Smart Sustainable Concrete Construction

A framework for concrete contractor participation

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We agree with the statement from the American Institute of Architects (AIA) Carbon Leadership Forum (CLF) Part III of the Embodied Carbon Toolkit for Architects: "Concrete mix design has a huge impact on embodied carbon. Architects should collaborate with the structural engineer and contractor to ensure that reducing embodied carbon in concrete is a priority."[1] This article sets out the framework for concrete contractors' participation in smart sustainable concrete construction. The American Society of Concrete Contractors (ASCC) initiated a Sustainability Committee in 2022, and this article reflects input from that committee; however, the views expressed herein are those of the authors.

Participation in Accordance with AIA Guide

Concrete contractors' participation in sustainable concrete construction aligns with AIA's "Guide for Sustainable Projects."[2] This document provides design and construction practices intended for projects that offer sustainable benefits. Special definitions are used to facilitate the development of coordinated agreements for sustainable projects and provide a blueprint to achieve that goal. The following definitions will be embedded in the contractors' sustainability framework:

- **Sustainable objective**—The owner's goal of incorporating sustainable measures into the design, construction, maintenance, and operations of a project to benefit the environment, enhance the health and well-building of building occupants, and/or improve energy efficiency. The sustainability objective is identified in the sustainability plan;
- **Sustainable measure**—A specific design or construction element; post-occupancy use, operation, maintenance; or monitoring requirement that must be completed to achieve the sustainable objective. The owner, architect, and contractor shall have responsibility for the sustainable measure(s) allocated to each of them in the sustainability plan;
- **Sustainability plan**—A contract document that identifies and describes the sustainable objective; the targeted sustainable measures; implementation strategies selected to achieve the sustainable measures; the owner's, architect's, and contractor's roles and responsibilities associated with achieving the sustainable measures; the specific details about design reviews, testing, and/or metrics to verify achievement of each sustainable measure; and the sustainability documentation required for the project. The sustainability plan is developed by the owner and design team at the sustainability workshop. The concrete contractor and ready mixed concrete producer want to attend—and should be required to attend—the sustainability workshop. This workshop needs to take place early in the design phase; and
- **Sustainability documentation**—All documentation related to the sustainable objective or to a specific sustainable measure that the owner, architect, or contractor is required to prepare in accordance with the contract documents. Responsibility for preparation of specific portions of the sustainability documentation will be allocated among the owner, architect, and contractor in the sustainability plan. Periodic review of the documentation and plan goals should be undertaken to establish that the project goals will be met.

Framework for Communication

While planning is an important part of all concrete construction, it is vital for successful sustainable concrete construction. Sustainable concrete construction is based on specific structural elements, with design and construction requirements particular to each element on the project (for example, foundations, columns, walls, or slabs).

Sustainable concrete mixtures are developed for each specific concrete element based on the engineer's requirements, the contractor's needs, the owner's sustainability objectives, and the architect's sustainability plan. This carefully constructed communication flow establishes the framework for smart sustainable concrete construction.

The proposed element-by-element approach is consistent with AIA MasterSpec® 033000 Cast-in-Place Concrete specification[3] that requires specific concrete mixtures by element: A. Footings, B. Foundation walls, C. Slabs-on-ground (normalweight [NW]), D. Suspended slabs (NW), E. Suspended slabs (lightweight [LW]), F. Concrete toppings (NW), G. Building frame members, and H. Building walls.

Structural design requirements

ACI 318-19(22)[4] provides structural requirements for concrete elements such as slabs, beams, columns, walls, foundations, and other items. The Code requires the licensed design professional to specify design information and compliance requirements such as strength, durability, and construction requirements for each element in the contract documents.

The Code, Section 4.9—Sustainability, also permits the engineer to specify sustainability requirements in the construction documents, with the caveat that the strength, serviceability, and durability requirements take precedence over sustainability considerations.

To achieve the design requirements, contractors' means and methods are specifically tailored for each concrete element, and ready mixed concrete producers customize concrete mixtures for these elements. Thus, it is not surprising that sustainable concrete construction is best delivered by considering the requirements of each element separately, including the embodied carbon. This approach provides a total project embodied carbon level that allows for optimization of each element—maximizing the overall project quality and performance delivered to the owner.

The engineer's requirements are best communicated in a table organized by element and grouped into categories such as strength, durability, and compliance requirements. Table 1 provides an example of this communication. The table conveys the specifed compressive strength at a designated age (f_c'); durability requirements for freezing and thawing (F), sulfate exposure (S), contact with water (W), and corrosion protection of reinforcement (C); and finally, compliance requirements such as maximum water-cementitious materials ratio (*w*/*cm*), maximum nominal aggregate size, air content, maximum water-soluble chlorides, and limits on the amount of supplementary cementitious materials (SCMs). The table also proposes slump and slump flow requirements be jointly determined by the engineer and concrete contractor.

Construction recommendations

Project specifications set strength and durability requirements for each concrete mixture per element. But just as strength and durability parameters vary by element, so do the construction needs. Thus, the contractor provides constructability recommendations for each element such that the concrete mixture, designed to meet the project requirements, can be pumped, placed, finished, and cured. To facilitate this communication, the contractor should also develop a table to establish the construction needs for each element. This detailed communication is an important component of the framework for concrete contractor participation at the sustainability workshop.

Table 2 provides an example of a contractor's table with blank columns for adding other parameters as necessary. The recommendations in Table 2 can be used for initial planning, then, after detailed discussion between the contractor and design team, filled out to reflect the specific element-by-element constructability requirements for which the ready mixed producer can develop appropriate mixtures. The table uses three separate recommendations to describe typical element-by-element constructability recommendations for a project. Note that construction recommendations are not always numerical-based, which is why Table 2 uses three levels of importance: HI—high importance, MI—medium importance, and LI—low importance.

