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Advancing Concrete Sustainability in Marine Structures

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Abstract: The optimization of sustainability with reinforced concrete relies on concrete mix designs as well as proper selection of structural systems and materials. Sustainability can be further enhanced with proper repair and maintenance that extends the life of existing concrete structures. Resources continue to be developed to aid in achieving desirable levels of sustainability as related to concrete structures while not compromising the intended performance. The use of supplementary cementitious materials (SCMs) has long been recognized as a method to improve the sustainability of concrete. This current practice of SCMs is reviewed along with concrete structural system selection and use of glass fiber reinforced polymer reinforcement (GFRP). GFRP is well suited for corrosive environments such as salt water and air. Further, there is possibility of using sea water to produce concrete that is reinforced with GFRP. GFRP wraps may be employed to provide external reinforcement and corrosion protection for structural concrete elements. Resources are readily available to assist the design professional in meeting the sustainability goals and challenges of current and forthcoming owner requirements.

Key words: carbon neutrality, cement, concrete, corrosion, reinforcement, sustainability

1. Introduction

Concrete is the most used manufactured building material. Approximately 14 billion m^3 were used in 2020 as found in GCCA (2023) [1], and thus, concrete has a significant environmental footprint regarding global warming potential (GWP). It is important to recognize that GPW potential is only one component in determining the environmental impact of materials. When considering alternates to concrete or optimizing the sustainability attributes of concrete, it is important that the entire environmental impact potentials be considered: global warming, acidification, eutrophication, smog creation, and ozone depletion. Each of these also needs to be considered along with use of precious potable water and project requirements which should include but not be limited to longevity, durability, and constructability.

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2. Impact of Cement on GWP

Cement consumption in 2020 was approximately 4.2 billion tonnes which equates to approximately 1.35 billion m^3 as found in GCCA (2023) [1]. While the cement component of concrete is only 9.6 percent, due to the volume of carbon dioxide generated in the manufacture of portland combined with the volume of concrete used, the result is a significant carbon footprint. Three significant components in portland cement manufacturing producing carbon dioxide are the chemical conversion of limestone to cement (process emissions), use of fossil fuels to create sufficient heat for the process to occur, and the electricity used to rotate the kilns. Re-carbonation, or carbon uptake, is a natural process undergone by concrete exposed to the air. The maximum re-carbonation is equal to the process emissions, about 60% of the total carbon dioxide emissions. The amount of re-carbonation that occurs in concrete structures is dependent on the thickness of the concrete elements. The thicker the element, the less concrete is exposed to air. However, when structures are demolished and concrete crushed, a significant amount of re-carbonation occurs, especially if the crushed concrete is stockpiled prior to reuse. Currently, it is recommended that re-carbonation be considered as 25% of the total process emissions as found in GCCA (2023) [1]. As more electric power generation using fossil fuels is replaced by power from renewable energy, the global warming emissions produced for electric will be reduced.

3. Use of SCMs

The environmental impact from environmental product declarations (EPD) of the primary materials in concrete is shown in Table 1 for cement [2-4]; commonly used supplementary cementitious materials (SCM) [5-7]; and typical aggregates as found in Polaris Materials (2017) [8]. For concrete, the most significant environmental impact is GWP. GWP is measured as carbon dioxide equivalents (CO_2e) and the largest contribution is from cement.

Table 1 Environmental impact potential of concrete ingredients.

