APPENDIX C—SUSTAINABILITY AND RESILIENCE *(NEW APPENDIX)*

CODE

C.1—Terminology

C.1.1 *Terminology*

class of concrete—characterization of concrete of various qualities or usages, usually by compressive strength.

environmental product declaration (EPD)—declaration providing environmental data using predetermined parameters meeting the requirements of ISO 21930.

global warming potential (GWP)—index used to determine the energy absorption caused by the emissions of different gases associated with a product, normalized to an equivalent mass of carbon dioxide over a period of 100 years.

hazard event—potential cause of damage to a structure and the magnitude or intensity associated with that cause.

life cycle assessment (LCA)—compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product throughout its life cycle.

resilient design—design process that anticipates, addresses, and mitigates risks associated with known natural or human-caused hazards by balancing construction cost, material consumption, recovery of functionality, and potential financial loss should a particular hazard event occur.

sustainable design—design process that considers the balance among social, economic, and environmental principles from the Work's conception through the end of its service life.

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RC.1—Terminology

RC.1.1 *Terminology*

global warming potential (GWP)—This index was developed as a single parameter to estimate the global warming impact of different gaseous emissions.

hazard event—Selecting the demands for which a structure will be designed requires establishing the hazards to which the structure may be subjected and the intensities of those hazards for target risk levels. For example, a structure might be subjected to frequent earthquakes with small intensities and very infrequent earthquakes with large intensities.

resilient design—The design of resilient concrete structural systems includes:

(a) Assessing the importance of the structure with respect to its functional, social, and economic roles in the community

(b) Evaluating the hazards to which the structure may be exposed (such as flood or earthquake) and the estimated magnitudes associated with target risk levels in the present and in the future

(c) Assessing the vulnerability and sensitivity of the structure to damage

(d) Assessing the consequences of damage to the structure caused by the hazard event(s)

(e) Evaluating the interdependent effects of the structure on other physical and social systems

In the context of the community of which individual structures are a part, resilience may include the community's ability to absorb disturbances while retaining the same basic structure and functionality, the capacity for self-organization, and the capacity to adapt to stress and change. The hazard design criteria and required recovery time following a hazard event should be based on the use, importance, and occupancy of the structure.

sustainable design—The design of sustainable concrete structural systems seeks to achieve balance between the production of concrete elements and the required performance characteristics in all phases of the structural system's life cycle. This approach includes measures to reduce the consumption of resources, including but not limited to water, aggregates, cementitious materials, reinforcing steel, and fuels; considers economic value and societal and cultural impacts; and minimizes impacts on the environment. When considering sustainable design, the Code places emphasis on the environmental impacts. Users should also consider social and economic principles of sustainable design that are not directly addressed

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Whole Building Life Cycle Assessment (WBLCA)—life cycle assessment (LCA) of the complete building.

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by the Code. The principles of resilience and resilient design should be considered in sustainable design.

C.2—Scope

C.2.1 This appendix provides requirements for the sustainable design and resilient design of structures when required by the owner or the authority having jurisdiction.

RC.2—Scope

RC.2.1 This appendix provides requirements specific to design, concrete materials and mixtures, and construction procedures to support the sustainability and resilience goals for the Work.

Strength, serviceability, and durability are implicit attributes for achieving a sustainable and resilient design.

Selecting materials that minimize environmental impact may improve the sustainability of structural concrete. These materials may include but are not limited to alternative cementitious materials, supplementary cementitious materials, alternative aggregates, and recycled materials.

Whole Building Life Cycle Assessment (WBLCA) may be used to demonstrate the quantitative improvement of a sustainable design.

The design of sustainable concrete structures should also consider resilience. Structures that cannot be economically repaired or reoccupied after being damaged by a hazard event are demolished (and sometimes replaced) or abandoned, often resulting in a loss to the community. Demolishing structures is an unsustainable practice as it generates waste that impacts human health and the environment and contributes to the embodied energy of the demolished structure, often with little benefit to society. Structures designed for resilience are not necessarily sustainable, although their designs may incorporate sustainable materials or principles.

C.2.2 The requirements of Appendix C shall be in addition to those in Chapters 1 through 26.

C.2.3 If the provisions of Appendix C are incorporated in a design, the licensed design professional shall identify and state the applicable sustainability and resilience requirements in the construction documents.

RC.2.3 Establishing stakeholders' sustainability and resilience goals during design and construction allows for optimization of design, materials, and construction and consideration of innovative technologies to achieve reduced environmental, societal, and economic impacts throughout all phases of the life of the structure.

