SPECIFYING SUSTAINABLE CONCRETE

Presented by:

BUILD WITH STRENGTH

Figure 1: Rowan, San Francisco. One of San Francisco's newest and sleekest residential structures uses a giant, zigzagging concrete exoskeleton and stands out from other buildings. The exterior is for much more than show—it negates the need for interior columns, maximizing the interior space for residents. Concrete on the project used high volumes of fly ash to reduce environmental footprint.

LEARNING OBJECTIVES

1. Analyze the difference between performance-based specification and prescriptive specifications.
2. Evaluate how performance-based specifications can improve performance and lower environmental impact of concrete structures.
3. Learn how to implement performance-based specifications in projects.
4. Demonstrate the importance of balancing structural and architectural performance of concrete with green building strategies.

CONTINUING EDUCATION

AIA CREDIT: LU/ELECTIVE
AIA COURSE NUMBER: AR122019-2

AIA Continuing Education Provider

Use the learning objectives above to focus your study as you read this article. To earn credit and obtain a certificate of completion, visit **http://go.hw.net/AR122019-2** to view the entire CEU and complete the quiz. CEU courses are free of charge once you create a new learner account; returning users log in as usual.

By: Lionel Lemay, Executive Vice President, Structures and Sustainability, NRMCA
Colin Lobo, Executive Vice President, Engineering, NRMCA
Karthik Obla, Vice President, Technical Services, NRMCA

INTRODUCTION

Sustainable concrete is difficult to define. There are many factors that can influence the way concrete is manufactured, designed, built, used and recycled that ultimately affect the environmental footprint of the structures built with concrete. Whether one is designing a building, pavement, bridge or dam, concrete is an important component used as foundation and superstructure, and these structures can have a significant impact on the environment throughout their lifecycle.

Design professionals can influence the performance and environmental impact of structures through effective design and project specifications regardless of the materials being used. However, concrete is unique in that it is so versatile both in terms of physical characteristics (size, shape, appearance, etc.) and mechanical properties (strength, stiffness, permeability, etc.) that design professionals can influence quantity of materials used and optimize performance, including environmental impacts, of concrete and concrete structures significantly through design decisions and project specifications. For example, using a higher-grade reinforcement and higher strength concrete for columns can reduce the section size and thereby the quantity of concrete and reinforcing steel. This results in more efficient and competitive designs, and the overall cost may be reduced.

A holistic approach is important. A focus on green construction should be appropriately balanced with maintaining (or not sacrificing) performance. Sacrificing performance may impact public safety (the intent of building codes) or require structures to be repaired or re-constructed at higher frequencies. This defeats the general purpose of sustainable development in the longer term.

PRESCRIPTIVE VERSUS PERFORMANCE SPECIFICATIONS

Specifications for concrete in construction documents establish project requirements where the contractor and material suppliers must comply. Project specifications that adhere to industry standard specifications, such as *ACI 301 Specification for Structural Concrete*, generally applicable for buildings, are supportive of performance-based criteria and sustainable concrete construction and can be adopted by reference in a project specification. However, many project specifications incorporate additional, unnecessary prescriptive requirements that contradict ACI 301 and detract from performance and environmental benefits.

A prescriptive specification imposes constraints on concrete mixture proportions or means and methods of construction. Examples of prescriptive criteria include limits on the composition of the concrete mixture such as minimum cement content, limits on the quantity and characteristics of supplementary cementitious materials (SCM), maximum water-cementitious materials (w/cm) ratio, grading of aggregates, etc.

A performance specification outlines the characteristics of the fresh and hardened concrete, depending on the application and aspects of the construction process that are necessary. These requirements should not restrict innovations by the concrete producer or the concrete contractor. Performance specifications should clearly specify the test methods and the acceptance criteria that will be used to verify and enforce the performance criteria. Performance specifications should provide the necessary flexibility to the contractor and producer to provide concrete mixtures that meet the performance criteria.

The general concept of how a performance-based specification works is as follows:

- There is a qualification and certification system that establishes the standards for concrete production facilities and the people involved.
- The design professional would define the performance requirements of the concrete for the different components of the structure.
- Producers and contractors would partner to ensure that the right mixture is designed, delivered and installed to meet the performance criteria.
- A submittal would document that the mixture will meet the specification requirements and include pre-qualification test results.
- While the concrete is being placed, a series of field acceptance tests would be conducted to determine if the concrete meets the performance criteria.
- There would be a clear set of instructions outlining what happens when concrete does not conform to the performance criteria.

Figure 2: Standing at 1,100 feet tall, the Wilshire Grand Center in Los Angeles is the tallest building west of the Mississippi. The building uses a mixed concrete and steel structural system consisting of composite concrete and steel floors that span from an internal concrete core to perimeter concrete-filled steel box columns. Concrete for the 18-foot thick mat foundation was kept cool by circulating chilled water through 90,000 feet of polypropylene hoses that were eventually filled with grout.