Material	Environmental Impact Potential				
	Global Warming, kg CO_2 eq	Ozone Depletion, kg CFC-11 eq	Acidification, kg SO_2 eq	Eutrophication, kg N eq	Smog Formation, kg O_3 eq
Portland Cement - ASTM C150 [1]	922	2.10 E^{-05}	1.75	1.02	32.9
Portland-Limestone Cements [1]	846	2.17 E^{-05}	1.64	0.94	30.2
Blended Cements - ASTM C595 [1]	742	1.99 E^{-05}	1.46	0.95	26.6
Slag Cement [1]	147	2.40 E^{-05}	2.0	0.33	37.6
Fly Ash [2]	19.8	1.98 E^{-13}	3.84 E^{-04}	6.50 E^{-05}	30.2
Silica Fume [2]	2.92	9.88 E^{-10}	7.26 E^{-03}	1.05 E^{-03}	No Data
Washed Sand [2]	1.65	7.56 E^{-08}	0.02	3.60 E^{-03}	0.52
#57 Gravel [2]	1.55	6.48 E^{-08}	0.02	2.99 E^{-03}	0.52
#7 Gravel [2]	1.55	6.42 E^{-08}	0.02	2.96 E^{-03}	0.52
[1] Industry-wide EPD; [2] Single source EPD.					

It is obvious that replacing cement with supplementary cementitious materials can substantially reduce the environmental footprint of concrete. It is noteworthy that fly ash has been classified as a recovered material and currently is assumed to have no contribution to the environmental footprint other than transportation, as found in NRMCA (2022) [9]. However, due to improved air pollution control at coal-fired electric power generation facilities, more recently produced fly ash tends to have high loss of ignition (LOI). The high LOI is detrimental to the performance of concrete and thus fly ash with a high LOI must be processed, often by electrolysis, to make it suitable for use as an SCM. Product category rules for fly ash are under development.

4. System Selection

The use of SCMs is not the only way to reduce the environmental impact of concrete. Increasing the intensity of cement to create high strength concrete allows for the reduction in the size of members as demonstrated in Szoke (2021) [10]. Using high cement dosage high strength concrete (HSC), 83 MPa, in lieu of normal strength concrete (NSC), 27 MPa for concrete columns could allow 45% reduction in cross-sectional area. Typical NSC and HSC concrete contain SCMs. While the cement dosage for HSC may be 55% more, due to the smaller cross-sectional area, the cement consumption is reduced by 42%. The HSC columns have a GWP that is 13% less than those produced with NSC. Additionally, less water is required, 45% less aggregate is used, and the smaller lighter elements permit reductions in foundation sizes. For most building applications, because concrete elements tend to be protected from the elements, high dose SCM HSC concrete is possible, such as was achieved with the Freedom Tower in New York City as reported by Pirozzi (2011) [11]. The HSC concrete with a design compressive strength of 94 MPa was achieved with intensities of 208 kg/m^3 for cement 356 kg/m^3 for SCMs. Satisfying project requirements for HSC with low cement intensities usually requires the use of admixtures and rigorous mix design testing.

Other examples, as shown in Szoke (2021) [10], can reduce the overall volume of concrete, such as the use of voided slabs. Switching from conventional beam and slab construction to flat plate interim floor construction can reduce the volume of concrete as well as the reducing the floor-to-floor height by as much as 10%. Such a reduction in floor-to-floor height reduces both the amount of material required to enclose the building and the overall energy transfer through the building façade by 10%. Also, this equates to a 10% reduction in the volume of air inside the building that must be conditioned over the life of the building.

System selection can provide for substantial reductions in reducing the carbon footprint of structures. The engineer needs to be creative and working with the entire design team in the early stages of project design to combine system selection and alternative materials to optimize sustainability while still providing for life safety and the required durability.