The owner or licensed design professional may specify requirements that exceed the minimum requirements of the Code. Such requirements may include higher strengths, more restrictive deflection limits, enhanced durability, increased sustainability, and improved resilience. Identifying hazard events to which a structure may be subjected during its life, evaluating the risks associated with those hazards, and accepting or mitigating those risks are steps of establishing the resilience goals for the Work.

C.3—Evaluation of Sustainability of Structural Concrete Systems

C.3.1 If structural system sustainability is to be quantified, an assessment shall be required. The assessment shall be deemed to be satisfied by (a) and (b).

RC.3—Evaluation of Sustainability of Structural Concrete Systems

RC.3.1 Comparing the relative sustainability of different structural systems is an important part of sustainable design.

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(a) The quantification shall be part of a whole building life cycle assessment (WBLCA) conducted in accordance with ASTM E2921.

(b) The WBLCA shall include the following:

(1) At a minimum, the environmental impact categories included in the WBLCA shall include global warming potential, acidification potential, eutrophication potential, ozone depletion potential, and smog potential.

(2) The life cycle inventory categories included in the WBLCA shall include water consumption, solid waste, total energy demand, and total nonrenewable energy demand.

(3) It shall be permitted to include operational energy in the WBLCA.

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Life cycle assessment (LCA) is a tool to evaluate the environmental impacts associated with any product throughout its life cycle. Whole building life cycle assessment (WBLCA) is an adaptation of an LCA that studies the whole building as a system.

If a WBLCA is to be conducted, the owner should designate a member of the project team who is responsible for gathering the design information from the designers and conducting the WBLCA. The WBLCA may be performed by the structural engineer, architect, specialty sustainability consultant, or other designee.

It is possible to affect the sustainability of a structural system by making adjustments to various elements of the system, and the code does not preclude the use of comparisons between individual parts of the system. However, WBLCA is the only method available to quantify the environmental impacts of the entire system.

ASTM E2921 establishes criteria for conducting a WBLCA. ASTM E2921 requires that a defined service life be used to compare the building design to a reference building. WBLCA can be used to review a variety of impacts during different phases of the building life cycle. Requirements of ASTM E2921 are based on ISO 14040 and ISO 14044 and provides guidelines on service life, life cycle stages, product replacement, operational energy, comparison to a reference building, and analysis tools.

ASTM E2921 does not define strategies to improve upon the reference building. Practitioners can, however, reference Yang (2018) and Kestner et al. (2010) for guidelines on the reference building and strategies to improve upon it. Strategies outlined in these references include structural material quantity reduction, optimized concrete mixtures, structure as the finish, alternate structural systems, performance-based design, carbon-sequestering materials, salvaged materials, and many others.

For more information on WBLCA implementation, practitioners may also reference Simonen (2014), Bayer et al. (2010), and Bowick et al. (2014).

(b)(1) These environmental impact categories are mandatory according to ISO 21930, the standard that governs environmental product declarations (EPDs) for building products.

(b)(3) Inclusion of operational energy in the WBLCA captures the potential reduced energy use in the building due to the thermal mass effects of the concrete.

Many WBLCAs require operational equivalence between comparisons, but this does not mean operational energy can be excluded from the analysis. One part of operational equivalence assumes the occupants experience given comfort levels in terms of temperature, but this assumption does not adequately capture thermal mass effects. Using different amounts of concrete in other locations in the building will affect occupant comfort.

Annual energy use is calculated using a whole building energy simulation. In a whole building energy simulation, a thermodynamic model of a building is created, and software simulates the operation and response of the building. During the whole building energy simulation, the heating and cooling loads of each space in a building over a defined period are calculated, typically over a calendar year. Based on these loads, the operation and response of the equipment and systems that control temperature and humidity, and distribute heating, cooling, and ventilation to the building are simulated. This analysis is required to determine the fuel and electricity used to provide the necessary heating, cooling, and electricity. Modeling must be performed using non-steady-state methods to fully capture thermal mass effects.

Recommendations for consideration of thermal mass effects are included in ACI PRC-122, Gajda and VanGeem (2000), VanGeem (1987), and VanGeem et al. (1983).

Including operational energy is necessary for a full WBLCA to capture the impact of thermal mass effects from concrete elements.

C.3.2 The building alternative chosen for the Work shall show improvement over the reference building assessed in the WBLCA.