The best example of a performance criterion is strength. By specifying compressive strength, a concrete producer can design a mixture to meet the strength criteria through experience and testing. The mixture proportions are not specified, just the target strength leaving the product formulation entirely in the hands of the manufacturer. It permits the producer to develop a mixture that not only meets the strength requirement but also does it economically, where cement content can be minimized or supplementary cementitious materials (SCMs) such as fly ash, slag cement or other innovative technologies can be used to reduce cost, improve performance like workability and durability and reduce environmental impact.

On the other hand, the best example of a prescriptive criterion is minimum cement content. This takes away the ability of the concrete producer to optimize concrete formulation. What is often seen in a project specification is a compressive strength requirement in addition to a minimum cement content, and very often a contradictory maximum water-cement ratio. Generally, the minimum cement content requirement is much higher than would be required to meet the specified compressive strength. This results in concrete that is more expensive (cement is the most expensive ingredient in concrete). The concrete may crack from high shrinkage or thermal effects, and the cement increases the carbon footprint of the concrete (since cement has a relatively high carbon footprint).

INFLUENCE OF PRESCRIPTIVE SPECIFICATIONS: SUSTAINABILITY, PERFORMANCE AND COST

Common prescriptive requirements found in concrete specifications and their effects on performance, including sustainability and cost, are summarized in Table 1. Most of these requirements do not support sustainability goals and often increase the cost of concrete.

The intended concrete performance can be attained without specifying prescriptive requirements. The following is a detailed discussion of how prescriptive criteria listed in Table 1 can influence performance and sustainability of concrete.

GLOSSARY

1. Portland cement—Most common type of cement in general use around the world as a basic ingredient of concrete, mortar, stucco, and non-specialty grout

1. Portland cement—Most common type of cement in general use around the world as a basic ingredient of concrete, mortar, stucco, and non-specialty grout

2. Supplementary cementitious materials (SCMs)—fly ash, slag cement, and silica fume used to increase strength, durability and workability

3. Fly ash—one component of coal ash which is used as an SCM in concrete

4. Silica fume—Waste byproduct of processing quartz into silicon or ferro-silicon metals in an electric arc furnace, used as an SCM in concrete

5. Prescriptive specification—contains detailed descriptions of what specific materials must be used as well as the installation instructions

6. Low alkali cement—portland cements with a total content of alkalies not above 0.6 percent, used in concrete made with certain types of aggregates that contain a form of silica that reacts with alkalies to cause an expansion that can disrupt a concrete

7. Slag cement—hydraulic cement formed when granulated blast furnace slag (GGBFS) is ground to suitable fineness and is used to replace a portion of portland cement

8. Global Warming Potential (GWP)—developed to allow comparisons of the global warming impacts of different gases

9. ASTM—American Society for Testing and Materials, an international standards organization that develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services

10. LEED—Leadership in Energy and Environmental Design, most widely used green building rating system in the world

Table 1. Impact of Prescriptive Specification on Sustainability, Performance and Cost

Specification Provision	Impact		
	Sustainability	Performance	Cost
1. Restrictions on type and source of cement	↓	⇕	↑
2. Not permitting cements conforming to ASTM C1157 and ASTM C595	↓	⇔	⇔
3. Restriction on cement alkali content	↓	⇔	↑
4. Restriction on type and source of aggregates	↓	⇔	↑
5. Restrictions on characteristics of aggregates	↓	⇔	↑
6. Minimum content for cementitious materials	↓	⇕	↑
7. Restriction on quantity of SCM	↓	↓	↑
8. Restriction on type and characteristics of SCM	↓	↓	↑
9. Restriction on type or brands of admixtures	⇔	↓	↑
10. Same class of concrete for all members in a structure	↓	⇔	↑
11. Requiring higher strength than required for design	↓	⇔	↑
12. Invoking maximum w/cm when not applicable or one that is not compatible with the design/specified strength.	↓	⇔	↑
13. Requiring a high air content or requiring air content for concrete not exposed to freezing and thawing	↓	↓	↑
14. Restricting the use of a test records for submittals	↓	↓	↑
15. Restriction on changing proportions when needed to accommodate material variations and ambient conditions	↓	↓	↑
16. Requirement to use potable water	↓	⇕	↑
17. Not permitting recycled aggregates and materials	↓	⇕	⇕
18. Not requiring accredited testing labs	↓	⇔	↑
19. Specific limitations on slump	↓	↓	⇕

1. Cement Type and source: Specifications often restrict Type (e.g. ASTM Type II) of cement or restrict use to certain sources. Unless there is a building code requirement or specific reason for durability or other property, these restrictions should be avoided. These restrictions may force the use of materials unfamiliar to the producer, require a greater over-design, cause incompatibility with other materials and/or require material to be transported a longer distance. Use of innovative products may be prevented. These restrictions do not support environmental goals and most often increase the cost of concrete.

2. Cement specification: Specifications often restrict the use of cements to ASTM C150. Blended cements conforming to ASTM C595 and performance cements conforming to ASTM C1157 are optimized for performance by cement manufacturers and often have a lower carbon footprint. These include portland-limestone cements (Type IL) and those blended with pozzolans (Type IP) and slag (Type IS). Permitting the use of blended cements supports sustainability. Cost implications are neutral. Concrete producers still have the flexibility of using additional SCMs to develop mixtures to meet the needs of a project.