Table 1:
Engineer's requirements

Element	Specified compressive strength (f_c')				Freezing and thawing (F)				Sulfate (S)				In contact with water (W)			Corrosion protection of reinforce-ment (C)			Max	Nom. max. aggregate size, in.	Air content, %	Max. water-soluble chlorides	Limits on type or amount of SCMs	Slump or slump flow
	psi	Age, days: 28	56	90	F0	F1	F2	F3	S0	S1	S2	S3	W0	W1	W2	C0	C1	C2	*w/cm*					
Foundations																								Values selected in collaboration with concrete contractor
Footings	5000			X	X						X			X			X		0.45	3/4	6	0.30	NA	
Mats	7000			X	X							X		X			X		0.40	3/4	6	0.30	NA	
Basement walls	5000	X				X					X				X		X		0.45	3/4	6	0.30	NA	
Walls																								
Shear	8000		X		X				X				X			X			NA	3/4	0	NA	NA	
Architectural	5000	X			X				X				X			X			NA	3/4	0	NA	NA	
Other																								
Columns																								
Lower story	10,000		X		X				X				X			X			NA	3/4	0	NA	NA	
Upper story	7000	X			X				X				X			X			NA	3/4	0	NA	NA	
Slabs																								
Elevated (NW)	5000		X		X				X				X			X			NA	3/4	0	NA	NA	
Elevated (LW)	4000	X			X				X				X			X			NA	3/4	0	NA	NA	
Topping slabs	4500	X			X				X				X			X			NA	3/4	0	NA	NA	
Slabs-on-ground																								
Trowel finish	4500	X			X				X				X			X			NA	3/4	0	NA	NA	
i. Broom finish	5000	X						X		X				X				X	0.40	3/4	6	0.30	YES	
ii. Decorative finish	4500	X			X				X				X			X			NA	3/4	0	NA	NA	
iii. Polished finish	4500	X			X				X				X			X			NA	3/4	0	NA	NA	
iv. Other																								

Note: 100 psi = 0.7 MPa; 1 in. = 25 mm

Concrete producer's mixture selection

With both the engineering requirements and contractor recommendations, the concrete producer develops a specific mixture for each element that sets a carbon baseline for discussion. Table 3 is an example of communicating the proposed mixture designs element-by-element. The natural and crushed aggregate quantities must be provided separately as the global warming potential (GWP) is different; upstream processes for natural aggregate are quarry and sort, and for crushed aggregate, quarry, crush, and sort. Besides the proposed mixture design, the GWP is also provided for each mixture.

Employing sustainability workshop

This concise, directed communication, on an element-by-element basis provided by the engineer, contractor, and ready mixed concrete producer, should be discussed at the sustainability workshop to assist in establishing the sustainability objective, measure, and plan. Comparing the three tables can assist in eliminating conflicts or generating additional discussion. For example, Table 1 shows the specified compressive strength for NW concrete as 5000 psi (34 MPa) at 56 days for elevated slabs. Table 2 indicates that high early strength is of high importance for constructability of elevated slabs.

Owners typically want the cost and schedule benefit of form removal in 3 days that requires 75% of the specified compressive strength. For a specifed concrete strength at 56 days, it may take 5 to 7 days or longer to achieve 75%. While the 56-day specifed compressive strength will enable a lower cementitious content and thus, lower GWP, it will be offset by a cost and schedule increase. The owner and design team need to determine the optimum balance for these requirements.

Implementing Low-Carbon Concrete Requirements

While the proposed element-by-element approach is best suited for implementing low-carbon concrete requirements for an overall project, there are different methods for meeting low-carbon concrete requirements:

- Cement limit per mixture (Marin County,[5] New York[6]);
- Embodied carbon limit per mixture (Marin County,[5]

Table 2:
Contractor's recommendations

Element	Fresh concrete properties					Hardened concrete properties			Construction		
	Set time	Slump or slump flow	Air content	Bleed water	Add if needed	Early-age strength	Surface hardness	Add if needed	Pump	Place	Finish
A. Foundations											
1. Footings	LI	MI	LI	LI		LI			MI	MI	LI
2. Mats	LI	MI	LI	LI		LI			HI	MI	LI
3. Basement walls	LI	HI	LI	LI		LI			HI	HI	LI
B. Walls											
1. Shear	LI	HI	LI	LI		LI			HI	HI	LI
2. Architectural	LI	HI	MI	LI		MI			HI	HI	HI
3. Other											
C. Columns											
1. Lower story	LI	MI	LI	LI		LI			HI	HI	LI
2. Upper story	LI	MI	LI	LI		LI			HI	HI	LI
D. Slabs											
1. Elevated (NW)	HI	HI	HI	HI		HI			HI	MI	HI
2. Elevated (LW)	HI	HI	HI	HI		MI			HI	MI	HI
3. Topping slabs	HI	HI	HI	HI		MI			HI	MI	HI
4. Slabs-on-ground											
v. Trowel finish	HI	HI	HI	HI		MI			LI	MI	HI
vi. Broom finish	MI	MI	LI	MI		LI			LI	MI	MI
vii. Decorative finish	HI	HI	HI	HI		MI			LI	MI	HI
viii. Polished finish	HI	HI	HI	HI		MI	HI		LI	MI	HI
ix. Other											

Note: LI—low importance; MI—medium importance; HI—high importance

GSA,[7] NBI[8]);

- Cement limit per project (Marin County[5]); and
- Embodied carbon limit per project (Marin County,[5] NBI,[8] NRMCA[9]).

5000 psi foundation, parking lot, and elevated slab mixture

As an example, there are varying requirements for 5000 psi concrete based on the design intent and construction practices for a foundation, parking lot, and elevated slab. While the strength is the same, there can be different durability and construction needs for each element. For example, a 5000 psi mixture used in a foundation will have a strikeoff (screed) finish and later-age strength requirements (90 days). This foundation mixture will work well with high levels of SCMs, and thus will have a lower GWP. The parking lot will have a bullfloat and broom finish and possibly a 56-day strength requirement. The strength requirement could change based on when the parking lot needs to be opened for either construction or public traffic. The parking lot mixture will work well with

