STUDY OF LIMITS FOR CEMENT AND GWP OF CONCRETE

This is a summary of a study of both cement content and embodied carbon in concrete used in Northern California. The first section of the summary is intended to be included as an appendix to support the proposed code language. The second section documents the history and process of setting limits in this project in order to provide additional context.

In order to evaluate the cement and embodied carbon (referred to in this report as GWP) impacts for different concrete mix designs in use in Northern California, a wide set of data was analyzed. The set includes (1) data from the National Ready-Mix Concrete Association's (NRMCA) Life Cycle Assessment (LCA) report for the US[1] and Pacific South West (PSW), which includes California[2], (2) data from ClimateEarth, which include one major ready-mix producer in the Bay Area as well as producers in Seattle and Texas[3], and (3) data collected by structural engineers in the Structural Engineer's Association of Northern California (SEAONC)[4]. This analysis is summarized in the figures below.

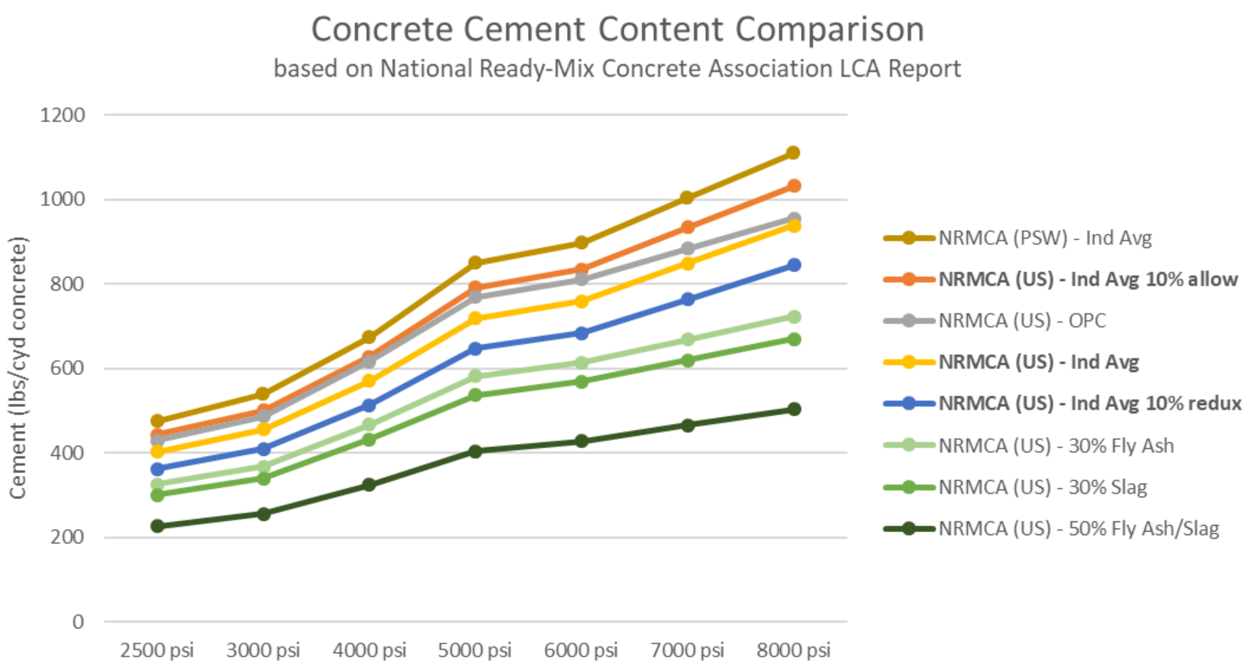

Figure 1: NRMCA cement use per strength mix design options

Figure 1 plots data from the NRMCA report and shows that the amount of cement required for different concrete mixes varies significantly based upon strength as well as the type of mix (most

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[1] https://www.nrmca.org/sustainability/EPDProgram/Downloads/EPD10080.pdf

[2] https://www.nrmca.org/sustainability/EPDProgram/Downloads/NRMCA_Benchmark_Report_-_October_14_2014_web.pdf

[3] https://www.nrmca.org/sustainability/EPDProgram/Downloads/EPD10080.pdf

[4] https://docs.google.com/forms/d/e/1FAIpQLSfKVqr8_DFliFwtcc2d086ZekvwJCv0MLRGUCtw-HQG8oQj8A/viewform

notably the addition of supplementary cementitious materials such as fly ash, from coal plants, or blast furnace slag, from steel mills, that reduce the amount of cement required). This chart presents pounds of cement per strength as building industry professionals are used to assessing these metrics. There is a strong correlation between the amount of cement used and the embodied carbon footprint (GWP) of concrete. See Figure 2 for the NRMCA data plotted by GWP.

The NRMCA data is created using aggregated information from across a broad region (includes all of California and other states as well as a range of supplier types etc.). Cement is a primary ingredient to concrete acting as the binder to lock together sand and rocks into finished concrete. Increasing cement tends to increase the concrete strength. The amount of cement required to achieve a specified strength also depends upon the quality and strength of the aggregate (rocks) and the time the concrete needs to be at the specified strength. The committee assessed that the aggregate available in Northern California is generally of higher quality than the average in the PSW which allows for lower cement in the standard mixes in Northern California compared to the NRMCA PSW regional average.

In order to better understand the composition of concrete mixes in use in the San Francisco Bay Area, a group of volunteer structural engineers in SEAONC began collecting information about concrete used in their jobs including the strength, application (e.g. for slabs or columns) and mix proportions. Over 400 mix designs were collected, primarily for projects within San Francisco. The min, max, and mean of these are reported in Figure 2.