5. Complexity of Sustainable Concrete

Achieving sustainable concrete that satisfies overall project requirements, is often more complex than simply replacing cement with SCMs. This is demonstrated by investigating minimum durability requirements for non-prestressed cast-in-place concrete produced with normal weight aggregate as found in ACI (2016) [12]. Other minimum criteria, not presented here, are applicable to prestressed cast-in-place concrete, precast concrete, and concrete produced using lightweight aggregate. Primary factors that impact the durability of concrete include mass transport (movement of liquid or ions through the concrete); freezing and thawing; alkali aggregate reaction; sulfate attack; chemical attack; physical salt attack, corrosion of metals; and abrasion. Thus, optimizing sustainability for concrete in marine environments is often more challenging than for concrete in most buildings where concrete elements are typically protected from moisture, salts, and freeze-thaw cycles. The durability requirements are based on types and extend of exposure shown in Table 2, as required in ACI (2019-1) [13]. The applicable freeze thaw resistance classifications for marine structures are: F0 where the concrete is exposed to water, but no freezing and thawing; F2 where exposed to fresh water and subjected to freezing and thawing; and F3 where exposed to seawater and subjected to freezing and thawing. Sulfate resistance categories are based on the sulfate content of the soil or water in contact with the concrete. Where concrete is exposed to seawater, sea spray or deicing salts, the exposure category is S1. Where concrete is exposed to water, the classifications are W1 or W2, depending on the permeability of the concrete. The fourth group of classifications are for corrosion resistance, being C1 where concrete is exposed to fresh water and C2 where concrete is exposed to seawater.

The minimum durability requirements shown in Table 3 through 9 are based on ACI (2020) [14]. There are no freeze-thaw resistance requirements where concrete is not exposed to freezing or thawing. Where concrete is frequently exposed to water and freezing or thawing the air content as shown in Table 3 and the water cementitious material ratio and compressive strength requirements shown in Table 4 must be satisfied. Where the frequent exposure is to seawater, there are maximum limits on the amount of SCMs as shown in Table 5. Fly ash shall not exceed 25% of the total cementitious materials and slag cement shall not exceed 50%. Further, the maximum amount of total SCMs is 50% where fly ash and slag cement are used together, with or without other SCMs, and 35% where fly ash is used with other SCMs excluding slag cement. As with all durability requirements presented, where concrete mix designs deviate from these requirements, performance should be demonstrated by testing.

Table 2 Summary of concrete exposure categories and classes.

Category	Class	Condition	
Freezing and Thawing	F0	Not Exposed to Freezing and Thawing	
	F1	Exposed to Freezing and Thawing with Limited Exposure to Water	
	F2	Exposed to Freezing and Thawing with Frequent Exposure to Water	
	F3	Exposed to Freezing and Thawing with Frequent Exposure to Both Water and Deicing Chemicals	
Sulfate (SO_4^{2-})		Water Soluble Sulfate in Soil by Mass	Dissolved Sulfate in Water, ppm
	S0	$SO_4^{2-} < 0.10$	$SO_4^{2-} < 150$
	S1	$0.10 \leq SO_4^{2-} < 0.20$	$150 \leq SO_4^{2-} \leq 1500$ or seawater
	S2	$0.20 \leq SO_4^{2-} \leq 2.00$	$1500 \leq SO_4^{2-} \leq 10{,}000$
	S3	$SO_4^{2-} > 2.00$	$SO_4^{2-} > 10{,}000$
In Contact with Water	W0	Dry in Service	
	W1	In Contact with Water where Low Permeability Is Not Required	
	W2	In Contact with Water where Low Permeability is Required	
Corrosion Protection of Reinforcement	C0	Dry or Protected from Moisture	
	C1	Exposed to Moisture but Not External Source of Chlorides	
	C2	Exposed to Moisture and External Source of Chlorides[1]	
[1] Deicing chemicals, brackish water, seawater, or spray from these sources.			

Table 3 Total air content, percent, for concrete exposed to freezing and thawing.

Exposure Class	Nominal Maximum Aggregate Size, mm						
	10	13	19.0	25	38	50	75
F2 – Freezing, Frequent Water	7.5	7.0	6.0	6.0	5.5	5.0	4.5
F3 – Freezing, Frequent Water and Salts							
[1] See Table 2 for details on Exposure Class							

Table 4 Freezing and thawing exposure.

Exposure Class[1]	Maximum *w/cm*	Minimum f'_c, MPa
F2 – Freezing, Frequent Water	0.45	31
F3 – Freezing, Frequent Water and Salts	0.40	34

Table 5 Maximum supplementary cementitious materials for concrete assigned to exposure class F3.