Table 3:
Ready mixed producer's selections

Mixture properties and ingredients	Foundations			Walls		Columns		Slabs						
	Footings	Mats	Basement walls	Shear	Architectural	Lower story	Upper story	Elevated (NW)	Elevated (LW)	Topping slabs	SOG*—trowel finish	SOG—broom finish	SOG—decorative finish	SOG—polished finish
Compressive strength, psi	**5000**	**7000**	**5000**	**8000**	**5000**	**10,000**	**7000**	**5000**	**4000**	**4500**	**4500**	**5000**	**4500**	**4500**
w/cm	0.45	0.39	0.45	0.39	0.45	0.36	0.39	0.45	0.53	0.48	0.48	0.48	0.48	0.48
Portland cement, lb/yd³	576	719	576	719	576	800	7000	576	475	526	526	526	526	526
Fly ash, lb	101	126	101	126	101	154	719	101	83	92	92	92	92	92
Slag cement, lb	28	35	28	35	28	41	126	28	23	26	26	26	26	26
Total cementitious content, lb	**705**	**880**	**705**	**880**	**705**	**995**	**880**	**705**	**581**	**644**	**644**	**644**	**644**	**644**
Mixing water, lb	315	341	315	341	315	352	341	315	308	310	310	310	310	310
Crushed coarse aggregate, lb	1029	1018	1029	1018	1029	1004	0.39	1029	0	1056	1056	1056	1056	1056
Natural coarse aggregate, lb	505	499	505	499	505	475	1018	505	0	518	518	518	518	518
Total coarse aggregate, lb	**1534**	**1517**	**1534**	**1517**	**1534**	**1479**	**1159**	**1534**	**0**	**1574**	**1574**	**1574**	**1574**	**1574**
Crushed fine aggregate, lb	154	152	154	152	154	154	499	154	149	158	158	158	158	158
Natural fine aggregate, lb	1171	1159	1171	1159	1171	1187	152	1171	1130	1202	1202	1202	1202	1202
Total fine aggregate, lb	1325	1311	1325	1311	1325	1341	1517	1325	2364	1360	1360	1360	1360	1360
Man. lightweight aggregate, lb	0	0	0	0	0	0	0	0	990	0	0	0	0	0
Total aggregate content, lb	2859	2828	2859	2828	2859	2820	2828	2859	2364	2934	2934	2934	2934	2934
Fine to total aggregate, %	46	46	46	46	46	48	46	46	100	46	46	46	46	46
Target air content, %	6	0	6	0	6	0	0	0	6	0	0	6	0	0
Air-entraining admixture, fl oz.	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Plasticizer/superplasticizer, fl oz.	7	3	7	3	7	5	1	7	7	7	7	7	7	7
Set accelerator, fl oz.	10	20	10	20	10	24	3	10	10	10	10	10	10	10
Total weight, lb/yd³	**3878**	**4049**	**3878**	**4049**	**3878**	**4167**	**4049**	**3878**	**2168**	**3888**	**3888**	**3888**	**3888**	**3888**
GWP, kg CO_2e/yd³	**405**	**525**	**405**	**575**	**405**	**675**	**525**	**405**	**650**	**342**	**342**	**405**	**342**	**342**

*SOG is slabs-on-ground

Note: 100 psi = 0.7 MPa; 1 lb/yd³ = 0.6 kg/m³; 1 lb = 0.45 kg; 1 fl oz. = 30 mL moderate levels of SCMs. The elevated slab mixture will have a trowel finish, will need high early strength for either form removal or stressing of post-tensioning strands, and will have the highest cementitious material content and GWP.

While the SCM contents and the GWP values for the foundation, parking lot, and elevated slab mixtures will differ, the important parameter is the weighted average GWP generated by the project's concrete, allowing the engineer, contractor, and ready mixed producer the flexibility to provide the quality and performance, by element, to the owner. The method for implementing low-carbon concrete needs to account for this and still deliver the overall sustainability objective as identified in the sustainability plan of the "embodied carbon budget" for concrete and the project with the understanding that the percentage of GWP reductions will be different across all different concrete elements.

Marin County

Compliance to the Title 19 Marin County Building Code, Chapter 19.07 – Carbon Concrete Requirements (refer to Table 4 and Textbox 1)[5] includes two pathways to reduce greenhouse gas (GHG) emissions by reducing cement levels or replacing lower carbon-emitting cementitious materials in concrete designs. Compliance options for this code include the cement limit method by mixture and project, and the embodied carbon method by mixture and project. The cement and embodied carbon limits, based on specified compressive strength, are shown in Table 4 and are the basis for the four compliance options. These requirements apply to all plain and reinforced concrete installed within the unincorporated areas of Marin County, CA, USA. Compliance is verified with a cradle-to-gate Environmental Product Declaration (EPD), and the statute provides exemptions to the provisions.

The Marin County Code[5] includes NW and LW concretes, high-early-strength concrete, and other approved cements, such as portland-limestone cement (PLC). The high-early-strength concrete allows for a 30% increase in cement or embodied carbon limits, when approved by the building official. The 30% represents a value determined by various stakeholders and is assumed to achieve the high early strength in 1 to 7 days. Recognizing the need of early strength for form removal, the Marin County Code specifically includes beams and slabs above grade as high-early-strength concrete.

The maximum cement contents may be increased proportionally above the tabulated values if the approved plant-specific EPD is lower than 1040 kg CO_2e/metric ton (2080 lb/ton). The 1040 kg CO_2e/metric ton represents the PCA 2016 industry-wide EPD[10] for cements specified in ASTM C150/C150M and C1157/C1157M. The 2021 PCA industry-wide EPD[11] for PLC (ASTM C595/C595M) lists the GWP as 846 kg CO_2e/metric ton. Thus, if using PLC, the cement limits in Table 4 may be increased by 23%.