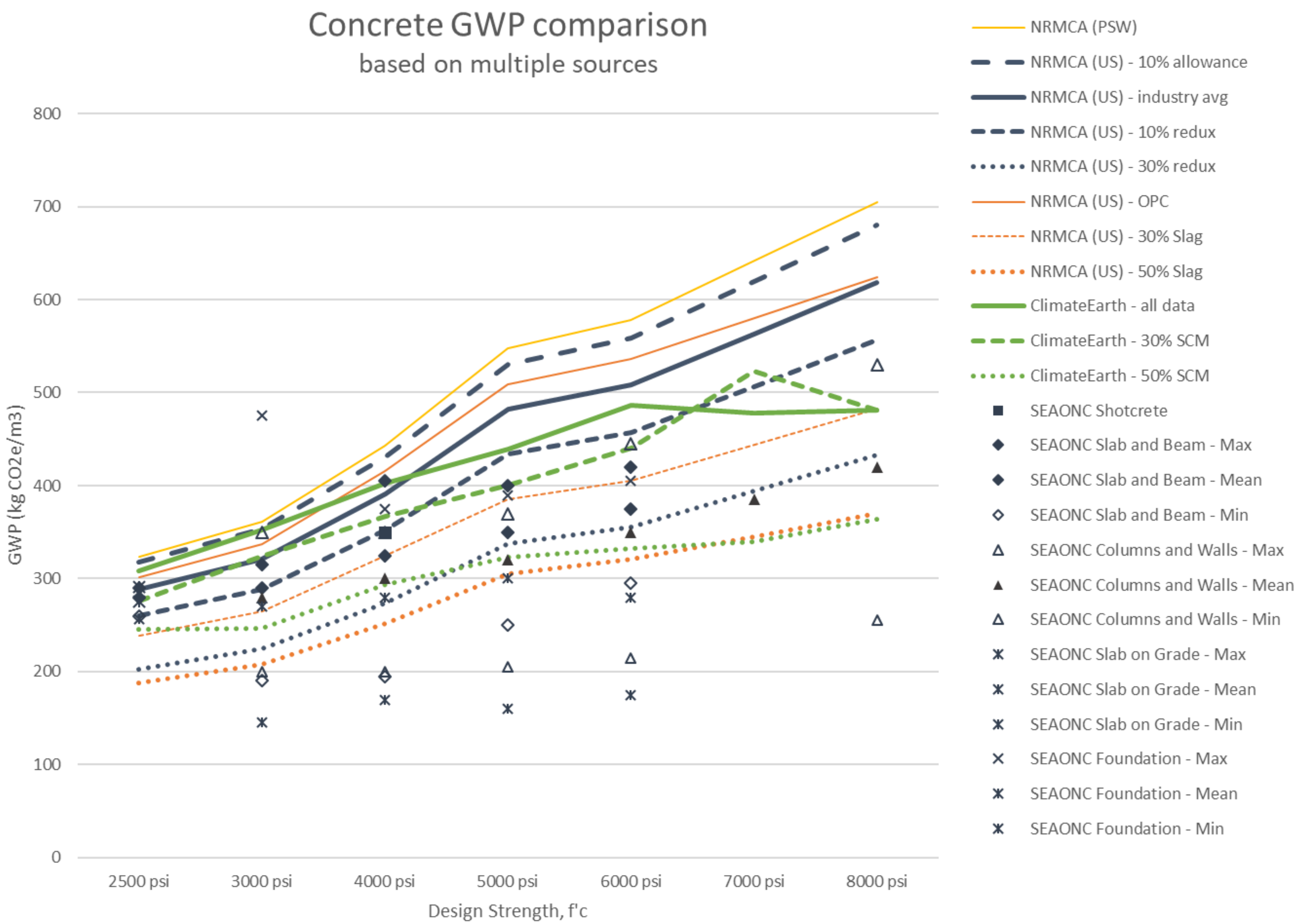

Figure 2 GWP of NRMCA industry average data and collected SEAONC mixes and Climate Earth data

As noted in Figure 2, the great majority of SEAONC mixes collected fall below the 10% reduction to the NRMCA benchmark number. For higher strength mixes, the majority fall below the 30% reduction based on the NRMCA benchmark.

Based upon this analysis and discussions among the committee regarding the typical use of low strength concretes (smaller jobs with potentially smaller ready mix suppliers and applications such as sidewalks that can have high early strength requirements for serviceability) as well as noting the 'kink' in the NRMCA data at 5,000 psi concrete, the limits currently proposed in the code draft are:

- for f'c $\leq$ 3,*000* psi, we use 90% of the NRMCA values;
- for f'c = 4000 psi we use 80% of NRMCA values, and;
- for $\geq$ 5000 psi we use 70% of NRMCA values.

Figure 3 shows the proposed limits in a bright blue solid line noted as 'Option 6'.

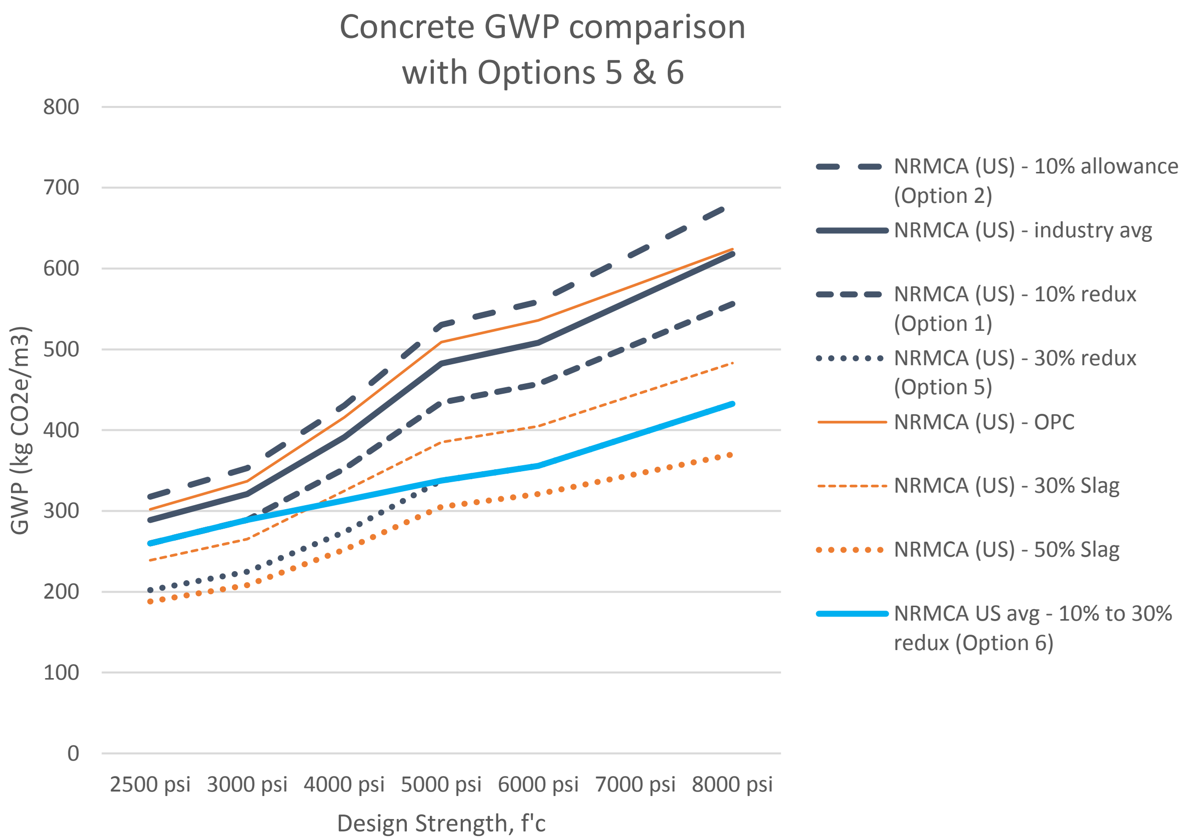

Figure 3: Limit target in June draft language (Option 6)

Note, that concretes needing early strength – precast, prestressed, beams and slabs above grade, and retaining walls requiring immediate backfill – have been allowed a 30% increase in these limits, based on review and deliberation between local suppliers and concrete industry materials experts within the stakeholder group.