Supplementary Cementitious Material	Maximum Percent of Total Cementitious Material by Mass
Fly Ash of Natural Pozzolans	25
Slag Cement	50
Silica Fume	10
Total Fly Ash, Natural Pozzolans, Slag Cement and Silica Fume	50
Total Fly Ash, Natural Pozzolans and Silica Fume	35

Table 6 Suitability of cementitious materials exposed to water-soluble sulfate.

Exposure Class		Maximum Expansion, Percent		
		At 6 Months	At 12 Months	At 18 Months
S1 – Soil $0.10 \leq SO_4^{2-} < 0.20$ S1 – Water $150 \leq SO_4^{2-} \leq 1500$ (seawater)		0.10	NA	NA
S2 – Soil $0.20 \leq SO_4^{2-} \leq 2.00$ S2 – Water $1500 \leq SO_4^{2-} \leq 10,000$		0.05	0.10 if > 0.05 at 6 mos.	NA
S3 – Soil $SO_4^{2-} > 2.00$ S3 – Water $SO_4^{2-} > 10,000$	Option 1	NA	NA	0.10
	Option 2	0.05	0.10 if > 0.05 at 6 mos.	

Since the sulfate content of soil and/or water needs to be determined for most sulfate resistance classifications, only classification S1, which includes exposure to seawater, is discussed here. When tested accordance with ASTM C1012, Standard Test Method for Length Change of Hydraulic-Cement Mortars Exposed to a Sulfate Solution, the maximum expansion of the cement shall 0.10% at 6 months. To meet the sulfate resistance requirements there are restrictions on the types of cement and use of admixtures containing chlorides combined with maximum water cement ratios and minimum design compressive strengths. Durability requirements expressed here are select requirements for demonstration purposes and all applicable durability requirements contained in ACI 301 Specification for Concrete Construction are to be satisfied. For exposure to seawater, ACI 301 contains provisions for portland cement combined with tricalcium aluminate. Other types of cement than those listed may be permissible based on testing. The use of blended cements requires the addition of pozzolans and where Type V cement is the only cementitious material, there are alternative requirements for expansion testing.

Where concrete is exposed to water, there are maximum limits on the water cement ratio and minimum requirements for compressive strength based on permeability of the concrete, as shown in Table 8. There are additional requirements based on aggregate and cementitious material expansion tests. There are further requirements where natural pozzolans or fly ash have a CaO content greater than 18% or fly ash has an alkali content greater than 4.0%.

For corrosion protection there are limits on the water cement ratio, compressive strength, chloride ion content and amount of SCMs as shown in Table 9.

As a simplified example, consider low permeability concrete (W2) produced with portland cement, slag cement, and 38 mm aggregate and subject to freezing that thawing (F3) with frequent exposure to seawater (S1 and C2). The durability requirements for water cement ratio, compressive strength and air content would be determined using the information provided in Table 10. The maximum water cement ratio is 0.40, minimum compressive strength is 34 MPa, air content is 5.5 and maximum percent of slag cement is 50%. Additional requirements include, but are not limited to, 0.10% expansion of the cementitious material at 6 months, use of Type II portland cement; and 0.15% maximum chloride content.

Table 7 Sulfate Exposure Requirements.

Exposure Class				Cement Types			
		Max. *w/cm*	Min. f'_c, MPa	ASTM C150	ASTM C595	ASTM C1157	$CaCl_2$ Admixture
S1 – Soil $0.10 \leq SO_4^{2-} < 0.20$ S1 – Water $150 \leq SO_4^{2-} \leq 1500$		0.50	27	II	(MS)	MS	NA
S2 – Soil $0.20 \leq SO_4^{2-} \leq 2.00$ S2 – Water $1500 \leq SO_4^{2-} \leq 10,000$		0.45	31	V	(HS)	HS	None
S3 – Soil $SO_4^{2-} > 2.00$ S3 – Water $SO_4^{2-} > 10,000$	Option 1	0.45	31	V	(HS)	HS	None
	Option 2	0.40	34	V	(HS)	HS	None

Table 8 Concrete exposed to water.