New York

New York Senate Bill S542A[6] (January 6, 2021) required the Office of General Services (OGS) to establish requirements for lower carbon concrete. Type III cradle-to-gate EPDs are used to verify compliance. OGS provides cement limit contents (listed as follows) but also sets a minimum 30% inclusion of SCMs and encourages the use of blended aggregates for a reduction in percentage of paste. The cement content limits are:

Table 4:
Cement and embodied carbon limit pathways (Table 19.07.050 in Reference 5)

	Cement limits for use with any compliance method 19.07.050.2 through 19.07.050.5	Embodied carbon limits for use with any compliance method 19.07.050.2 through 19.07.050.5
Minimum specified compressive strength f_c', psi*	Maximum ordinary portland cement content, lb/yd³†	Maximum embodied carbon kg CO_2e/m³, per EPD
Up to 2500	362	260
3000	410	289
4000	456	313
5000	503	338
6000	531	356
7000	594	394
7001 and higher	657	433
Up to 3000 lightweight	512	578
4000 lightweight	571	626
5000 lightweight	629	675

*For concrete strengths between the stated values, use linear interpolation to determine cement and/or embodied carbon limits

†Portland cement of any type per ASTM C150/C150M

Note: 100 psi = 0.7 MPa; 1 lb/yd³ = 0.6 kg/m³; 1 kg/m³ = 1.7 lb/yd³

- Mixture designs are limited to a maximum portland cement content of 400 lb/yd^3 (237 kg/m^3):
  - This does not include sidewalks, slabs-on-ground, or any application that requires a final finish; and
- Mixture designs are limited to a maximum portland cement content of 300 lb/yd^3 (178 kg/m^3) for mass concrete and all concrete applications below grade and against earth, or below grade and confined concrete such as concrete fill within steel pipe piles:
  - The design may also limit the cement content to 300 lb/yd^3 for other applications, provided the performance requirements established by the design professional are met.

The new rule will take effect on January 1, 2025, and apply to all state agency contracts exceeding 1 million USD with more than 50 yd^3 (38 m^3) of concrete, or Department of Transportation contracts above 3 million USD with at least 200 yd^3 (153 m^3) of concrete.

General Services Administration

The General Services Administration (GSA) uses an embodied carbon limit per mixture approach requiring a product-specific cradle-to-gate Type III EPD to show compliance for all GSA projects that use at least 10 yd^3 (8 m^3) of concrete. GSA does allow a waiver request process if it is not feasible to meet the EPD requirement or GWP limits. In

Textbox 1: Per Marin County Code[5]

19.07.050.1 Allowable Increases

(1) *Cement and Embodied Carbon Limit Allowances*. Cement or Embodied Carbon limits shown in Table 19.07.050 can be increased by 30% for concretes demonstrated to the Building Official as requiring high early strength. Such concretes could include, but are not limited to, precast, prestressed concrete; beams and slabs above grade; and shotcrete.

(2) *Approved Cements*: The maximum cement content may be increased proportionally above the tabulated value when using an approved cement, or blended cement, demonstrated by approved EPD to have a plant-specific EPD lower than 1040 kg CO_2e/metric ton. The increase in allowable cement content would be (1040/plant = specific EPD%).

19.07.050.2 Cement Limit Method – Mixture

Cement content of a concrete mixture using this method shall not exceed the value shown in the Table 19.07.050. Use of this method is limited to concrete with specified compressive strength not exceeding 5000 psi.

19.07.050.3 Cement Limit Method – Project

Total cement content shall be based on total cement usage of all concrete mixture designs within the same project. Total cement content for a project shall not exceed the value calculated according to Eq. (19.07.050.3).

Eq. 19.07.050.3:

$Cem_{proj} < Cem_{allowed}$, where $Cem_{proj} = \Sigma Cem_n\, v_n$ and $Cem_{allowed} = \Sigma Cem_{lim}\, v_n$

and n is the total number of concrete mixtures for the project; Cem_n is the cement content for mixture n in kg/m^3 or lb/yd^3; Cem_{lim} is the maximum cement content for mixture n per Table 19.07.050 in kg/m^3 or lb/yd^3; and v_n is the volume of mixture n concrete to be placed in yd^3 or m^3.
Applicant can use yd^3 or m^3 for calculation but must keep same units throughout.

19.07.050.4 Embodied Carbon Method – Mixture

Embodied carbon of a concrete mixture, based on an approved Environmental Product Declaration (EPD), shall not exceed the value given in Table 19.07.050.

19.07.050.5 Embodied Carbon Method – Project

Total embodied carbon (EC_{proj}) of all concrete mixture designs within the same project shall not exceed the project limit ($EC_{allowed}$) determined using Table 19.07.050 and Equation 19.07.050.5.

Eq. 19.07.050.5:

$EC_{proj} < EC_{allowed}$, where $EC_{proj} = \Sigma EC_n\, v_n$ and $EC_{allowed} = \Sigma EC_{lim}\, v_n$

and n is the total number of concrete mixtures for the project; EC_n is the embodied carbon potential for mixture n per mixture EPD in kg/m^3; EC_{lim} is the embodied carbon potential limit for mixture n per Table 19.07.050 in kg/m^3; and v_n is the volume of concrete n mixture to be placed in yd^3 or m^3.
Applicant can use yd^3 or m^3 for calculation but must keep same units throughout.

September 2022, GSA[7] (Table 5) revised its GWP limits to reflect a 20% reduction in the limits proposed by the New Buildings Institute (NBI).[8] On average, the GSA GWP requirements for the standard concrete mixture are about the same as Marin County, while the GSA GWP requirements for the LW concrete mixture are about 20% lower.

New Buildings Institute

In the proposed IBC language (refer to Table 6 and Textbox 2), the NBI provides an embodied carbon limit per mixture and per project. The embodied carbon limits are based on specified compressive strength and are satisfied by submitting a product-specific cradle-to-gate Type III EPD.

Table 5:

GSA carbon limits.[7] These numbers reflect 20% reduction from GWP (CO_2e) limits in proposed code language in Reference 8

Maximum GWP limits for GSA low embodied carbon concrete, kg CO_2e/m^3			
f_c', psi	Normal-weight	High early strength	Lightweight
up to 2499	242	314	462
2500 to 3499	306	398	462
3500 to 4499	346	450	501
4500 to 5499	385	500	540
5500 to 6499	404	526	N/A
6500 and up	414	524	N/A

Note: 100 psi = 0.7 MPa; 1 kg/m^3 = 1.7 lb/yd^3

Table 6:

CO_2e limits in concrete mixture (Table 1903.5.1 in Reference 8)

Specified compressive strength f_c', psi	Maximum, kg/m^3	High early strength maximum, kg/m^3	Lightweight concrete maximum, kg/m^3
up to 2499	302	408	578
2500 to 3499	382	516	578
3500 to 4499	432	583	626
4500 to 5499	481	649	675
5500 to 6499	505	682	N/A
6500 and greater	518	680	N/A

Note: 100 psi = 0.7 MPa; 1 kg/m^3 = 1.7 lb/yd^3

Textbox 2: NBI Lifecycle GHG impacts in Building Codes[8]

(International Building Code, Chapter 19 Concrete, Section 1903 Specifications for Tests and Materials)

1903.5 Embodied CO_2e of concrete materials.

Concrete products used in the building project shall be in accordance with Sections 1903.5.1 or 1903.5.2.