Furthermore, lightweight concrete typically has a higher GWP aggregates in the San Francisco Bay Area likely due to two primary factors: the energy needed to produce and transport lightweight and additional cement that is required to bring lightweight aggregate concrete to strength. Lightweight concrete has other performance benefits and thus should have different limits. Thus alternate limits for lightweight concrete are appropriate. The suggested method of increasing limits for lightweight concrete is to permit a 25% increase in cement and a 100% increase for GWP.

PROJECT HISTORY & PROCESS

The limits proposed above were developed based upon an iterative process with consultation from the advisory committee. This section summarizes the history of this discussion and is provided to support the recommendations noted above. The tables below present different sets of options for how limits on maximum cement content (Path 1) and maximum global warming potential (Path 2) of the proposed "low carbon concrete building code" *(in separate document)*. Options 1-4 were generated before the stakeholder meeting on June 13th, 2019. Options 5 and 6 were added as an outcome of the meeting.

Option 1 applies a factor of 0.9 on the industry average cement content and GWP from the National Ready Mix Concrete Association (NRMCA), for Path 1 and Path 2, respectively. Option 2 applies a 1.1 factor instead, but this option was thrown out in the last stakeholder meeting. Option 3 applies a 0.9 factor on strengths at 5000psi and above only, so the values for strengths below 5000psi are the industry average numbers with no factor applied. Option 4 is similar to Option 3 except that different % SCM values have been selected from the NRMCA industry averages for different concrete applications. These values are shown relative to local concrete data collected from various sources on graphs below.

OPTION 1: 10% *reduction* from NRMCA US Industry Average

Minimum specified compressive strength f'c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	362	260
3000	410	289
4000	513	352
5000	647	434
6000	683	457
7000	764	507
8000 and above	844	556

OPTION 2: 10% allowance over NRMCA US Industry Average

Note: Option 2 was eliminated in 06/2019 stakeholder meeting

Minimum specified compressive strength f'_c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	442	318
3000	501	353
4000	627	431
5000	791	530
6000	835	559
7000	933	619
8000 and above	1032	680

OPTION 3: NRMCA US Industry Average *up to* 4000psi, then *10% redux* for 5000psi and above

Note: Option 3 was developed to smooth out the kink that occurs at 5000psi

Minimum specified compressive strength f'_c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	402	289
3000	455	321
4000	570	392
5000	647	434
6000	683	457
7000	764	507
8000 and above	844	556

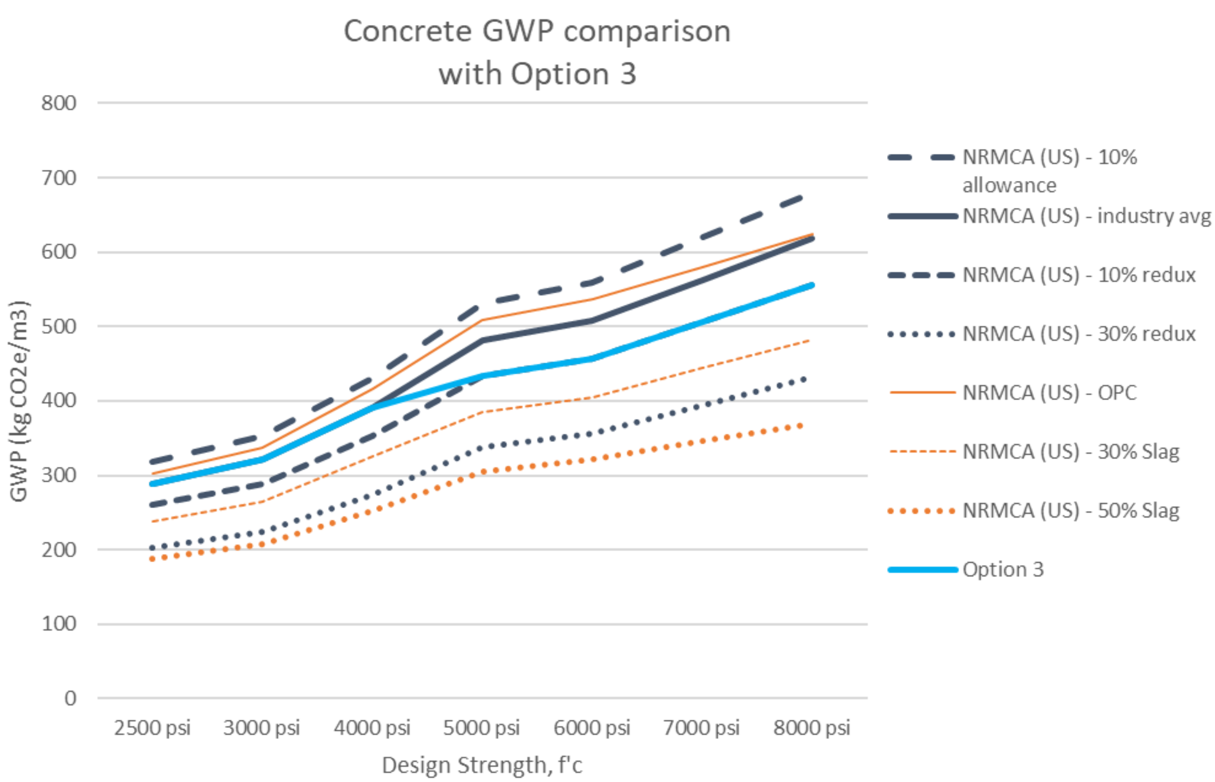

Figure 4: Concrete GWP comparison with Option 3

OPTION 4: Categorized by Strengths and Application

Note: Option 4 was deemed too complicated for the purposes of local government permitting and applicants

Foundation & Shear Walls (subset of Option 4)

Roughly based on NRMCA US Industry Average for 50% SCMs

Minimum specified compressive strength f'_c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	282	226
3000	319	250
4000	361	277
5000	404	305
6000	427	321
7000	465	346
8000 and above	503	370