RC.3.2 Because a WBLCA includes building components whose design and optimization falls outside the scope of a structural concrete code, the code does not require specific improvement. Project teams should determine the appropriate improvement while considering specific project goals or governing general building codes. For example, an improvement of 5% in three environmental impact categories is a common starting point for minimum requirements.

C.4—Resilience

C.4.1 If resilience provisions beyond building code requirements are to be considered in the structural design of the concrete structural system, the provisions of C.4 shall be permitted to be used.

C.4.2 The design of the concrete structural system and the elements of which it is composed shall consider resilience for appropriate hazards in accordance with (a)through (e):

(a) intended use of the structure
(b) risks associated with geographic location
(c) consequences of damage or loss of use
(d) tolerance of the owner for varying levels of damage or loss
(e) associated time required to recover from a damaged state

RC.4—Resilience

RC.4.1 The resilience of a structure is commonly described in terms of functional resilience. The Portland Cement Association defines functional resilience as “a building’s capacity to provide viable operations through extended service life, adaptive re-use, and during the challenges of natural and man-made disasters” (PCA 2022). Abrahams et al. (2021) discuss functional recovery.

RC.4.2 A partial list of hazards that the designer and owner should consider include fire, flood, wave action, wind, snow, earthquake, foundation settlement or heave, corrosion, and deterioration. These primary hazards can result in secondary hazards. For example, earthquakes can result in loss of electrical power, interior flooding, and release of hazardous materials.

The Fortified Commercial Wind Standards, developed by the Insurance Institute for Building and Home Safety (IIBHS), provide guidance on identifying hazards for a specific site. It covers a range of hazards including hurricane, tornado, hail, and high wind (IIBHS 2020).

RELi is a rating system adopted by the U.S. Green Building Council (USGBC). Related to resilience, it guides planning, design, maintenance, and operations; risk adaptation and mitigation for acute events; comprehensive adaptation and mitigation for a resilient present and future;

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and applied creativity and contextual factors for resiliency (USGBC 2021).

In the U.S. Resiliency Council (USRC) rating system, buildings are rated in three areas (safety, damage, and recovery) corresponding to the average performance of a building under consideration, given a single earthquake causing ground shaking at the site of the building consistent with the Design Basis Event (2/3MCE$_R$) as defined in the ASCE 7-16 provisions (USRC 2019).

National Institute of Standards and Technology (NIST) Special Publication 1190, Community Resilience Planning Guide for Buildings and Infrastructure Systems, Volumes I and II provide guidance on reviewing hazards and design considerations (NIST 2016a,b).

Other guidance for determining hazards includes:

(a) FEMA Flood Map Service Center web search portal (FEMA Flood Map Service Center n.d.)
(b) Coastal Flooding Tools (Data.gov n.d.)
(c) Climate Central's "Surging Seas" sea level rise analysis for coastal U.S. states (Climate Central n.d.)
(d) FEMA Wind Zone Map (FEMA Wind Zone Map n.d.)
(e) NOAA National Weather Service's National Hurricane Center (NOAA National Hurricane Center n.d.)
(f) NOAA National Climatic Data Center's U.S. Tornado Climatology (NOAA U.S. Tornado Climatology n.d.)
(g) USGS Earthquake Hazards Program maps (USGS n.d.)
(h) FEMA map Wildfire Activity by County 1994 – 2013 (FEMA Wildfire Activity 2024)
(i) FEMA Federal Fire Occurrence Map Viewer (FEMA Federal Fire n.d.)
(j) U.S. Drought Monitor updated weekly (U.S. Drought Monitor n.d.)

Passive survivability is defined by the Better Buildings Solution Center at the U.S. Department of Energy as "the ability of buildings to maintain habitable conditions in the event of a heating/cooling system loss." (DOE 2021)

Concrete buildings can support passive survivability, which is related to extending essential services, public safety, and thermal comfort of the occupants after a natural or human-caused disaster. Resources related to this concept include:

(a) CBE Thermal Comfort Tool (CBE n.d.)
(b) Occupational Exposure to Heat and Hot Environments (DHS 2016)

C.4.3 The required levels of performance above the minimum requirements of this Code shall be included in the construction documents.

RC.4.3 Model building codes, such as the International Building Code, provide minimum requirements to safeguard public health, safety, and general welfare of the occupants of buildings and structures. A building owner may require that a concrete structural system be designed with more robust performance, serviceability, and durability than the building code prescribes, and these requirements should be included in the construction documents. Enhanced performance may require designing and detailing the structural system for

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increased magnitudes of load events, or more stringent deformation requirements. Consideration of the slow onset of hazard events that develop over time (for example, drought or melting of permafrost) may also be required. Enhanced durability features may include increased concrete cover, decreased permeability, increased corrosion resistance, or other design enhancements to increase service life.