Exposure Class	Maximum *w/cm*	Minimum f'_c, MPa
W1 – Water, Low Permeability Not Required	NA	17
W2 – Water, Low Permeability Required	0.50	27

Table 9 Conditions requiring corrosion protection.

Exposure Class	Maximum *w/cm*	Minimum f'_c, MPa	Maximum Soluble Chloride Ion Content in Concrete, Percent by Mass of Cementitious Materials [1]
C1 – Moisture, No Chlorides	NA	17	0.30
C2 – Moisture with Chlorides	0.40	34	0.15

[1] The maximum cementitious material content shall not exceed two times the mass of portland cement.

Table 10 Example for a low permeability concrete exposed to seawater and freezing and thawing.

Exposure Class	Maximum *w/cm*	Minimum f'_c, MPa	Air Content	Max. Percent Slag Cement as Total Cementitious
F3 – Freezing, Frequent Water and Salts	0.40	34	5.5	50
S1 – Seawater	0.50	27	--	--
W2 – Low Permeability	0.50	27	--	--
C2 – Moisture with Chlorides	0.40	34	--	50
Design Requirements	**0.40**	**34**	**5.5**	**50**

6. Protection of Reinforcement

In addition to the selecting appropriate properties for concrete, corrosion protection of metals embedded in concrete is also crucial. Corrosion of metals in concrete requires the presence of moisture and oxygen. All concrete cracks, creating opportunities to allow a presence of moisture and oxygen and where deicing salts, seawater, or sea air are present, entry of chlorides into the concrete. Temperature and shrinkage reinforcement in concrete helps to minimize the size of cracks and thus mitigates mass transport. In addition to mass transport, carbonation (reabsorption of CO_2), while beneficial for lowering the overall GWP of concrete, lowers the alkalinity of concrete which may lead to or increase the rate of corrosion as found in ACI (2019-2) [15]. As steel corrodes, it changes from iron to iron oxides and ultimately iron hydroxides. The volume of the corroded materials can be 2 to 3.5 times the volume of the iron. As shown in Table 11, for common exposure conditions in marine structures, the cover requirements are often thicker than those required for where concrete elements are not exposed to weather or in contact with ground as shown in ACI (2019) [15].

Table 11 Minimum Concrete Cover, in mm.

Exposure	Member	Steel Reinforcement	Cover
Cast Against and Permanently in Contact with Ground	All	All	75
Exposed to Weather or in Contact with Ground	All	No. 19 through No. 57 Bars	50
		No. 16, W31 or D31 Wire and Smaller	38
Not Exposed to Weather or in Contact with Ground	Slabs, Joists and Walls	No. 43 and No.57 Bars	38
		No. 36 Bars and Smaller	19
	Beams, Columns, Pedestals, and Tension Ties	Primary Reinforcement, Stirrups, Ties, Spirals and Hoops	38

In corrosion-aggressive environments concrete cover may not be sufficient to provide the durability and longevity required. In lieu of conventional uncoated steel reinforcement, epoxy coated, galvanized, and stainless-steel reinforcement as described in ACI (2019-2) [15] may provide improved performance. For epoxy coated steel reinforcement, it is important that the bars be free of salts prior to being coated; the coating be free of cracks and defects, especially important if bars are bent after being coated; and the coating have adequate roughness for bonding to the concrete. Epoxy coatings should be 175 to 300 µm for No. 16 bars or smaller and up to 400 µm for bars greater than No. 16. Galvanized bars are particularly beneficial where concrete is subjected to carbonization. Zinc dissolves in high pH environments and relies on the formation of a protective film of calcium hydroxyzincate. Chromate salt may be added to fresh concrete to prevent hydrogen evolution. The zinc coating must remain intact during bending. It is sometimes preferred to use hot-dip galvanizing of pre-shaped bars. Stainless steel performs very well in many corrosion-aggressive environments. In some instances, for cost savings, stainless steel bars are used for outer reinforcement elements and basic steel used for interior elements that are more protected. Coordination may be challenging.