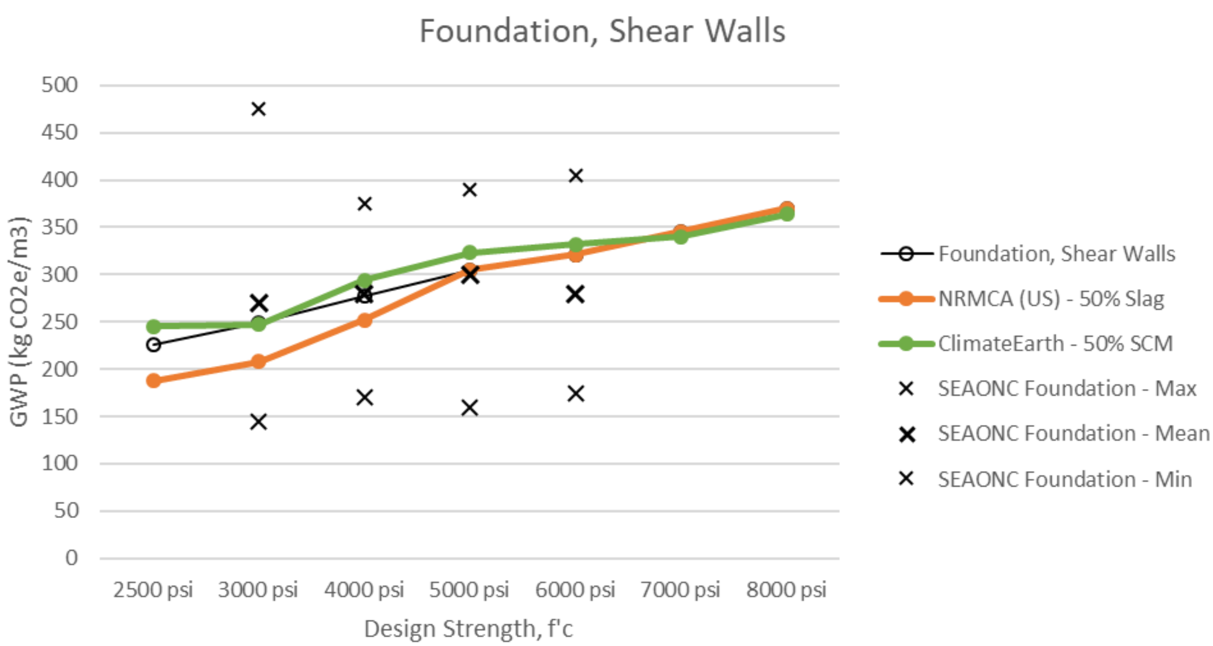

Figure 5: Concrete GWP comparison with Option 4; Foundations and Shear Walls

Columns & Walls (subset of Option 4)

Roughly based on NRMCA US Industry Average for 40% SCMs

Minimum specified compressive strength f'_c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	324	252
3000	364	278
4000	413	311
5000	461	343
6000	487	361
7000	530	390
8000 and above	573	418

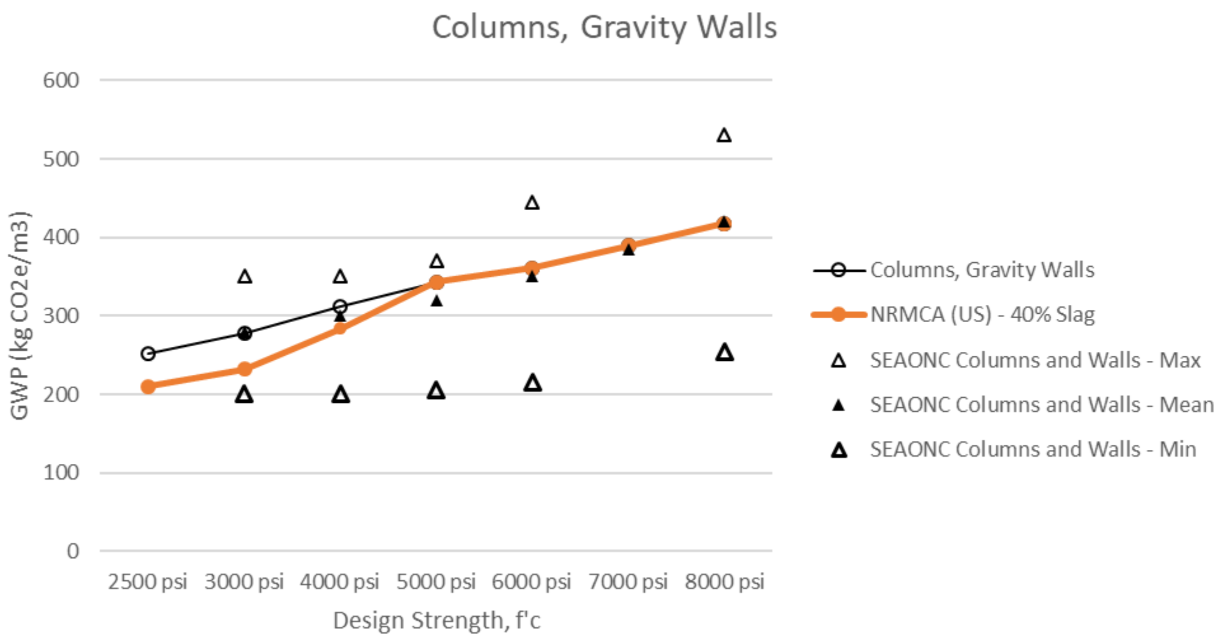

Figure 6: Concrete GWP comparison with Option 4; Columns and Walls

Suspended Beams & Slabs, Fill In Metal Deck (subset of Option 4)
Roughly based on NRMCA US Industry Average for 30% SCMs

Minimum specified compressive strength f'c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd[3]	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	372	318
3000	420	353
4000	479	392
5000	537	434
6000	568	457
7000	619	507
8000 and above	669	556