Exceptions:

- Precast concrete;
- Masonry units complying with Section 2103.1.2; and
- Projects where no concrete suppliers with product-specific Environmental Product Declarations (EPDs) for concrete are located within 10 miles of the project site, where Type III industry-wide EPDs and an inventory of CO_2e values for all concrete mixtures are provided to the authority having jurisdiction (AHJ).

1903.5.1 CO_2e Limit Method – Mixture

The total CO_2e of the concrete mixtures used in the project shall not exceed the value given in Table 1903.5.1 based on the compressive strength of the concrete. CO_2e content shall be documented by a product-specific Type III Environmental Product Declaration (EPD) for each product. EPDs used for compliance with this section shall be certified as complying with the goal and scope for the cradle-to-gate requirements in accordance with ISO Standards 14025 and 21930 and be available in a publicly accessible database.

1903.5.2 CO_2e Limit Method – Project

Total CO_2e (CO_2e_{proj}) of all concrete placed at the building project shall not exceed the project limit ($CO_2e_{allowed}$) determined using Table 1903.5.1 and Eq. (1903.5.2.).

Eq. (1903.5.2):

$CO_2e_{proj} < CO_2e_{allowed}$, where $CO_2e_{proj} = \Sigma CO_2 Envn$ and $CO_2e_{allowed} = \Sigma CO_2e_{lim}\ v_n$

and n is the total number of concrete mixtures for the project; CO_2E_n is the GWP for mixture n per mixture EPD in kg/m^3; CO_2e_{lim} is the GWP limit for mixture n per Table 1903.5 in kg/m^3; and v_n is the volume of mixture n concrete to be placed.

The project carbon limits can use the element-by-element approach as it sums up the GWP for each mixture and compares that to a benchmark limit established by using the carbon limits per mixture.

NRMCA

GSA and NBI use carbon limits on a national basis, while the National Ready Mixed Concrete Association (NRMCA) calculates the average environmental impacts for eight different regions in the United States (Fig. 1).[9] These benchmarks (Table 7) represent the environmental impacts of products with varying strengths for different applications and exposure conditions, which can be used to compare these environmental impacts to those of concrete mixtures supplied for each project. NRMCA uses the Athena Impact Estimator for Buildings[12,13] to define a reference building with benchmark GWP in a chosen region to a proposed building(s) with GWP mixtures selected to be lower than the benchmark mixtures.

Fig. 1: NRMCA regions for the calculation of average environmental impacts of concrete production[9]

NRMCA[12] provides an example where the concrete mixtures in the proposed building(s) would result in a 36% reduction in GWP compared to the benchmark concrete mixtures in the same building. Considering they were overly optimistic with regard to the percentages of portland cement replacement, they recommend selecting a target 30% reduction in GWP from the refence building.

NRMCA proposes specification language based on their example:

"Supply concrete mixtures such that the total Global Warming Potential (GWP) of all concrete on the project is 30% or more below the GWP of a reference building using Benchmark mixes as established by NRMCA and available for download at www.nrmca.org. Submit a summary report of all the concrete mixtures, their quantities and their GWP to demonstrate that the total GWP of the building is 30% or more below the GWP of the reference building. Contractor may use the Athena Impact Estimator for Buildings software available at www.athenasmi.org or other similar software with the capability of calculating GWP of different mix designs."[12]

While NRMCA uses total CO_2e, we prefer a weighted average of CO_2e/yd^3. For their example, NRMCA sets the benchmark reference building at 6,220,000 CO_2e, proposing a 30% reduction to establish a target of 4,354,000 CO_2e.[12] The reference building has 16,884 yd^3 (12,909 m^3) of concrete. Thus, the weighted average for the reference building is 368 CO_2e/yd^3 (6,220,000/16,884) or 482 CO_2e/m^3 (6,220,000/12,909) and the target is 258 CO_2e/yd^3 (4,354,000/16,844) or 337 CO_2e/m^3 (4,354,000/12,909). We believe the weighted average provides a better understandable reference than the total CO_2e and prefer its use. The 2022 California Green Building Standards[14] also use a weighted average approach.

Existing and proposed embodied carbon policy

The CLF[15] provides an interactive map with links to information regarding 115 city/county, state, and national

Table 7:
NRMCA regional carbon limits for benchmark mixtures[9]

	NRMCA carbon limits, kg CO_2 e/m^3								
f_c' at 28 days, psi	Eastern	Great Lakes	North Central	Pacific Northwest	Pacific Southwest	Rocky Mountain	South Central	South Eastern	National average
2500	240	232	241	235	257	232	226	247	240
3000	264	255	264	261	279	255	245	268	262
4000	314	303	312	316	323	301	286	309	308
5000	378	363	372	386	378	358	336	360	365
6000	399	383	394	408	401	379	356	382	385
8000	472	452	460	487	456	440	409	435	446
3000 LW	517	499	487	518	500	484	468	478	492
4000 LW	573	551	537	575	546	532	510	521	540
5000 LW	628	603	591	632	594	580	555	562	588

Note: 100 psi = 0.7 MPa; 1 kg/m^3 = 1.7 lb/yd^3

policy/programs within North America.

Environmental Communication—PCR, LCA, and EPD

Figure 2 illustrates the sequence in developing an EPD. Product Category Rules (PCRs) define parameters for a Life Cycle Analysis (LCA), used to generate an EPD.