3. Low alkali cement: Specifications often require the use of a low alkali cement to minimize the occurrence of deleterious expansive cracking due to alkali silica reactions. Manufacturing low alkali cements increases the use of natural resources and energy and can increase waste generation during cement manufacture. It should be noted that a recent revision to ASTM C150 has removed the option to order a low alkali cement. It is recognized that the total alkali content in concrete from the cement is more significant. Mitigation of alkali silica reactions can be accomplished using SCMs and admixtures. Requiring the use of low alkali cement will increase cost and not support environmental goals. It should be noted that alkali silica reactivity is only a concern when concrete is exposed to moisture; therefore, most concrete in buildings is not affected.

4. Type and source of aggregate: Specifications may restrict the aggregate type and require the use of a specific source—crushed vs. gravel, mineralogy, specific supplier or source, etc. This could force the use of materials that the producer may not be familiar with and prevent mixtures from being optimized for performance. The cost of aggregate might increase due to transportation. These requirements will not support sustainable development and can adversely impact performance. There may be situations where imported aggregates may be necessary. Examples include higher modulus or for architectural concrete.

5. Characteristics of aggregates: Specifications often place restrictions on the characteristics of aggregates, such as grading, specific gravity, particle shape and size. In some areas, local aggregate supplies may not comply with all requirements of referenced specifications, such as ASTM C33, but have a good history of use. This allowance is recognized in the building codes. However, when the requirements prevent the use of local materials or require use of materials that are not commonly used or locally available, it will increase cost and detract from sustainable development without significant benefits in concrete performance.

6. Limits on Cement content: Many specifications impose minimum cement content for different classes of concrete. Requiring minimum cement content constrains the innovation of the concrete producer to optimize concrete mixtures, can result in inherent incompatibility with other requirements of the specifications, such as strength or w/cm. These can result in unintended consequences, such as increased volume changes due to temperature or drying shrinkage that will result in cracking or reduced durability. It is a fallacy to assume that higher cement content results in improved durability. Minimum cement content requirements can impact cost and the environment with questionable benefits to quality, performance and durability.

On the other hand, attempts to force green construction should not set limits on maximum cement content. This could compromise constructability or performance of concrete in the structure resulting in reduced service life.

7. Quantity of SCM: Some specifications place limits on the quantity of SCMs. Often, the use of more than one type of SCM is prohibited. This prevents optimizing concrete mixtures for performance and durability. The only building code restriction is for exterior concrete subject to application of deicing chemicals. Maximum limits on the quantity of SCM increases cost and does not support sustainable development. Increasingly, projects seeking green certification impose prescriptive requirements on concrete mixtures such as minimum replacement for cement or minimum recycled content. These requirements can often impact the performance of fresh and hardened concrete properties, such as setting characteristics, ability to place and finish and rate of development of in-place properties. In the long run, this may impact the quality of construction or the service life of the structure. The implication to initial cost may be reduced, but it could cost more in the long term. Alternatives to limiting quantities of SCM to lower environmental impact are discussed later.

Figure 3: Denver International Hotel & Transit Center in Denver used complex mix designs including high strength, self-consolidating and lightweight concrete for the transit and hotel canopy abutments, the hotel ballroom's transfer beams and slab and the structure's sloping roof deck. Many of the walls and columns within the structure are "architecturally exposed," requiring a clean and attractive finish. Beyond being able to fulfill the project's design challenges, builders chose concrete for its fire resistance and strength.

This article continues on http://go.hw.net/AR122019-2. Go online to read the rest of the CEU course, complete the corresponding quiz for credit, and receive your certificate of completion.

QUIZ

1. Prescriptive specifications impose constraints on concrete mixture proportions or means and methods of construction. These include:
   - a. Minimum concrete content
   - b. Limits on the composition of the concrete mixture
   - c. Limits on the quantity and characteristics of supplementary cementitious materials
   - d. All of the Above

2. According to the course, the best example of a performance criterion is _______, which allows the producer to design a mixture that can meet the criteria through experience and testing.
   - a. Strength
   - b. Water
   - c. Height
   - d. Air content

3. Specifications often require the use of a _____ alkali cement to minimize the occurrence of deleterious expansive cracking due to alkali silica reactions.
   - a. High
   - b. Low
   - c. Medium
   - d. Ultra-high

4. According to the course, some situations may require imported aggregates such as:
   - a. Higher modulus
   - b. Architectural concrete
   - c. Both A & B
   - d. None of the above

5. Air content requirements vary by aggregate size because the volume of paste changes. It is permitted to reduce air content when the specified strength exceeds _____ psi.
   - a. 1000
   - b. 2000
   - c. 5000
   - d. 2500

6. The quality of water being used to produce concrete and the provisions permitting the use of non-potable water with proper testing and evaluation is addressed in which regulation?
   - a. ASTM C1602
   - b. ASTM 1508
   - c. ICC 9876
   - d. ASTM C1800