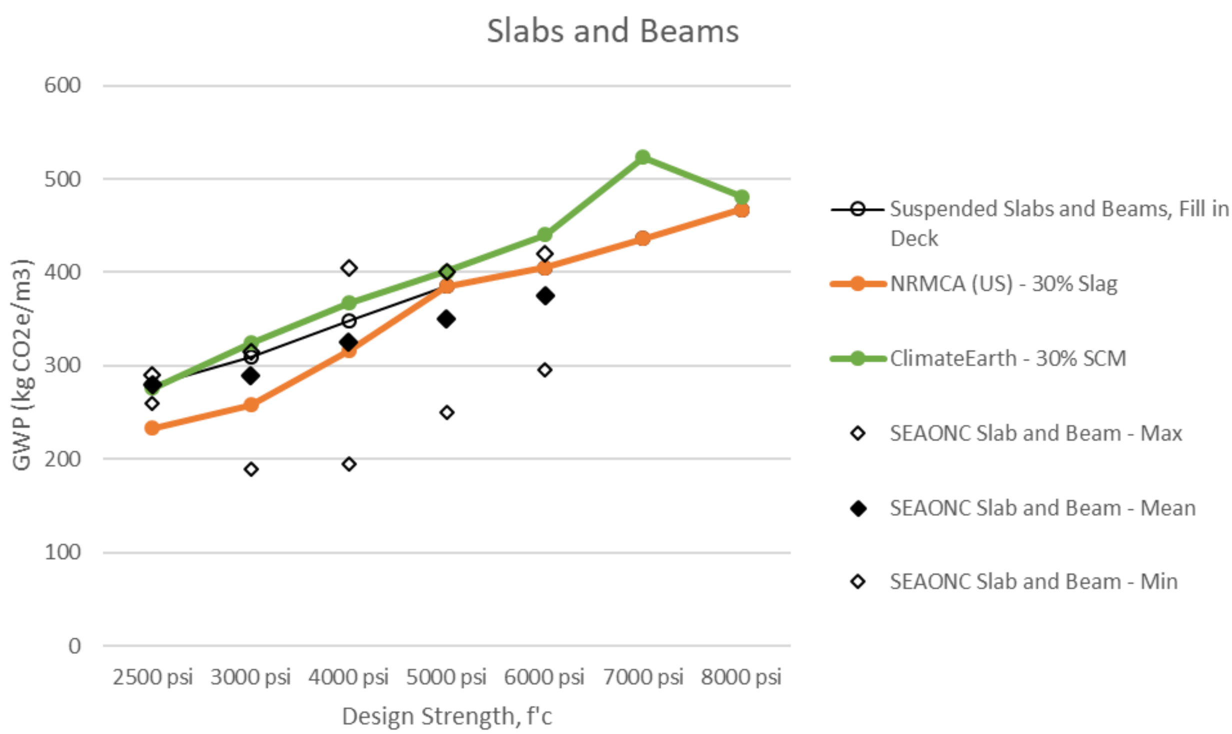

Figure 7: Concrete GWP comparison with Option 4; Suspended Beams and Slabs, Fill In Metal Deck

Other (subset of Option 4)

Roughly based on NRMCA US Industry Average

Minimum specified compressive strength f'_c (psi) at 28 days	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	432	318
3000	487	353
4000	570	392
5000	613	434
6000	649	457
7000	727	507
8000 and above	804	556

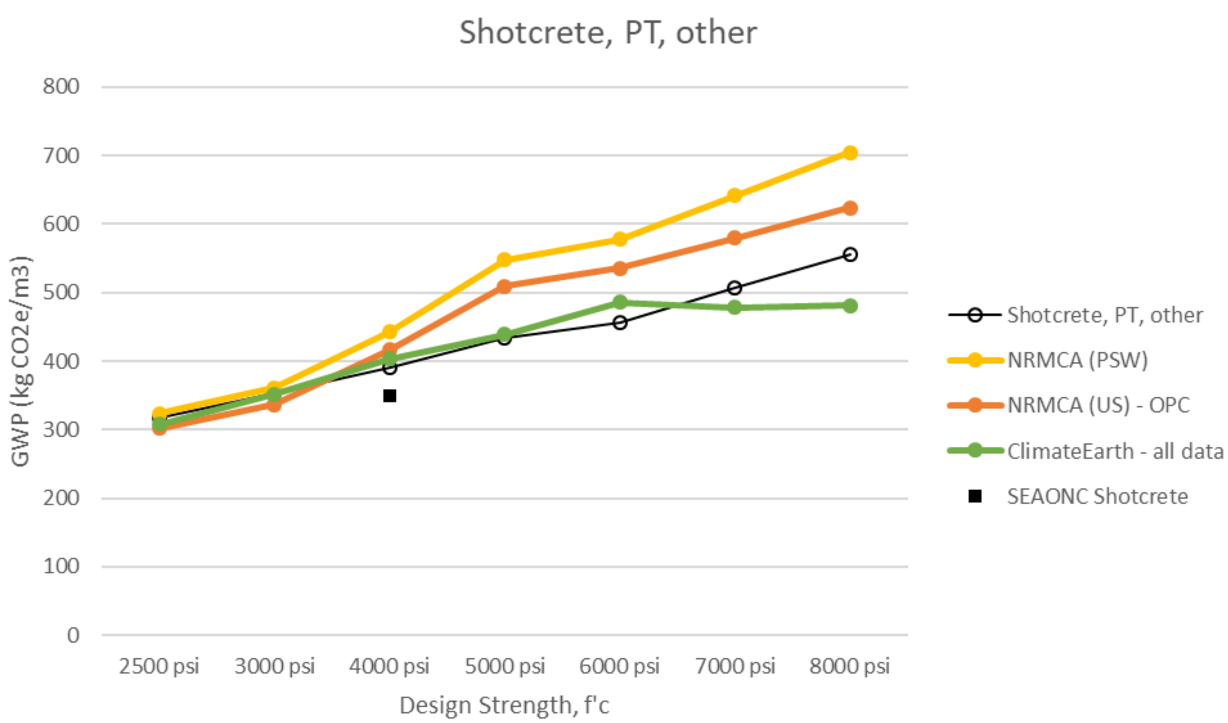

Figure 8: Concrete GWP comparison with Option 4; Other

OPTION 5: 30% *reduction* from NRMCA US Industry Average

Minimum specified compressive strength f'c (psi) at X days[1]	Maximum ordinary Portland cement content, lbs/yd[3]	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	281	202
3000	319	225
4000	399	274
5000	503	338
6000	531	356
7000	594	394
8000 and above	657	433
1. Engineer must specify X days, X = time to when the specified strength is actually needed		

OPTION 6: 10% reduction from NRMCA US Industry Average up to 3000psi, 30% reduction at 5000 psi and higher, interpolation between values at 4000psi

Note: This is the option selected by the stakeholder group and represented in the proposed code

Minimum specified compressive strength f'c (psi) at X days[1]	Maximum ordinary Portland cement content, lbs/yd[3]	Maximum Embodied Carbon, kg CO2e/m3
up to 2500	362	260
3000	410	289
4000	456	313
5000	503	338
6000	531	356
7000	594	394
8000 and above	657	433
1. Engineer must specify X days, X = time to when the specified strength is actually needed		

