architectural Considerations

The use of SCMs has a minor impact on the finish color of the concrete. Fly ash and slag can vary in color and can have an effect on the finish color of the concrete. In the bay area, the fly ash used is generally dark in color while the slag is generally light. With these colors, ternary mixes (a mix of fly ash, slag, and cement) do not have a noticeably different hue than a full cement mix. Since the sources and colors of fly ash can vary, discussions with local suppliers and the project architect are recommended when specifying SCMs in exposed concrete.

Mix designs with high cement replacement have improved density over full cement mixes. This reduces water infiltration through the concrete and improves the durability of the concrete.

Construction Impacts

The addition of fly ash and slag into concrete mixes can be met with hesitation from contractors who are less familiar with the products. There was also a learning curve that ready-mix suppliers had to go through that lead to some slow strength gain and consistency issues during early adoption of SCMs.

This has changed. The major ready-mix suppliers in California are now accustomed to the use of SCMs and can get better performing mixes at 50% cement replacement than with full cement mixes.

In terms of the speed, the grade of slag available in the West has higher strength gain at 28 days than cement. Fly ash does react later than cement, but it also acts as a water reducer. The increased early strength of the lower water content mix can offset the delayed strength gain of the flyash. High quality aggregates, like those currently found in the Bay Area, are helpful in keeping water content low.

Both fly ash and slag (to a lesser extent) help to reduce the heat of hydration. This can provide benefits to construction, especially in large pours such as mat foundations.

Comparative GWP Analysis

To provide tangible numbers on the impact of using low carbon concrete mixes, the committee analyzed 3 real world projects of various sizes. The committee multiplied the volume of concrete used on each case study project by both the average GWP of the 4000 psi concrete mix designs collected with cement replacement, and without. See Figure 10 for the results. The 4000 psi compressive strength was chosen, as it served as a reasonable average of the various concrete strengths used on a project. The average cement replacement in 4000 psi mixes with cement replacement was 25%. The committee then compared the resulting reduction in GWP to the number of passenger vehicles driving on the road for one year using data from the Environmental Protection Agency's Greenhouse Gas Equivalencies Calculator (Greenhouse Gas, 2018). The goal of this comparison was to provide the results of using cement replacement in a recognizable format.

The committee found that for a typical San Francisco residence with a simple concrete mat foundation and short concrete retaining walls, using a concrete mix with cement replacement would save an amount of CO_2 equivalent to taking one car off the road for a year. In comparison, the committee found that for a high-end Hillsborough residence with a large portion of its structure constructed out of concrete, using a concrete mix with cement replacement would save an amount of CO_2 equivalent to taking 24 cars off the road for a year. For larger scale projects, the committee found the savings to be even more drastic. Using a concrete mix with cement replacement on an 8-story tower, would save an amount of CO_2e equivalent to taking 76 cars off the road for a year. Lastly, the committee found that for a large scale, multi family, multi block residential development using a concrete mix with cement replacement, would save an amount of CO_2e equivalent to taking 247 cars off the road for a year. See Figure 10 below.

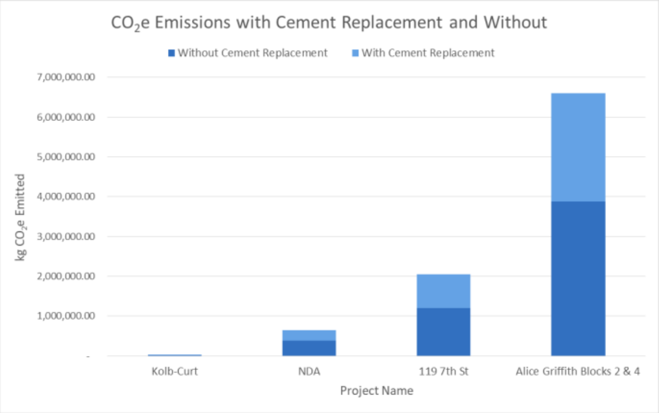

Figure 10

When looking at the impact cement replacement has on a project's embodied carbon, it is important to consider how many projects of that nature will be built. In the example of the small scale single family residence, taking one car off the road for a year might not seem like a significant reduction in emissions. However, it is worth considering the number of houses similar to that single family residence that would be built each year. If each house were to use concrete mixes with cement replacement, the impact would be very significant. Also, this comparison uses an "easy target" reduction - the average mix with cement replacement being specified within the data, with a 25% cement replacement. The lowest carbon mixes within the data, at 70% cement replacement, had emissions of 116 kg $CO_2e/y3$, a further 48% reduction from the "easy target" mix. Specifying mixes at this level of reduction would double the carbon savings reported above.