7. According to the course, for a concrete mixture to be sustainable, it must meet performance requirements of the key stakeholders and meet the following criteria:
   - a. Minimize energy and CO2 footprint
   - b. Minimize potable water use and waste
   - c. Increase use of recycled content
   - d. All of the Above

8. A ________ is the investigation and evaluation of the environmental impacts of a product, process or service.
   - a. Life Cycle Assessment (LCA)
   - b. Environmental Product Disclosure
   - c. ICC Report
   - d. Responsible Sourcing

9. Under the LEED Product Disclosure and Optimization Credits, which of the following reports are verified and disclosed:
   - a. Environmental Product Declarations
   - b. Health Product Declarations
   - c. Corporate Sustainability Reports
   - d. All of the Above

10. Based on research conducted at MIT, greenhouse gas emissions due to operational energy of the building are responsible for ___________ of life cycle emissions.
    - a. 20–25%
    - b. 30–35%
    - c. 60–70%
    - d. 95–96%

SPONSOR INFORMATION

BUILD WITH STRENGTH

Build with Strength, a coalition of the National Ready Mixed Concrete Association, educates the building and design communities and policymakers on the benefits of ready mixed concrete, and encourages its use as the building material of choice. No other material can replicate concrete's advantages in terms of strength, durability, safety and ease of use.

8. Type and characteristics of SCMs: Specifications often prohibit the use of some types of SCMs or impose restrictions over and above those in the ASTM material specifications—such as lime content, alkali content, loss on ignition or grade of slag cement. These will prevent the use of locally available materials that likely have good past performance and will require materials to be imported. The result will increase cost and detract from meeting environmental goals while the impact on performance is questionable.

9. Type and brand of admixtures: Most specifications include a list of specific admixture brands and suppliers. Often the listed products are no longer available in the market. Concrete producers frequently have business relationships with admixture suppliers and have experience with the use of certain products. Forcing the use of specific products will impact the ability of the concrete producer to provide concrete mixtures of consistent quality and performance.

10. Same class of concrete for all components: Concrete members in a structure are often designed based on different strength levels and exposure classes. Requirements for foundations may differ from beams and columns; slabs may have different requirements. Specifications often indicate the same class for all concrete on a project. This can cause problems during placing and finishing. There are considerable cost savings and environmental benefits if the concrete is specified as required for the different structural members on a project. It makes sense to use high strength concrete for columns and shear walls, for example, but it rarely benefits slabs and beams. Also, exposure classes should be assigned to specific components. For example, concrete protected from the environment and not subject to freezing and thawing should not have the same exposure class as concrete exposed to weather.

11. Higher strength than required by design: If a higher strength is specified or required for durability, designers should use that to their advantage when designing the structure and minimize section size when applicable.

12. Max w/cm when not required: The building code requires the use of a maximum w/cm for durability and assigns a minimum specified strength that is in alignment with the required w/cm. Many specifications incorporate limits on w/cm for elements not subject to durability concerns. This includes all interior concrete. Imposing a low w/cm limit likely increases the cement content of concrete mixtures and affects the ability to place and finish concrete. Use of a max w/cm, where not required, increases cost and does not support sustainable development.

13. Air content: Air content requirements for concrete vary by aggregate size because the volume of paste changes. It is further permitted to reduce the specified air content when the specified strength exceeds 5000 psi. In many vertical members that will not be critically saturated and require a high design strength, air-entrained concrete may not be required. Air-entrained concrete is not required for interior structural members. Many regions in the southern US have a long history of durable concrete that is not air entrained, even though temperatures may occasionally dip below freezing. Most specifications state a constant air content requirement regardless of aggregate size and often increase it, assuming this will improve freeze-thaw durability. Air content reduces strength, and additional cement is required to offset this strength decrease. This can result in increased propensity for thermal and shrinkage cracking. Specifying air content that is not appropriate for a structural member increases cost and materials while likely reducing performance and sustainability.

14. Use of test record for submittals: Specifications often indicate that the concrete mixture should be designed to produce an average strength at a fixed value greater than the specified strength. This essentially prohibits the use of past test records that allows for a statistically based average strength. This discourages concrete producers that have good quality control from optimizing concrete mixtures to a lower strength level and thereby conserving materials. This requirement increases cost, does not support sustainable concrete and could result in unintended problems due to high cementitious materials content.

15. Restriction on changes to mixtures: Ingredient materials vary as do environmental conditions during the project. Real time adjustments are necessary to accommodate these variations and to ensure consistent concrete characteristics. Several specifications prohibit such minor changes to concrete unless a submittal, often with supporting test data, is provided to the engineer of record. It is recognized that the engineer of record should be notified for major revisions to mixtures, but prohibition of changes can cause considerable negative impact to concrete performance.

16. Use of potable water: ASTM C1602 addresses the quality of water that can be used to produce concrete and includes provisions to permit the use of non-potable water with proper testing and evaluation. Specifications that prohibit the use of non-potable water increase cost and result in the generation of considerable volumes of wastewater. Specifications that require the use of potable water detract from sound environmental management practices at concrete production facilities.