In 2022 a new standard has been developed for structural concrete reinforced with glass fiber reinforced polymer reinforcement (GFRP) ACI (2022) [16]. Concrete reinforced with GFRP reinforcement may be an ideal solution for corrosion-aggressive environments. Concrete reinforced with GFRP reinforcement performs very differently than concrete reinforced with steel. Currently, the standard requires the GFRP reinforcement to conform to ASTM D7975, ASTM (2022) [17] and limits the use to structures assigned to Seismic Design Categories (SDC) A, B, and C. GFRP reinforcement is not permitted for members that are part of the seismic lateral force resisting system in SDC B or C. Proper consideration is necessary for elements that may be subjected to seismic later forces even where elements are not part of the seismic lateral force resisting system. GFRP is not to be used where the service temperature is more than 15°C above the glass transition temperature of the polymer as the polymer will soften and de-bond from the glass fibers and the concrete. Glass transition temperatures tend to range between 100 and 121°C. Also, due to this softening, concrete reinforced with GFRP reinforcement is not to be used for concrete elements where fire-resistance ratings are required, unless acceptable performance documented by tests or analysis is approved. GFRP reinforcement is not susceptible to corrosion by salts. Concrete for elements reinforced with GFRP reinforcement could be produced using sea water, preserving precious fresh water. Due to the chlorides present in sea water, the time for the concrete to cure will be delayed, but this could be compensated for with the use of additives.

7. Preservation

Concrete is known for its durability and longevity. Replacement of concrete structures is relatively infrequent, adding to the many sustainability attributes. Proper protection, maintenance, and repair is necessary to maximize the preservation of existing concrete elements. Many options exist to enhance the durability and longevity of concrete in corrosion-aggressive environments as described in ACI (2019-2) [14].

Water resistant sheet or liquid applied membranes can reduce mass transport. Barrier surface treatments are viable options where the surface of the concrete is exposed. In addition to membranes, protection may be provided by polymer impregnation or overlays of polymer concrete, low-slump concrete, silica fume concrete, or latex modified concrete. Other methods to extend the life of reinforcement include chemical corrosion inhibitors and cathodic protection. Elements of these systems must be considered prior to placement of the concrete, new construction. Cathodic protection with zinc was previously mentioned but there are other coatings specifically designed for protection of steel reinforcement. The steel needs to be coated with an appropriate electrolyte prior to placement. Impressed current cathodic protection is an alternate to electrochemical circuits. This is accomplished by installing an anode directly in contact with the electrolyte and passing a low voltage direct current from the anode through the electrolyte to the steel reinforcement.

There are a variety of repair options available where damage has occurred. External reinforcement, including fiber reinforced polymer sheet membrane may be employed to strengthen concrete members. Proper assessment and repair are crucial to enhancing the durability of damaged concrete members as provided in in ACI (2021) [18].

8. Conclusions and Steps Forward

Currently there are many options and strategies to reduce the environmental footprint of concrete construction: primarily, selection of the most appropriate concrete systems or elements; optimizing mix designs that satisfy the project requirements; and appropriate selection of materials. Another option is to preserve existing structures through proper assessment and repair as described in ACI (2021) [18]. Whatever choices are made, it is important to assure the health, safety, and welfare of public and achieve the appropriate levels of durability and longevity of concrete construction. It is important, especially with optimization of mix designs, for designers, owner's representatives, contractors, concrete producers, and material suppliers to work together in the early stages of projects to assure material availability and that project requirements, both during and after construction, can be satisfied.