PCRs define how data is collected for a specific type of product. PCRs may include the boundary conditions, data used, and system inputs. When these parameters are followed, it allows reviewers to achieve consistent results, which then allows different products to be compared.

An LCA is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a product throughout its life cycle (ISO 14040[16]).

An EPD provides standardized reporting of the GWP of concrete and other construction materials. GWP is the potential climate change impact of a product measured by LCAs reported in units, typically kilograms, of CO_2e also marked as CO_2e, CO_2eq, or CO_2-e. Note that EPDs for concrete can be based on yd^3 or m^3.

Types of product claims

International Standards Organization (ISO) standards identify three types of environmental claims for products:

- Type I claims are third-party verified labels based on criteria set by a third party and governed by ISO 14024[17];
- Type II claims are self-declarations made by manufacturers or retailers and governed by ISO 14021.[18] Type II claims are not third-party verified; and
- Type III claims contain quantified product information based on life-cycle impacts and are governed by ISO 14025.[19] Type III claims must be third-party verified.

PCR

PCRs provide guidelines for calculating industry-average and product-specific EPDs for each product type. For example, the PCR for concrete defines product-specific EPDs as one “for a specific product or group of concrete mix designs categorized by performance developed by a manufacturer for a specific ready mix plant location” and an industry-average EPD as one “for a specific product or group of concrete mix designs categorized by performance for a specified region.”[20]

Fig. 2: The sequence of processing an EPD. Product category rules (PCRs) define parameters for a life-cycle analysis (LCA) used to generate an EPD *(courtesy of Long Trail Sustainability website)*

EPD categories

EPDs vary in their level of product, supply chain, and regional specificity. The following categories of EPDs are used by purchasers to identify which level of specificity is required to comply with an EPD requirement:

- Industry-wide EPDs represent typical manufacturing impacts for a range of products or for a group of manufacturers. Industry-wide EPDs provide the least-specific data on a product’s embodied carbon footprint and cannot be used to compare products, but they are used in understanding the typical impact of a product. Industry-wide EPDs are available for portland cement, reinforcing steel, and concrete;
- Product-specific EPDs represent the impacts for a specific product and manufacturer across multiple facilities;
- Supply chain-specific EPDs—A product-specific EPD that uses supply chain-specific data in the LCA to model the impacts of key processes upstream in a product’s supply chain; and
- Facility-specific EPDs—A product-specific EPD in which the environmental impacts can be attributed to a single manufacturer and manufacturing facility.

CLF identifies the type of EPD required for different existing and proposed legislation.[21]

Batch-specific EPD

There are discussions about requiring “as-batch product specific EPD.” The argument is that the product-specific EPDs do not account for batching tolerances. ASTM C94/C94M[22] provides batching tolerances of ±1% for cement and SCMs, ±2% for aggregates, ±1% for mixture water, and ±3% for admixtures. Some ready mixed concrete producers indicate that they can produce an EPD for each batch. The documentation then changes from one product-specific EPD to an as-batched product-specific EPD, turning 2000 yd^3 (1530 m^3) of one mixture from one EPD into 200 EPDs (assuming 10 yd^3 truckloads). This is a dramatic change in documentation, and, as will be explained, one that concrete contractors do not believe is warranted.

EPD variability

The PCR for concrete requires a statement regarding data quality and variability in the EPD.[23] Options include one of the following:

A. This Product Carbon Footprint/GHG Inventory was created using industry average data for upstream materials. Variation can result from differences in supplier locations, manufacturing processes, manufacturing efficiency, and fuel type used. Climate change impacts could range between XXCO_2e and YYCO_2e per m^3 (insert actual range predicted); or

B. This Product Carbon Footprint/GHG Inventory was created using plant-specific data for upstream materials. Potential variations due to supplier locations, manufacturing processes and efficiencies, and fuel use are thus accounted for in this inventory.

Building Transparency provides information on the variability of EPDs using its EC3 model.[24] EPDs typically declare a single, deterministic value as a given product's impact. There can, however, be a high degree of uncertainty in the LCA. Conducting an uncertainty analysis requires analyzing a base LCA model for concrete.

DeRousseau et al.[25] conducted a probability-based cradle-to-gate LCA model representing process-related variability in the embodied carbon of concrete. Their paper lists life-cycle inventory data sources and probability distribution parameters. It also includes box plots to illustrate the range of life-cycle inputs for a concrete mixture (Fig. 3) and the distribution of embodied carbon for 10 concrete mixtures ranging from 3000 to 8000 psi (21 to 55 MPa) (Fig. 4).

The range in embodied carbon per unit of concrete (kg CO_2e/m^3) for the lower strength concretes is about 200, and for higher-strength concretes approaches almost 400. If we consider the interquartile range (IQR), it's about 40 for lower-strength concretes and about 60 for higher-strength concretes. Estimates for the standard deviation are three-quarters of the IQR, or about 30 for the lower strength and about 60 for the higher strengths. With this type of variability, requiring as-batched EPDs for concrete, where a 1% cement change affects the GWP by 4, isn't necessary. Also, this variability should be used as a guide to consider the precision required when making decisions about low-carbon concrete.

Concrete and reinforcement EPDs

In April 2021, NBI collected over 36,000 EPDs for concrete.[8] Some of that data is shown in Table 8 and represents six strength mixtures found in 23 states. California, New Jersey, New York, and Washington have the greatest number of ready mixed concrete EPDs. With 4000 and 5000 psi (28 and 34 MPa) being the most common concrete mixtures, this table reflects the trend with the majority of the EPDs in the 3500 and 4500 psi (24 and 31 MPa) strength classes. In August 2023, NBI reported that there are over 70,000 concrete EPDs.[26] But concrete contractor experience with EPDs varies. For example, in 2023, Baker Concrete was being supplied with concrete from 21 different ready mixed plants in Ohio.[27] Only three of the 21 plants could supply EPDs.