17. Recycled materials and aggregates: There are applications for concrete that can accommodate the use of recycled aggregates or other materials with minimal impact to concrete quality. Crushed returned concrete can be used as a portion of the aggregate for some applications to conserve virgin materials and minimize waste. The use of recycled material can contribute to credits in green construction rating systems. The use of crushed concrete as aggregate is recognized in industry standards. Judicious use of these materials will reduce cost and conserve natural resources and landfill space with minimal impact on performance.

18. Reliable testing: Improper testing procedures will increase variability and result in greater over-design of concrete mixtures. When concrete producers are aware of improper testing, they protect themselves by increasing the cementitious materials in concrete mixtures. This results in increased cost and does not support sustainable development. Selection of testing agencies should be based on quality of work, conformance to ASTM C1077 and having certified personnel conducting tests. Test reports should be distributed to producers as soon as available to help identify potential problems early.

19. Specific limitations on slump: Slump should be selected by the contractor and concrete supplier based on the placement and finishing requirements of the concrete. With the use of water reducing admixtures, slump cannot be taken as a representation of the quantity of water in the mixture. The target slump can be provided to the engineer of record in the submittal and can be used as a basis for quality assurance. Placing limits on slump usually results in reduced sustainability and performance and can increase cost.

EXAMPLE 1: AVOID SPECIFYING MIXTURE PROPORTIONS

The proportions of ingredients used for concrete mixtures can have a significant influence on the environmental footprint of concrete, but this determination should not be limited to the mixture composition—the impacts to constructability and performance of the structure must also be considered. For example, the mix design shown in Table 2 has 50% SCMs, which would generally be considered to have a low carbon footprint. Is this mixture sustainable? It is difficult to tell. This mixture may have higher compressive strength than that required for structural design. If the concrete was being proposed for a mass concrete member, one would generally need to have 70% slag cement to reduce temperature rise from heat of hydration. If this concrete mixture was being proposed for post-tensioned floors, it might not gain strength at an early enough age to allow post-tensioning in a timely manner, thus prolonging the construction schedule.

Table 2: Example concrete mix design

Portland cement	350 lb/yd^3
Slag cement	300 lb/yd^3
Silica fume	50 lb/yd^3
Coarse aggregate	1800 lb/yd^3
Fine aggregate	1200 lb/yd^3
Water	300 lb/yd^3
Air content	6%

In general, for a concrete mixture to be sustainable, it must be able to meet the performance requirements of the owner, designers, contractor and producer in addition to meeting the following criteria that support sustainable construction:

- Minimize Energy and CO_2 Footprint
- Minimize Potable Water Use
- Minimize Waste
- Increase Use of Recycled Content

SUGGESTED SPECIFICATIONS

One non-profit organization that represents and serves the concrete industry has developed a *Guide to Improving Specifications for Ready Mixed Concrete* guide to help designers improve concrete specifications. The following are a few general recommendations for proposed specification language (italics):

Manufacturer Qualifications: Concrete shall be supplied with the following current certifications:

- *Certified Concrete Production Facility*
- *Producer Quality Certification*
- *Green-Star Certification*
- *Quality Control personnel with responsibility for concrete mixtures certified as a Concrete Technologist Level 3*

The same organization has developed several education and certification programs to help qualify concrete producers to design, batch and deliver concrete for performance-based products while meeting the strictest environmental requirements.

Concrete Mixtures: Prepare design mixtures for each class of concrete on the basis of laboratory trial mixtures or field test data, or both according to ACI 301. Design mixtures shall meet the specified strength requirements listed below:

This is where the design professional can specify physical characteristics and mechanical properties of the concrete along with the durability criteria without prescribing the mix design. The guide specification provides alternate performance tests and criteria for ASR, shrinkage, etc.

LEED PROJECTS

LEED, along with other green building standards offer guidance for reducing environmental footprint of building materials. *Guide Specification for Concrete for LEED Projects* has also been published by the non-profit organization mentioned above. The documents focus on the Material and Resources (MR) credits of LEED and how to specify concrete to meet the intent of the credits.

Table 3: Specification for different components of concrete in a building

Application	Nominal Max. Aggregate Size*	Exposure Class*	f'c*
Interior slabs and beams	3/4 in.	F0, S0, P0, C0	4,000 psi
Interior Columns	3/4 in.	F0, S0, P0, C0	5,000 psi
Footings	1-1/2 in.	F0, S1, P0, C1	4,000 psi
Exterior slabs and beams	3/4 in.	F3, S0, P0, C1	5,000 psi

*Values are for example only. Each project would require a different set of criteria.

Figure 4: The Triangle Building in Denver used fifteen types of concrete including shotcrete, cast-in-place, high strength and lightweight concrete. Each variety serves a particular purpose and contributes to the building's LEED Gold Certification.