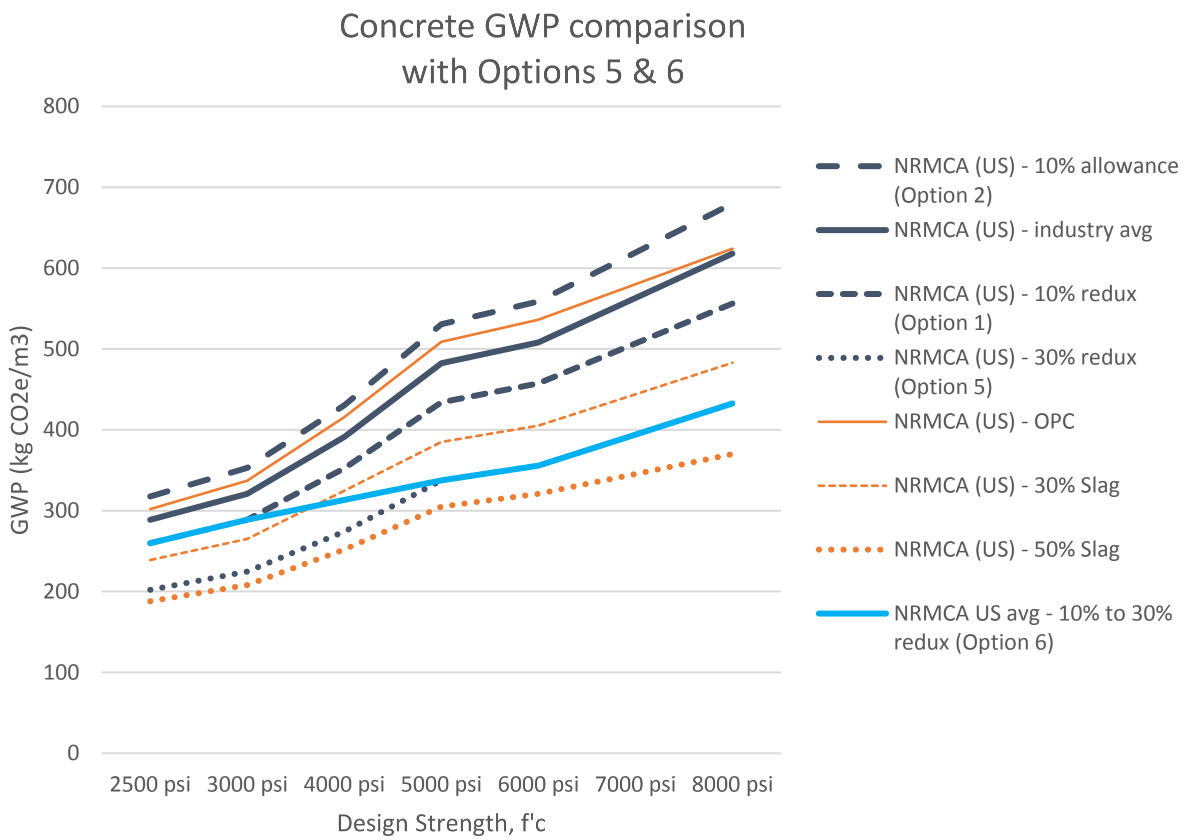

Figure 9: Concrete GWP comparison with Options 5 & 6

LIGHTWEIGHT CONCRETE

Local suppliers explain that a manufactured lightweight aggregate is more energy intensive to produce, and thus has relatively high embodied carbon. Therefore, lightweight concrete tends to have higher GWP values. A non-manufactured lightweight (such as pumice) tends to have lower strength, so higher cement contents are required and thus you still have higher GWP for those lightweight mixes. Sample mixes provided show the need to start the limits fairly high in comparison to the NRMCA industry averages for lightweight concrete.

Option 6: 25% increase in cement and 100% increase in GWP compared to NWC under Option 6

Note: This is the option selected by the stakeholder group and represented in the proposed code.

Minimum specified compressive strength f'_c (psi) at X days[1]	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Global Warming Potential, kg CO2e/m3
up to 3000	512	578
4000	571	626
5000 and above	629	675

Data provided locally also shows fairly little increase in cement and GWP as strength increases from 3000 psi to 5000 psi. This additional option decreases the percentage above industry average for each incremental increase in strength.

Option 7: 20% above NRMCA LWC US Industry Average up to 3000psi, 10% above for 4000psi, 0% above for 5000psi and greater

Minimum specified compressive strength f'_c (psi) at X days[1]	Maximum ordinary Portland cement content, lbs/yd^3	Maximum Global Warming Potential, kg CO2e/m3
up to 3000	552	595
4000	633	630
5000 and above	702	656