Generally, new practices, products, and technologies best gain broad acceptance through education, research, and standardization. Industry experts need to continue to be engaged in the development of new technologies with necessary standards to ensure desired outcomes and expedite acceptance. The American Concrete Institute (ACI) is an American National Standards Institute accredited standards development organization that provides forums for advancing concrete technology through its technical and standards development committees and subsidiaries. There are currently three subsidiaries striving to further advance concrete technologies discussed in this paper: Center of Excellence for Carbon Neutral Concrete, Center of Excellence for Nonmetallic Building Materials, and Center of Excellence for Advancing Productivity.

References

[1] GCCA (Global Cement and Concrete Association), available online at: http://www.gccassociation.org, last visited January 2023.

[2] PCA 1 (2021) Environmental Product Declaration Portland Cement, Portland Cement Association, Skokie, IL, available online at: http://www.cement.org, last visited January 2023.

[3] PCA 2 (2021) Environmental Product Declaration Portland-Limestone Cement, Portland Cement Association, Skokie, IL, available online at: http://www.cement.org, last visited January 2023.

[4] PCA 3 (2021) Environmental Product Declaration Blended Hydraulic Cement, Portland Cement Association, Skokie, IL, available online at: http://www.cement.org, last visited January 2023.

[5] SCA (2021) An Industry Average Environmental Product Declaration for Slag Cement, Slag Cement Association, Farmington Hills, MI, available online at: http://www.slagcement.org, last visited January 2023.

[6] Bau Material (2017), GmBH, Nurnberg, Germany, available online at: https://www.baumineral.de /downloads/file/492/EPD-Baumineral-018-EFA-F%C3% BCller-MR3_ENG.pdf, last visited January 2023.

[7] D. Walach, P. Dybel, J. Sagan, and M. Gicala, Environmental performance of ordinary and new generation concrete structures — A comparative analysis, *Environmental Science and Pollution Research* (2019) 3980-3990, Springer Nature, London, UK.

[8] Polaris Materials, Environmental Product Declaration, Polaris Materials, Vancouver, BC, Canada, (2017), available online at: https://pcr-epd.s3.us-east-2. amazonaws.com/344.EPD_Polaris_Materials_final.pdf, last visited January 2023.

[9] NRMCA (National Ready Mixed Concrete Association), Member industry-average EPD for ready-mixed concrete,

2022, available online at: http://www.nrmca.org, last visited January 2023.
[10] S. Szoke, K. Nahlawi, and J. Casilio, Enhancing sustainability through structural concrete system selection, in: *Proceedings of the Institution of Civil Engineers — Engineering Sustainability*, doi: https://doi.org/10.1680/jensu.21.00058.
[11] M. Pirozzi, *The Use of Sustainable, High-performance Concrete in New York City*, Port Authority of New York and New Jersey, New York, NY, 2011.
[12] ACI (2016) ACI PCR 201.2 *Guide to Durable Concrete*, American Concrete Institute, Farmington Hills, MI.
[13] ACI (2019-1) ACI CODE 318 *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, Farmington Hills, MI.
[14] ACI (2020) ACI SPEC 301 *Specification for Concrete Construction*, American Concrete Institute, Farmington Hills, MI.
[15] ACI (2019-2) ACI PRC 222 *Guide to Protection of Metals in Concrete Against Corrosion*, American Concrete Institute, Farmington Hills, MI.
[16] ACI (2022) ACI CODE 440.11 Building Code Requirements for Structural Concrete reinforced with Glass Fiber Reinforced Polymer (GFRP) Bars - Code and Commentary, American Concrete Institute, Farmington Hills, MI.
[17] ASTM (2022) ASTM D7957/D7957M Standard Specification for Solid Round Glass Fiber Reinforced Polymer Bars for Concrete Reinforcement, ASTM International, West Conshohocken, PA.
[18] ACI (2021) ACI CODE 562 Assessment, Repair, and Rehabilitation of Existing Concrete Structures — Code and Commentary, American Concrete Institute, Farmington Hills, MI.