While we have focused primarily on EPDs for concrete, there are many other products in concrete that must be considered:

- Reinforcing steel—CRSI industry-wide EPD reporting a cradle-to-gate GWP of 854 kg CO_2e/metric ton[28];
- Post-tensioning cables—Suncoast Post-Tension product specific EPD reporting a cradle-to-gate GWP of 1430 kg CO_2e/metric ton[29];
- Studrails—JORDAHL GmbH product-specific EPD reporting a cradle-to-gate GWP of 296 kg CO_2e/metric ton[30]; and
- Fibers—Euclid Chemical product-specific EPD for fiber reinforcement products reporting a cradle-to-gate GWP of 2.8 kg CO_2e/kg of fiber.[31]

Sustainability Workshop Recommendations

The agenda for the sustainability workshop that needs to occur during the design phase and include the concrete contractor must comprise items described in the following paragraphs.

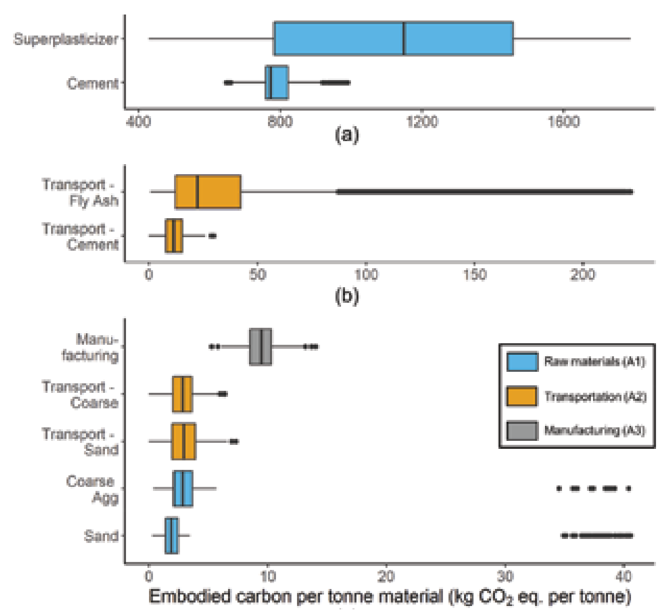

Fig. 3: Embodied carbon of life cycle inputs on a per metric ton basis categorized by (a) high; (b) medium; and low impacts (from Reference 25) (Note: 1 kg/tonne = 2 lb/ton)

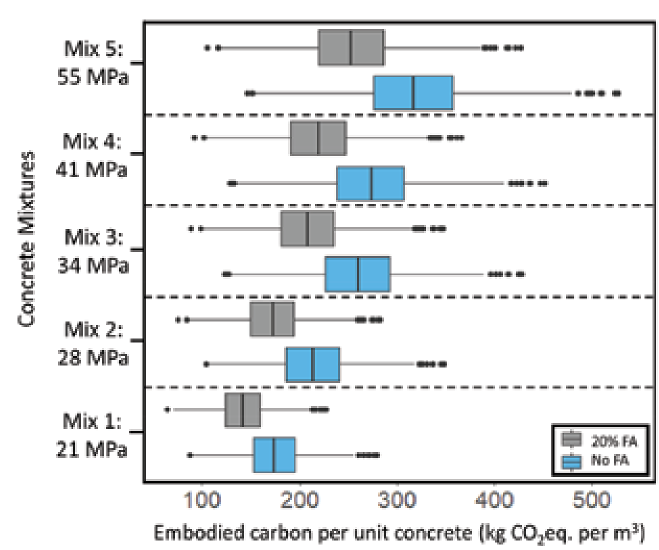

Fig. 4: Distribution of embodied carbon for 10 concrete mixtures (from Reference 25) (Note: 1 MPa = 145 psi; 1 kg/m³ = 1.7 lb/yd³)

Table 8:
EPDs per state and by strength

State	2499 psi	2500 psi	3500 psi	4500 psi	5500 psi	6500+ psi
AL	1	6	5	4	0	0
CA	569	4237	6012	5427	2041	785
CO	2	30	113	214	28	36
DC	1	4	4	3	3	4
FL	3	11	67	16	14	9
GA	8	115	135	75	22	11
IA	2	10	55	21	0	0
IL	0	6	70	52	32	15
MA	0	0	15	12	5	2
MD	5	25	20	15	16	20
NC	1	92	107	71	4	6
NE	0	16	63	25	0	0
NJ	60	883	1515	1014	204	16
NM	4	23	24	3	2	0
NV	2	1	0	5	1	1
NY	11	132	303	164	36	1
OH	10	26	19	12	0	0
OK	1	2	12	12	3	0
OR	24	299	529	197	42	4
SC	0	39	31	13	1	0
TX	0	26	16	29	6	0
VA	1	6	4	3	3	4
WA	42	164	451	412	250	87
	747	6,153	9,570	7,799	2,713	1,001

Note: 100 psi = 0.7 MPa

Exclusion and limitations

Although GSA applies its low-carbon concrete requirements to any project with at least 10 yd^3 of concrete, there might be a more practical limit, such as 500 yd^3 (380 m^3). The exclusion could also be based on gross floor area such as 5000 or 10,000 ft^2 (465 or 929 m^2). Shotcrete, precast concrete, and auger-cast concrete are often excluded from low-carbon concrete requirements. Consider whether to include or exempt flowable fill, cellular concrete, or other concretes, and whether GWP limits apply to repair or rehabilitation.

Limitations may also be placed on compressive strength. ACI 318-19(22) requires a minimum specified compressive strength of 2500 psi (17 MPa) at 28 days. In addition, NRMCA regional benchmarks are for concrete strengths of 8000 psi or less. Although it's not a large concrete volume, it should be discussed how to handle high-strength columns that may be 12,000 psi (83 MPa).

Supply chain

The building industry periodically experiences supply fluctuations for essential concrete construction materials including cement, fly ash, and aggregates. Cost fluctuations can also be a factor. Whenever possible, early involvement of the concrete contractor and their major product suppliers—during project design—can optimize the ability of the owner's design and construction team to manage the material supply chain. Early dialogue regarding pricing, mill orders, availability of price lock mechanisms, and delivery date projections can maximize benefits to the owner and help minimize project risk. For sustainable concrete construction, the lack of fly ash or slag cement would create substantial difficulties in achieving a project's carbon footprint target. As of July 2023, Type IL cement was only available in about 40% of the United States.