LEED MR credits attempt to take a holistic look at materials by adopting life cycle assessment (LCA) and product disclosure and optimization. LCA is the investigation and evaluation of the environmental impacts of a product, process or service. LCA evaluates all stages of a product's life to determine its environmental life cycle impacts. LCA is the most comprehensive approach to determining environmental impacts of a building. There is a credit in LEED called Building Life-Cycle Impact Reduction that rewards points if the building has lower life cycle impacts than a baseline building.

Whole Building LCA Credit: Specifications can require that product suppliers submit Life Cycle Inventory (LCI) data for their products or Environmental Product Declarations (EPDs) to help the design team conduct a Whole Building LCA. The concrete industry leads the way in conducting LCAs and publishing EPDs for their products. Many organizations, including the non-profit discussed above, have published EPDs for concrete and most would be willing to publish EPDs specifically for a project. The following example helps specifiers understand how concrete can contribute to lowering the overall footprint of a building and help meet the intent of the Building Life-cycle Impact Reduction credit in LEED.

EXAMPLE 2: USING LCA TO DEMONSTRATE LOWER IMPACTS

In this example, a cradle-to-gate LCA was conducted to determine the embodied impacts of concrete on a building to compare the Global Warming Potential (GWP) or carbon footprint of a reference building using typical concrete mixes with moderate amounts of SCMs, both fly ash and slag, and a proposed building using concrete mixes with relatively high volumes of fly ash and slag. The building is an 18-story residential tower located in the northeastern United States. For illustration purposes, only six different concrete mixes are selected for the project. In reality, a project of this size might have more concrete mixes. Compressive strengths and concrete volumes for each structural element are identified in Figure 5.

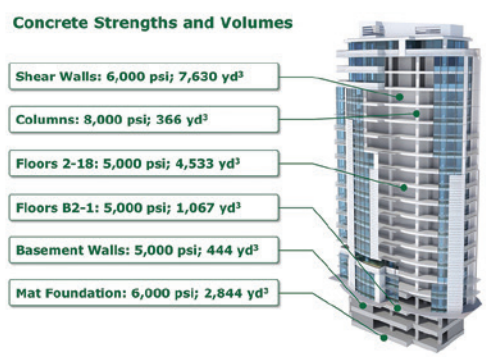

Figure 5. Specified compressive strength of concrete for an 18-story residential tower.

Table 4. Mix designs selected for the reference building (from benchmark report)

Concrete Element	Specified Compressive Strength (psi)	Portland Cement (lb/yd^3)	Slag Cement (lb/yd^3)	Fly Ash (lb/yd^3)	SCM content
Mat Foundation	6000	782	119	82	20%
Basement Walls	5000	741	112	78	20%
Floors B2-1	5000	741	112	78	20%
Floors 2-18	5000	741	112	78	20%
Shear Walls	6000	782	119	82	20%
Columns	8000	967	147	102	20%

Table 5. Mix designs selected for the proposed building (from IW EPD)

Concrete Element	Specified Compressive Strength (psi)	Portland Cement (lb/yd^3)	Slag Cement (lb/yd^3)	Fly Ash (lb/yd^3)	SCM content
Mat Foundation	6000 psi	256	342	256	70%
Basement Walls	5000 psi	242	323	242	70%
Floors B2-1	5000 psi	512	0	341	40%
Floors 2-18	5000 psi	581	0	249	30%
Shear Walls	6000 psi	427	256	171	50%
Columns	8000 psi	503	302	201	50%

The first step in the analysis is to identify typical concrete mixtures for the reference building. One organization publishes benchmark mix designs and their environmental impacts for eight different regions in the United States. This example uses the benchmark mix designs for the Northeast region.

The next step is to estimate mix designs that have significantly lower GWP than the benchmark mixes that still meet the performance criteria (strength, durability, etc.). It is important to keep in mind that concrete requiring high early strength should be limited to around 30% replacement of fly ash or slag. Concrete that does not require early age strength such as footings, basement walls and even some vertical elements like columns and shear walls could have as much as 70% fly ash and/or slag and could be tested at 56 or 90 days (instead of 28) to account for slower strength gain. These applications can also incorporate a significant volume of recycled aggregate with less risk. This example uses high volume SCM mixes from the organization's Industry-Wide EPD. A summary of the concretes selected for the reference and proposed building are provided in Tables 4 and 5.

Using the Athena Impact Estimator for Buildings (Athena IE) software, the reference building and proposed building were defined using the proposed mixes in Table 4 and 5 respectively. Athena IE has the benchmark mixes and the Industry-Wide EPD mixes pre-loaded into the software. The software also permits the user to define new mixes based on the existing mixes in the library or completely new mixes if that information is available from a concrete producer.

Once all the concrete information is defined for each project, the user can then run a report that will provide the estimated GWP along with other impacts for each building. The reference building will represent the largest impacts, and the proposed designs will represent lower impacts. The results for this example showed that the reference building has a GWP for concrete of 6.14 million kg CO_2 while the proposed building has a GWP for concrete of 3.92 million kg CO_2, meaning that the high volumes of fly ash and slag mixes resulted in 36% reduction in GWP.