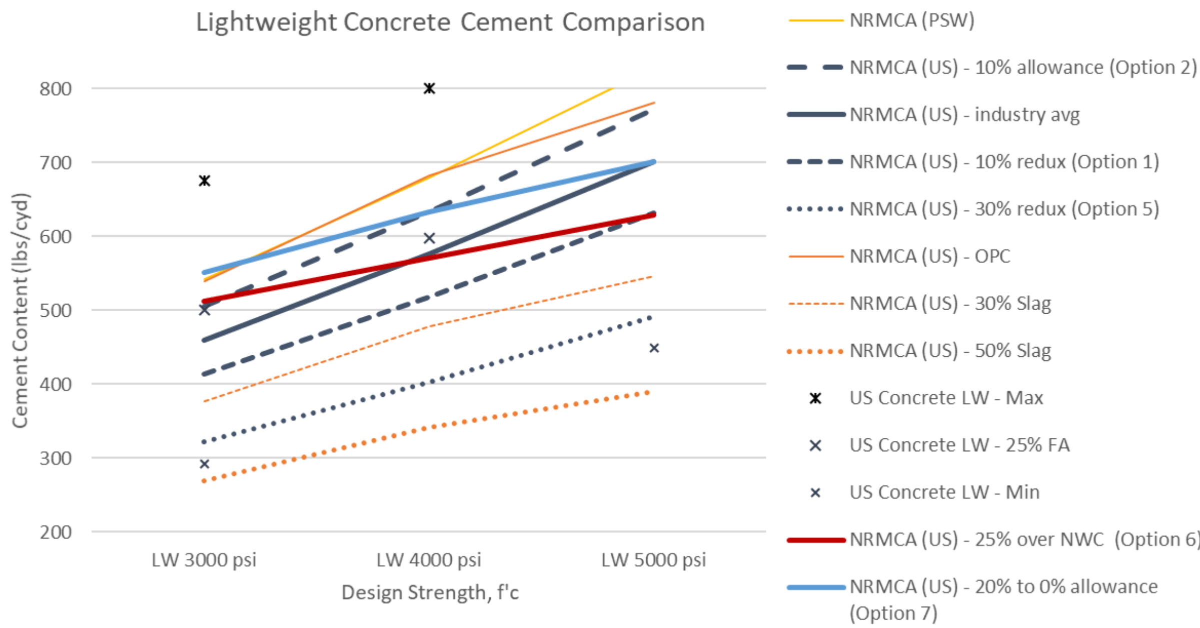

Figure 10: Lightweight Concrete Cement comparison with Options 6 & 7

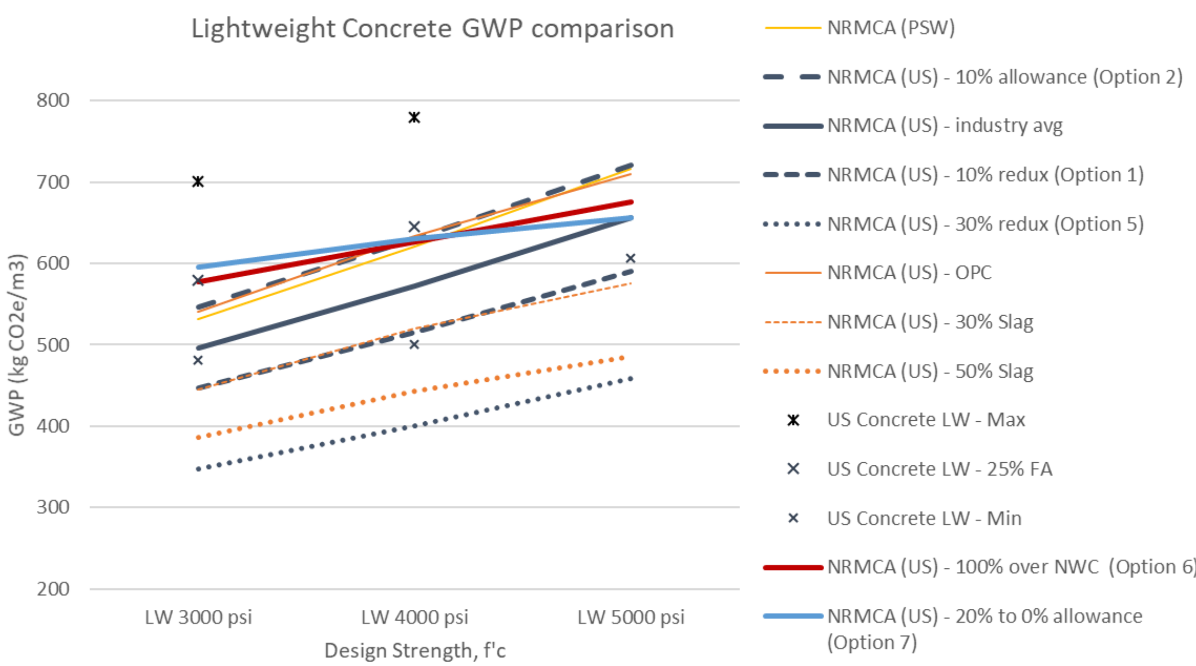

Figure 11: Lightweight Concrete GWP comparison with Options 6 & 7

EXPANDED DATA

Just before the last in-person stakeholder meeting on July 17, 2019, SEAONC provided the project team a new set of mix data from their second round of concrete mix collection by volunteer committee members and their colleagues. This set includes over 220 mixes from within the Bay Area and statistical analysis results are presented with the proposed limit line from Option 6, as well as the NRMCA Industry Average line, below. This additional data further supports that the proposed limits are both feasible and aggressive in averting excessive use of cement.