C.5—Concrete Mixtures

C.5.1 Specified sustainable design metrics for concrete mixtures shall satisfy the requirements of at least one of C.5.1.1, C.5.1.2, or C.5.1.3 as defined by the licensed design professional or building official.

C.5.1.1 The maximum global warming potential (GWP) limit for each class of concrete per unit volume shall be defined in accordance with C.5.1.1.1 and C.5.1.1.2.

C.5.1.1.1 The limit shall be defined as a GWP maximum limit for a class of concrete in accordance with (a) through (c) and C.5.2:

RC.5—Concrete Mixtures

RC.5.1 The design metrics used to specify sustainable design should account for the local availability of sustainability data and the sustainable design goals for the Work. The design metrics included in C.5.1.1 and C.5.1.2 are related to global warming potential reductions, and these alternatives are geared toward locations with different levels of available data for environmental impact of concrete mixtures. C.5.1.3 allows for the licensed design professional or building official to specify other sustainable design metrics.

The choice of a sustainable design metric may depend on the local data available for that metric. Design metric limits should be based on information derived from similar local projects or applicable benchmarks that are achievable in the local market.

Strategies for developing concrete mixtures that meet the Work's sustainability requirements include, but are not limited to:

(a) Use of lower impact primary cement, such as a blended cement
(b) Use of lower impact supplementary cementitious materials as a portion of the total cementitious materials
(c) Maximization of cement efficiency by optimizing concrete mixtures
(d) Specifying a later age at which design strength is required (for example, 56 or 90 days instead of 28 days if possible)
(e) Use of performance-based rather than prescriptive requirements for concrete mixtures (refer to ACI PRC-329)
(f) Use of technologies, such as additives and greenhouse gas sequestering, that reduce the defined sustainability metric while achieving required concrete properties
(g) Use of lower carbon processes for material production

RC.5.1.1 The use of C.5.1.1 is dependent on the availability of GWP data for concrete mixtures local to the Work. Therefore, applying this design metric should consider the ability of local producers to supply GWP data.

Similar to C.5.1.1, ACI CODE-323 includes a process for establishing limits on global warming potential (GWP) for concrete mixtures on projects.

RC.5.1.1.1 Concrete mixtures used in some applications tend to have higher GWP values than other concrete mixtures with the same f_c' value. Considering such appli-

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(a) Limits shall be assigned to classes of concrete based on f_c' unless data regarding specific applications is available.
(b) If data regarding specific applications is available, limits for those applications as a class of concrete shall be permitted.
(c) If a limit is assigned to a class of concrete based on f_c', the concrete in the Work shall be permitted to be categorized to the class of concrete of the same f_c' regardless of the age required to achieve that strength.

C.5.1.1.2 The GWP per unit volume for the concrete mixtures used in the Work shall be documented as defined in C.5.3.

C.5.1.2 A concrete-producer-specific demonstration of a reduction in concrete mixture GWP impacts shall be required in accordance with C.5.1.2.1 through C.5.1.2.4.

C.5.1.2.1 Demonstration shall compare each proposed concrete mixture to the average of all mixtures of a defined class from a single concrete producer.

C.5.1.2.2 The defined class of concrete mixtures shall meet the performance requirements of the Work and be available from the concrete producer's plants in the vicinity of the Work. Performance requirements shall include concrete mixture specified qualities and application type.

C.5.1.2.3 The required method of demonstrating GWP impact reduction shall be defined.

C.5.1.2.4 Reduction values reported for C.5.1.2 shall not be compared to reduction values reported by other producers.

C.5.1.3 A measurable sustainability limitation or requirement shall be specified by the licensed design professional or building official.

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cations separately allows achievable GWP limits specific to these applications to be set.

If the class of concrete is defined by f_c', the GWP associated with the f_c' design strength at any age can be compared to the GWP limit even if the GWP limit is determined from a benchmark f_c' at a different age. While most benchmarks utilize 28-day f_c' data, designers may specify longer timeframes to achieve an f_c' value as a strategy to reduce GWP.

RC.5.1.2 This option can be specified where there are a limited number of concrete producers in the vicinity of the Work and GWP data for concrete mixtures is not widely available. This design metric can also be specified in cases where regional industry average values for GWP are largely different from that achievable in the local area of the Work.