Proposed Specification Language

There are several ways one could write a project specification that would result in 30% reduction in GWP for concrete on a project. The following are two options:

Option 1

Supply concrete mixtures such that the total Global Warming Potential (GWP) of all concrete on the project is less than or equal to 4,298,000 kg of CO_2 equivalents as calculated using the Athena Impact Estimator for Buildings Software available at www.athenasmi.org.

Option 2

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 stipulated benchmark mixes. 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.

This example was simplified for illustration purposes. It only considered the effects of concrete during the material extraction and manufacturing stage on the environmental impacts of the building. For LEED, one must consider the impacts of all the materials and products associated with the structure and enclosure including structural elements such as concrete, reinforcing steel and structural steel (including fireproofing) and exterior cladding such as glass, aluminum and insulation. The Athena IE software does contain environmental impact information for most materials and products used in buildings and outputs the six environmental impacts required for the LEED v4 LCA credit. In addition, the Athena LCA software allows the user to input energy consumption data obtained from an energy analysis making it an ideal tool for conducting whole building LCA.

Product Disclosure and Optimization Credits: Product disclosure means reporting environmental, social and health impacts through third party verified reports, including Environmental Product Declarations (EPDs), Corporate Sustainability Reports (CSRs) and Health Product Declarations (HPDs), among others.

There are three Building Product Disclosure and Optimization credits, each having various options to lower impacts. The first option, Disclosure, requires the project use a certain number of permanently installed products that disclose impacts using EPDs, CSRs and/or HPDs. In LEED, a "product" is defined by the distinct function it serves. That means concrete has the advantage of contributing significantly because of concrete's wide range of applications or functions. For example, footings, foundations walls, shear walls, bearing walls, columns, beams, slabs, sidewalks and parking areas, each with a unique mix design, would all be considered different products in LEED and therefore contribute significantly to the number of products required to meet the intent of the credit.

The second option, Optimization, requires a certain minimum value of building products to demonstrate they perform better than previously disclosed impacts.

INFLUENCE OF DESIGN DECISIONS

Although project specifications can affect the performance of a project, the single biggest influence an architect and engineer can have on the environmental impacts of a structure is through efficient design. The following are several factors that affect the performance of concrete and concrete structures:

Design Loads. Every structure, at a minimum, must be designed to resist forces from gravity, service, wind, earthquakes, water, soil, fire and blast, among others. If a structure does not meet these minimum requirements, it would be deemed unsafe and therefore unsustainable. Usually a structural engineer designs the structure to resist minimum loads prescribed in a building code. Alternatively, the owner can choose higher loading to resist natural disasters or other loading over and above the building code minimums. Having a structure that can resist disasters without suffering significant damage would be considered more sustainable. After all, a green building that is destroyed during a natural disaster will ultimately increase environment burden since materials in the building (structure, fixtures, furnishings, etc.) will end up in landfills, and the building will be rebuilt using new materials.

Figure 6: Edith O'Donnell Arts & Technology Building, University of Texas, Dallas, uses a partially exposed concrete structure to take advantage of concrete's thermal mass properties which trap heat during cold months and keep structures cooler during warmer weather. Concrete's long life and durability is important for academic buildings that must address the needs of the university and its students for many decades. Some of the same properties that make concrete strong (its mass and rigidity) also make it virtually soundproof. The beauty of concrete is on full display in the partially exposed structure including polished concrete floors and beams in the lobby. The project achieved LEED Silver.

Structural Efficiency. Regardless of the design loading, an architect's and structural engineer's objective is to design the structural system for optimized performance and to minimize waste. There is no point in having a concrete mixture with low environmental impact if the structural member is overdesigned by 20%. Not only can efficient design lower the impact of the structural system, but it also tends to reduce impacts of other materials. For example, minimizing the depth of beams in the structure can significantly reduce the floor-to-floor heights of a building, thus leading to reduced quantity of exterior cladding and interior finishes which can lower environmental impacts of a building significantly.

Durability. A structure that needs constant maintenance and repair results in significant environmental impact. Structures exposed to harsh environments must be designed appropriately to resist deterioration. For concrete, that usually means consideration of freezing and thawing cycles, abrasion, chlorides (from road salt or marine environments) or sulfates (contained in soil or water). A combination of good design detailing along with durable concrete mix designs can result in a durable concrete structure. Appropriate concrete cover, corrosion resistant reinforcement, low permeability concrete, effective use of supplementary cementitious materials (SCMs), chemical admixtures that improve corrosion resistance, surface coverings and crack control are all potential strategies for providing a durable concrete structure. As discussed above, design professionals should assign exposure classes to concrete based on the severity of the anticipated exposure of structural concrete members. The building code provides specific requirements for concrete mixtures to resist various levels of exposure. In most cases the requirements are performance-based, thus eliminating the need for engineers to specify additional prescriptive criteria.

Constructability. Design decisions can also affect constructability. Smaller members with congested reinforcement take more time and energy and are typically more costly to construct. A project specification that requires a minimum quantity of fly ash greater than normal use could result in delayed strength gain that could add to the construction schedule since floors might not be able to be post-tensioned within a reasonable time frame or a bridge deck might not be able to open to traffic without significant delays. A project specification with a maximum limit on slag cement could result in concrete used for massive members to produce high heat of hydration and result in significant cracking. A project specification that limits slump to a certain value could result in concrete that cannot be pumped efficiently or finished effectively. All these consequences of prescriptive specification requirements could render the project unsustainable.