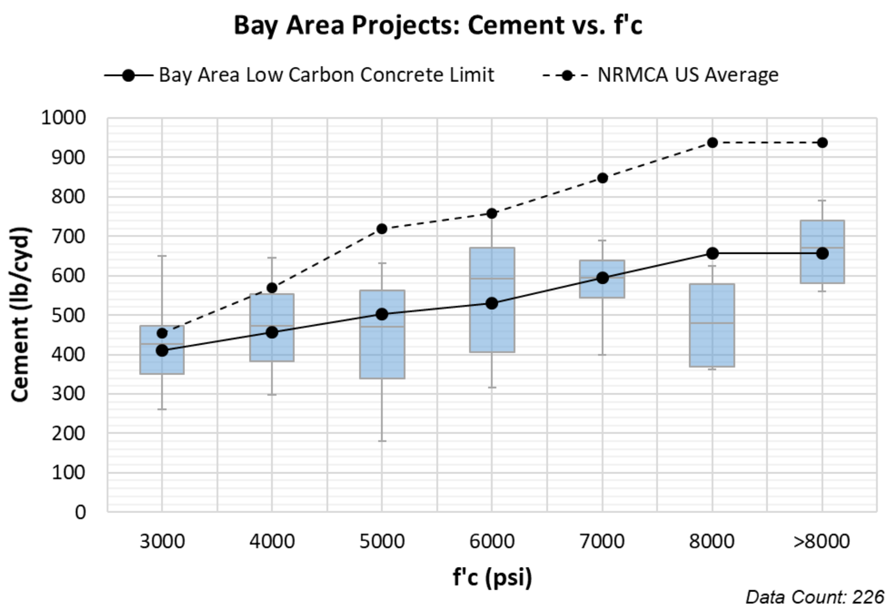

Figure 12: Bay Area Low Carbon Concrete Limit vs. NRMCA US Avg., Cement vs. f'c

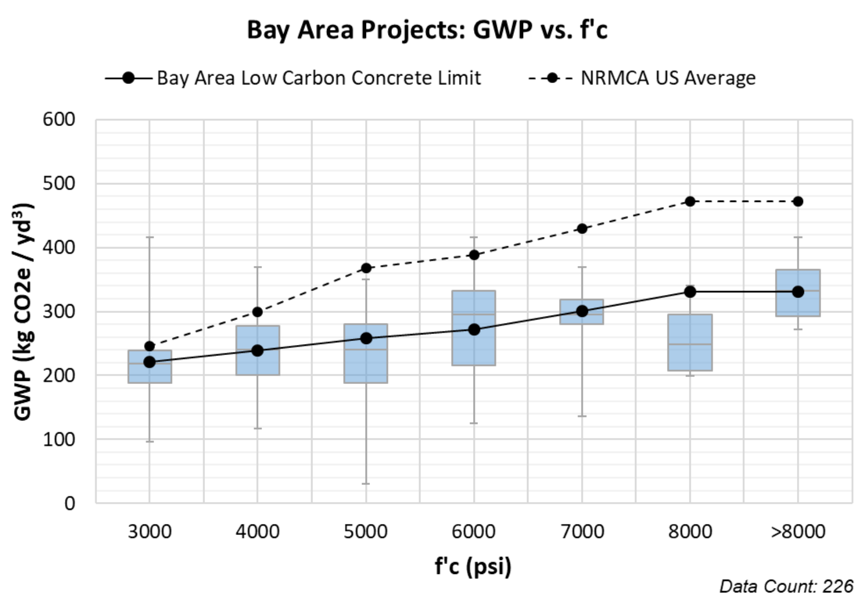

Figure 13: Bay Area Low Carbon Concrete Limit vs. NRMCA US Avg., GWP vs. f'c

Two additional charts below show the difference in data when the mixes are parsed into those with and without cement replacement, compared to the GWP limit line. The first of the two charts shows that mixes with cement replacement are numerous and can meet the limits easily, while the mixes without cement replacement comprise a smaller subset of the data and would have difficulty meeting the limits. Comparing these charts shows how introducing GWP limits will promote use of cement replacement and prevent continued use of mixes with excessive amounts of cement.

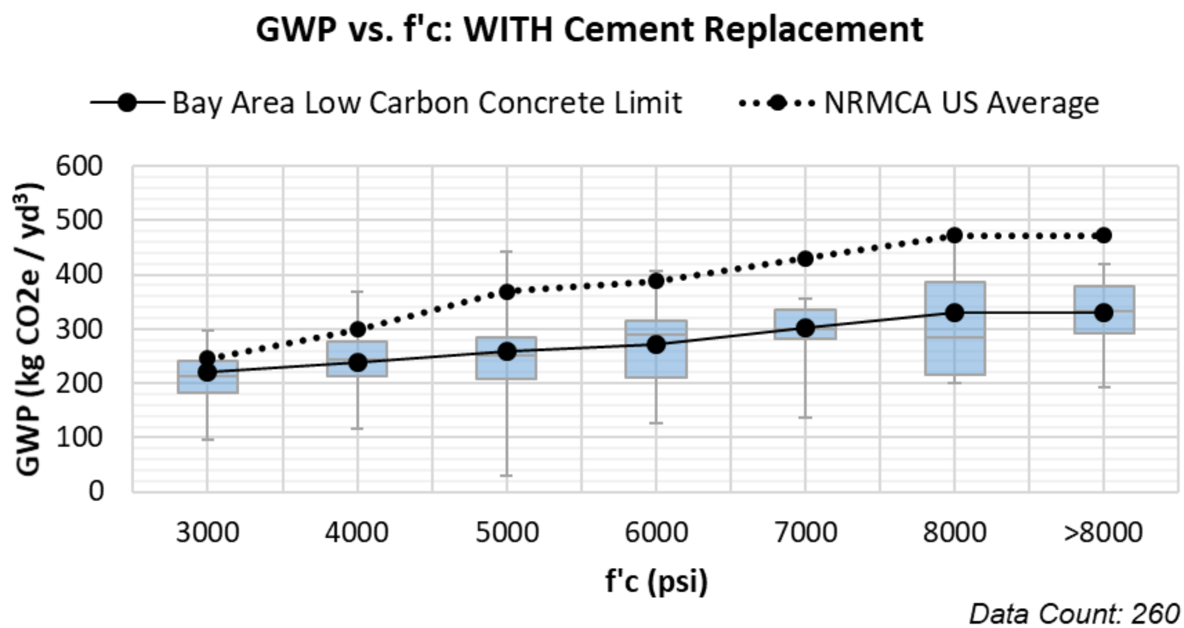

Figure 14: Bay Area Low Carbon Concrete Limit vs. NRMCA US Avg., GWP vs. f'c WITH Cement Replacement

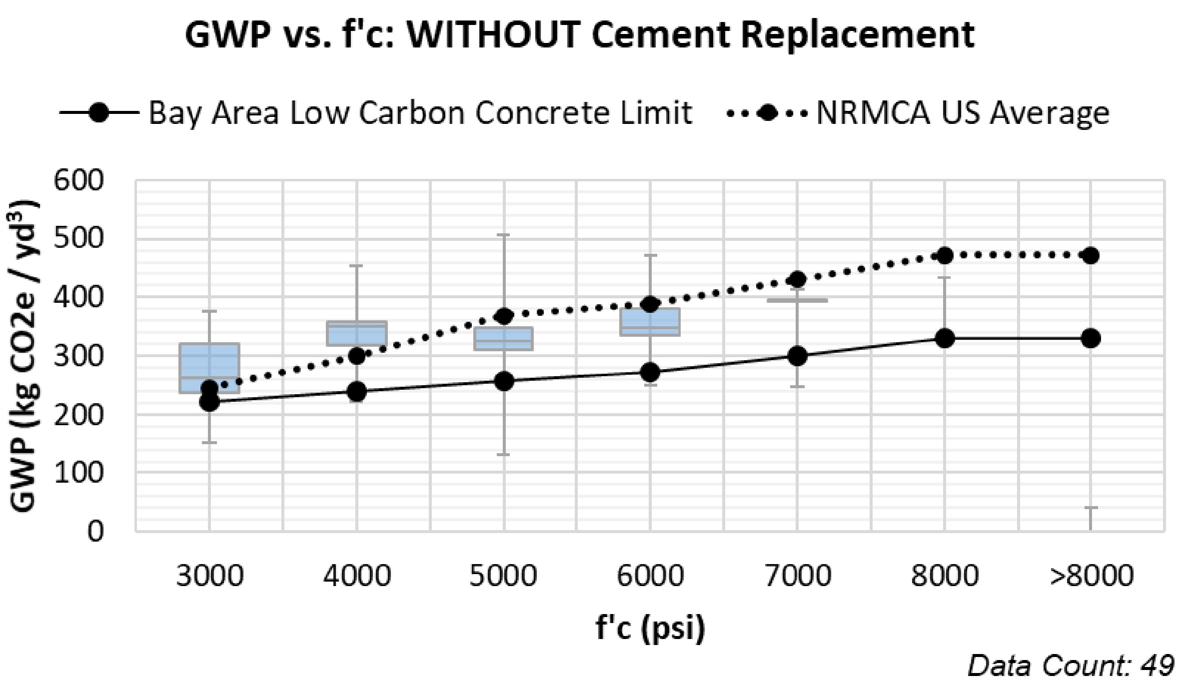

Figure 15: Bay Area Low Carbon Concrete Limit vs. NRMCA US Avg., GWP vs. f'c WITHOUT Cement Replacement