High early strength impact on GWP

High early strength, and/or modulus of elasticity (MOE) requirements for expediting construction schedule increases the amount of cement required to attain the early age strength specified. To meet the requirements of ACI 301 section 4.2.3,the concrete supplier must over design a mix to ensure the ultimate strength of the concrete at the specified age (i.e 28-days, 56-days, or other) is met. When a high early strength is required to expedite the construction schedule, the over design of the mix will be exponentially higher to meet the high early strength requirement, requiring a significant amount of more cement than required to meet the ultimate design strength.

For example, on a recent post-tensioned long span parking structure project in San Diego, decks/beams and columns both required a 5ksi 28-day strength concrete. The deck/beam mix required a 3ksi 3-day strength. The deck/beam mix required 7% more cement. A 3ksi 2-day strength mix required 22% more cement over its column mix counterpart, a significant increase. This is a delicate situation since an expedited construction means the sooner the structure is completed which can have significant cost implications.

The biggest challenge in high early strength mixes is the proportioning of the mix design. Having a small intermediate (pea-gravel) size aggregate in the mix as a third aggregate can cut down the cement and cement paste. A well graded optimized concrete mix will assist with reducing the cementitious material required to obtain strength. California with its slow setting type II/V cements may need to be on the higher side, but typically 50 to 70 lbs of cement can be cut out. That lowers both the cost and the CO_2 impact. A recent study in Canada and found that changing the gradation of aggregates reduced CO_2 by about 10% (Ahammed, 2017).

To balance the higher need for more cement in a high early strength mix, the structural engineer could specify the early strength, then set an ultimate strength requirement that is further out, say 56 days or more, to meet the ultimate strength requirements. One could also consider counting on the ultimate strength being much higher than needed intrinsically by specifying the early strength, and take advantage of that in the design to potentially reduce member sizes and reinforcement quantities.

What Can Be Done?

As a structural engineer for a project, you have a great opportunity to impact the sustainable performance of concrete because the code limits and prescribes the structural engineer to specify the concrete mix requirements. Having a better understanding of the constructability of an element can inform what concrete mix can be specified or required. A performance-based specification could be more suitable to allow the contractor to meet the requirements structurally and environmentally using the mix designs that work best for them. On the other hand, developing prescriptive specifications in coordination with a local industry partner can help ensure consistency of products in a low bid environment.

Recommended best practices are as follows:
For performance based specifications:

1) Control the embodied carbon in a mix by setting maximum limits on Portland cement or the life cycle GWP in a mix.
2) Specify the required ultimate concrete strength of the mix and any early strength requirements.
3) Specify a shrinkage limitation where needed.

For prescriptive specifications:

1) Specify cement replacement ratios using Supplemental Cementitious Materials such as slag and fly ash.
2) Choose an appropriate prescription for the total amount of water in the mix, with provisions for use of plasticizers or water reducers for meeting slump/workability. Mixes with less water meet higher strengths with less cement.
3) Specify a higher allowable water cement ratio to reduce unnecessary cement in the mix.
4) Provide a list of acceptable aggregates that are known to perform well.
5) Specify 56-day (or longer) strength. Concrete continues to gain strength well beyond 28 days, especially when including fly ash, which can slow strength gain. Specifying longer cure times can allow less over-design of the concrete mix by giving it more time to come up to strength.

Carbon Sequestration

While structural engineers can try to specify as much cement replacement as possible to lower cement content while supplies last, they should also consider other options for the future. Using carbon sequestration technologies, there are some companies pushing the boundaries of concrete replacement, and just like the gas-car to electric-car transition, it will likely take time and voluntary efforts from the industry at large. One example is Blue Planet who make carbonate rock out of sequestered carbon. The carbonate rocks are used in lieu of limestone, which is the primary source of cement. They also make coarse and fine CO_2-sequestered aggregates, which enable the option for CO_2-negative concrete mixes. While this has been used in a portion of the new terminal at San Francisco International Airport, the technology is mostly still in progress. (Blue Planet, 2019)