Project planning must include consideration of supply and cost fluctuations in the project's sustainability objective. More information on this topic is available in "ASCC Position Statement #45: Managing Concrete Projects: Concrete/Steel Price and Delivery Volatility Risks," *Concrete International*, June 2022.[32]

Specifications

Concrete mixture proportions have the greatest impact on carbon footprint. Because of this, the ready mixed producer needs to use performance specifications to achieve project goals. We recommend NRMCA's "Guide to Improving Specifications for Ready Mixed Concrete—With Notes on Reducing Embodied Carbon Footprint."[33] This document provides recommendations for specifying concrete to meet specific carbon footprint reduction goals while still maintaining all the performance characteristics required for concrete. It provides guidance on how to establish a carbon budget for a building, the submittals required to demonstrate compliance, and the qualifications of concrete producers to participate on a project that has a carbon reduction goal.

Timeline for trial mixtures

Unique to sustainable concrete mixtures is the desire to lower cementitious content, thus reducing the carbon footprint, by specifying compressive design strengths at ages later than 28 days. It is common for sustainable concrete mixtures to develop strengths at 56 or 90 days. Because these are not "off the shelf" mixtures, trial mixtures are used to establish proportions for concrete mixtures for each specific element. These trial mixtures are performed in accordance with ACI 301-20.[34] In addition to compressive strength, the trial mixtures confirm their suitability by meeting specified fresh and hardened concrete properties as well as the contractor's need to pump, place, and finish these mixtures for each specific element. Although appropriate sustainable concrete mixtures can be developed on the first round of trials, it sometimes takes multiple attempts. Plans need to consider the time necessary to develop suitable sustainable concrete mixtures.

Concrete waste

The PCR requires the LCA to include an assumed 5% concrete waste or actual recorded losses (loss = volume returned or disposed of divided by total volume produced at plant per year) when developing an EPD. Thus, for every theoretical yd^3 or m^3 in-place, the EPD provides GWP for 5% more. This discrepancy between theoretical volume and EPD volume needs to be discussed.

Specified compressive strength beyond 28 days

NRMCA benchmarks are compressive strength at 28 days. Other benchmarks such as GSA, Marin County, and NBI use specified

Table 9:
Concrete mixture performance schedule

Class	Application	Exposure class	Compressive strength f_c', ksi	Compressive strength Age, days	Max *w/cm*	Air content, %	Nominal max aggregate, in.	Drying shrinkage, %	Unit weight, lb/ft³	Design estimated volume, m³	Target GWP, kg CO_2e/m^3	Total Target GWP, kg CO_2e
1	Footings and wall footings	NA	4.0	56	—	—	1.5	—	NW	465	268	124,620
2	Foundation walls, piers, and grade beams	F2	4.5	56	0.45	5.5	1.5	—	NW	101	306	30,906
3	Column wraps	F3 C2	5.0	56	0.40	5.5	1.5	—	NW	14	320	4480
4	Interior slabs-on-ground	NA	4.0	28	—	—	1.5	≤ 0.04	NW	289	268	77,452
5a	Slab on metal deck	NA	4.0	28	—	—	0.75	≤ 0.04	NW	328	268	87,904
5b	Slab on metal deck	NA	4.0	28	—	—	0.75	≤ 0.04	LW	89	484	43,076
6	Shear walls	NA	4.0	56	—	—	1.5	—	NW	419	275	115,225
7	Miscellaneous	NA	3.5	28	—	—	0.5	—	NW	—	**Required project deliverable**	
8	Mud slab	NA	2.5	28	—	—	0.75	—	NW	—		
									Total	**1705**	**284**	**483,663**

Note: 1 ksi = 7 MPa; 1 in. = 25 mm; 1 lb/ft³ = 16 kg/m³; 1 kg/m³ = 1.7 lb/yd³; 1 kg = 2.2 lb

compressive strength without providing an age. Sustainable concrete mixtures are often specified by the engineer to achieve strength at 56 or 90 days. There are several approaches to handle this, but no matter which approach is used, it needs to be determined so that the appropriate carbon limits apply.

Resolution when not meeting requirements

Perhaps the most important discussion at the sustainability workshop is how to reach a resolution if the low-carbon concrete requirements are not met. Understandably, contractors need to know this to analyze their risk. The option to remove and replace would not seem to be a sustainable approach.

Concrete Contractor Recommendations

Based on the information presented, our recommendations for smart, sustainable concrete construction are as follows:

- **Sustainability objective:** Reduce the average weighted carbon footprint as measured by GWP by 15 to 25% with the final value to be determined at the sustainability workshop;
- **Sustainability measure:** Establish the GWP of a reference building using NRMCA regional benchmark mixtures with the Athena Impact Estimator for Buildings or other similar software with the capability of calculating GWP of different mixture designs;
- **Sustainability plan:** Use an element-by-element approach for design, construction, and concrete mixtures to provide owners the best overall quality and performance with the lowest possible carbon budget;
- **Sustainability documentation:** Using Type III cradle-to-gate product-specific EPDs in accordance with ISO Standards 14025 and 21930,[35] available in a publicly accessible database, to submit a summary report of all concrete mixtures, quantities, and GWP to demonstrate that the sustainability objective of the total GWP of the building is below the GWP of the reference building; and
- **Sustainability workshop:** Create a performance schedule for all concrete mixtures. An example of such a deliverable is shown in Table 9.

Final Note

We anxiously await the arrival of a standard produced by ACI Committee 323, Low-Carbon Concrete Code, which we understand will be published by the end of 2023, to provide a uniform, consistent approach on a national basis. We also are reviewing Carbon Budget software, a tool recently introduced by NRMCA, for integration into our framework.

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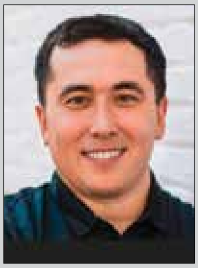

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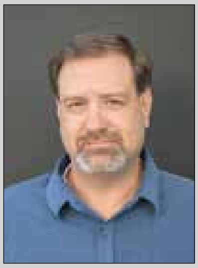

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