Energy Efficiency. Concrete buildings are typically more energy efficient than lighter framed buildings because of thermal mass. Thermal mass is a material's ability to store heat and release it over time. There are three characteristics of thermal mass. First, the time lag between peak heating and cooling loads and outside temperature peaks is greater for massive buildings. This feature can be used in buildings by delaying the need for heating or cooling energy to take advantage of off-peak demand. In an office building, that means heat gain can be delayed until everyone has gone home. Second, massive buildings have lower

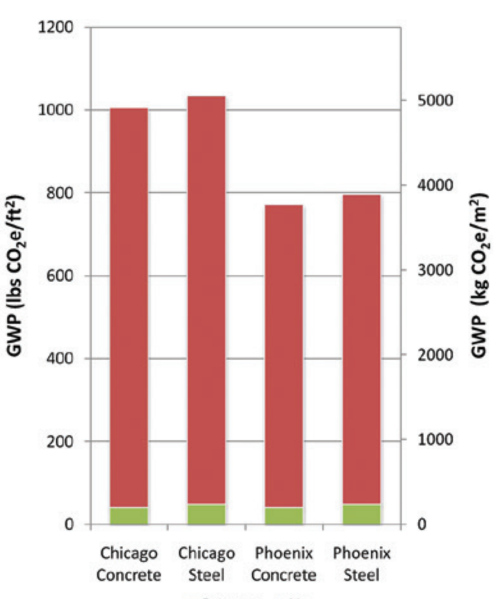

Figure 7. Total Global Warming Potential (GWP) over 60-year lifespan for commercial buildings.

Figure 8: The Gateway, Maryland Institute College of Art, Baltimore uses concrete to form distinctive circular structures sectioned into three pods of residential units surrounding a private central courtyard. The round shape of the residential wing, one of the building's central features, was formed by a faceted cylinder elevated on slender concrete columns. Concrete balconies and walkways ring the interior of the hollow residential wing, providing for basic circulation as well as vantage points for watching outdoor performances in the courtyard. The flexibility of concrete is on full display in the drum shape of the residential wing. Concrete structural slabs create the support the building needs to achieve its unique design.

peak heating and cooling loads allowing for smaller more efficient heating and cooling equipment. And third, massive buildings require less overall heating and cooling energy to maintain the same interior temperatures since temperature swings are moderated.

In a research report published by the Massachusetts Institute of Technology (MIT), the effects of thermal mass were explored using life cycle analysis for a 12-story, 46,321 m^2 (498,590 ft^2) commercial building. The building was analyzed for a 60-year life for two climates in two cities, Phoenix and Chicago, and for two different structural materials, concrete and steel. The analysis demonstrated that the greenhouse gas emissions due to operational energy of the building are responsible for 95–96% of life cycle emissions. Figure 7 demonstrates that the concrete building has approximately the same embodied emissions as steel but has lower operating emissions, which can lead to lower life cycle emissions.

Aesthetics. An architect can specify concrete with color, shape and texture for nearly any application. This distinguishes concrete from most other material in the sense that the surface of concrete structural systems can be exposed on the interior or exterior of a building. This helps to reduce the need for additional finish material, thus reducing environmental impact.

CONCLUSIONS

An environmentally conscious building owner is interested in a concrete structure that provides a long service life without significant defects and that has a low environmental footprint, not necessarily how much cement it contains. Using a performance specification, the concrete producer is free to select the mixture proportions and is held responsible for meeting the performance criteria. Since performance specifications would allow for mixture optimization and mixture adjustments during the project, there is an incentive for the designer and the producer to collaborate for optimal mix technology. With a performance specification, a superior concrete producer can improve product quality, stimulate innovation, reduce construction cost and minimize construction time—all while reducing environmental footprint. ■

REFERENCES

Guide to Improving Specifications for Ready Mixed Concrete, National Ready Mixed Concrete Association, Alexandria, VA, 2015. https://www.nrmca.org/research_engineering/RMC_Specs_Guide.htm.

Certified Concrete Production Facility, Producer Quality Certification, Green-Star Certification, Concrete Technologist Level 3, National Ready Mixed Concrete Association, Alexandria, VA, https://www.nrmca.org/certifications/

Guide Specification for Concrete for LEED Projects, National Ready Mixed Concrete Association, Alexandria, VA, 2016, https://www.nrmca.org/sustainability/EPDProgram/Downloads/LEEDv4GuideSpecforConcrete2-24-16.pdf

NRMCA Member National and Regional Life Cycle Assessment Benchmark (Industry Average) Report_Version 2.0, NRMCA Member Industry-Wide EPD for Ready Mixed Concrete, National Ready Mixed Concrete Association, Alexandria, VA, https://www.nrmca.org/sustainability/EPDProgram/Index.asp