RC.5.1.2.2 The intent of this provision is to compare the proposed mixtures with all mixtures from a producer that meet the same performance requirements. These requirements would include strength, air content, shrinkage limits, application (shotcrete for example), and any other defined performance requirements.

RC.5.1.2.3 Reduction could include the demonstration of a reduction in the amount of cement used per unit volume, the impact of the type of cement used, or other method defined by the licensed design professional or building official. If limitation on cement content is defined, the reduction reported would need to include a listing of the mass of cement per volume used in all the mixtures from the supplier that meet the specifications. In addition, a required reduction from the average mass of cement used in these mixes could be specified.

RC.5.1.2.4 Reduction values are unique to a concrete producer and should not be compared with those of other regional producers. If a comparison between producers is required, an approach that compares producers to a common benchmark should be used.

RC.5.1.3 This provision is intended to allow for sustainability limitations that are unrelated to GWP. The requirements in C.5.1.1 and C.5.1.2 are intended for GWP reduction and may not cover all the sustainability goals of the Work. C.5.1.3 may be used in combination with one of the GWP limiting requirements.

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Commonly tracked sustainability metrics include total primary energy consumption, ozone depletion potential, acidification potential, eutrophication potential, photochemical ozone creation/smog potential, total water consumption, and depletion of non-renewable material resources that may include the use of recycled material. Information about many of these parameters can be found in ISO 14044, ISO 21930, and environmental product declarations (EPDs). The licensed design professional or building official may set limits on one or more of these metrics.

C.5.2 *GWP maximum limits*

C.5.2.1 The maximum limits for each concrete class required in C.5.1.1.1 shall be defined as a GWP value per unit volume. Limits shall not be exceeded except as allowed in C.5.2.1.1. Where limits are referenced with respect to a benchmark, the benchmark shall be as defined in C.5.4.

C.5.2.1.1 Maximum limits of GWP for individual concrete mixtures shall be permitted to be exceeded provided the concrete GWP for all concrete in the Work does not exceed the concrete GWP total limit for the Work. The concrete GWP total limit for the Work shall be defined as the sum of the volume for each class of concrete multiplied by the corresponding GWP limit for that class of concrete.

RC.5.2 *GWP maximum limits*

RC.5.2.1 Maximum GWP limits for concrete classes should be set based on values known to be achievable in the concrete market local to the Work. For example, EPDs for concrete mixtures used in the local market or regional benchmarks, as described in RC.5.4.1, could be used.

RC.5.2.1.1 Maximum limits may need to be exceeded to accommodate constructability, early-age requirements, or other needs for certain applications. A GWP total limit for the Work allows for the GWP of individual concrete mixtures to exceed their class limit as long as the total limit for the Work is met.A weighted average approach, similar to that used in ACI CODE-323, could be used to set a GWP total limit for the Work.

C.5.3 *GWP documentation*

C.5.3.1 GWP values for concrete mixtures shall be documented in one of the following:

(a) an independently verified life cycle assessment (LCA) report
(b) an independently verified product-specific environmental product declaration (EPD)
(c) an independently verified LCA tool.

LCA reports, EPDs, and LCA tools shall conform to ISO 14044 and the relevant product category rule that conforms to ISO 21930.

C.5.3.2 Industry average reports and regional benchmarks shall be based on life cycle assessments complying with ISO 14044 and the relevant product category rule that conforms to ISO 21930.

RC.5.3 *GWP documentation*

RC.5.3.1 An EPD, in accordance with ISO 21930 and a valid concrete Product Category Rule (PCR), such as the PCR for Concrete V2.1 (NSF International 2021), can be used for GWP data. The EPD should include a minimum of life cycle stages A1-A3, which are equivalent to raw material supply, transport, and manufacturing.

GWP values used to comply with this section are to be developed using the same PCR as the benchmark, per the comparability requirements of ISO 21930.

C.5.4 *GWP Benchmark Definition*

C.5.4.1 The GWP benchmark shall be defined in terms of an industry, regional, or local average. The GWP for this benchmark shall be documented as defined in C.5.3.

RC.5.4 *GWP Benchmark Definition*

RC.5.4.1 The benchmark values included in Appendix C of NRMCA's regional benchmark report (Athena Sustainable Materials Institute 2022) or a benchmark report that follows the requirements of C.5.3 can be used to define the GWP benchmark.