Another example of a carbon sequestration technology is CarbonCure. This technology uses liquid CO_2 from industrial emitters that is injected into the concrete mix in a process known as CO_2 mineralization where CO_2 is converted to a mineral and permanently captured. This process can be used in both ready mix concrete as well as in masonry. This method is currently in use and allows for approximately a 5% reduction in the amount of cement required in a mix. (CarbonCure, 2019)

Future Local Code Changes

In 2018, the County of Marin was granted funds from the Bay Area Air Quality Management District (BAAQMD)'s Climate Protection Grant Program to reduce embodied emissions in the built environment by creating model code for low embodied-carbon concrete to be included in local green building ordinances throughout the Bay Area. Through a robust regional stakeholder engagement process led by the Carbon Leadership Forum, the group, which also includes StopWaste (Alameda County), Bruce King, and Arup, has generated code language and sample specifications, and is working on an implementation toolkit for cities and their local building departments. The proposed cement and GWP limits are 10-30% lower than the NRMCA industry averages, with allowances for applications needing high early strength (e.g. prestress and retaining walls) or special workability requirements (e.g. shotcrete). The project proposal was supported by the City and County of San Francisco, County of Alameda, City of Berkeley, USGBC, and over 30 building industry companies and organizations that work in the Bay Area.

The committee plotted the proposed initial carbon limits against the Bay Area mix designs in Figure 11 below. It appears that 50% or more of the mix designs in the Bay Area would already meet the proposed low carbon concrete code limits. While the intent is to lower the cement and GWP limits over time, and reach zero by 2050, the mix data collected from this project was instrumental in showing achievability of the initial reduction targets. For more information on this project, including draft low carbon concrete specification language, go to: https://www.marincounty.org/depts/cd/divisions/sustainability/low-carbon-concrete-project (County of Marin, 2019)

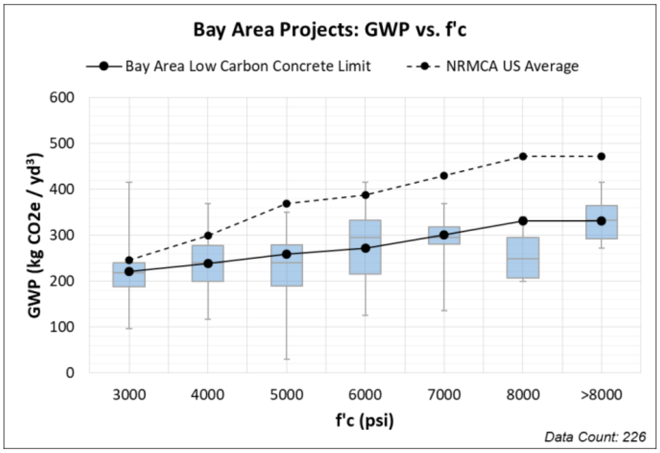

Figure 11

Other jurisdictions are also following suit. The City of Portland established a memorandum to require EPDs for concrete starting January 1, 2020; will establish GWP limits in April 2021; and will enforce those limits starting in January 2022 (City of Portland, 2019).

Conclusions

Mix design - including cement replacement ratios, concrete strength, water cement ratio, test age, aggregate type – has a direct impact on the Global Warming Potential of a mix. The data collected indicates that there is an opportunity to significantly reduce the carbon emissions of concrete used in California. Some of the mixes currently being used in the state have less than half of the GWP of the average mix used. Engineers play an important role in reducing these emissions by specifying and enforcing the use of low carbon mix designs. Specifications can be based on either performance criteria or prescriptive criteria.

The lowest carbon mixes include a mixture of slag, fly ash, and cement, with low water content and/or higher w/c ratio, 56 day or longer strengths, and minimal concrete overstrength. A prescriptive criteria would control these elements directly, while a performance criteria may specify the total GWP via an EPD, or the total cement within the mix. Either method is likely to be most successful when developed in coordination with local suppliers.

Limitations to the study include the low number of high strength, precast, and shotcrete mixes. Mixes from areas outside of the Bay Area were also limited. Further data collection in these areas would help the committee assist in efforts to set low carbon code limits outside the Bay Area, along with further recommendations on best practices for mix specification.

In addition to data collection on current practices, future studies by the committee could include case studies of emerging technologies and highly successful low carbon concrete projects. It is critical that we continue the conversation as well as continue to make concerted efforts to reduce embodied carbon from our structures through more thorough specifications and open dialogues with contractors and concrete suppliers.

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