Presented By:

The Top 10 Ways to Reduce Concrete's Carbon Footprint

960 W. 7th Street, Los Angeles. The design and construction team implemented several Top 10 strategies to reduce the embodied carbon of concrete for this new residential tower in Los Angeles. Photo: Courtesy of Brookfield Properties.

INTRODUCTION

Concrete is unique among building materials. Its formulation is highly influenced by its application. Design professionals and contractors have a greater influence on concrete formulation than they do with other building products. Concrete can be made stronger, lighter, more flowable, stiffer, less permeable, and even weaker depending on performance needs. All these formulations can be made at the same factory, within minutes of one another. No other building material is that versatile. Concrete does not rot, rust, or burn. It can be exposed to the elements or exposed for architectural reasons. Concrete is economical, available nearly everywhere, and made from the most abundant materials on the planet, usually from local sources.

Concrete is used for the tallest buildings, the longest bridges, the largest buildings, the busiest airports, the most efficient rapid transit systems, roadways, theaters, stadiums, schools, apartment buildings, and houses. Drinking water is transported in concrete pipes and reservoirs, and waste is treated in wastewater treatment plants made of concrete. Concrete is used in nearly every structure where people live, work, learn, and play. It is part of the infrastructure that connects us. It's the material that helped build modern society and will likely be part of improving modern society for some time.

According to UN Environment, Global Status Report 2017, the world is projected to add 320 billion m^2 (3.4 trillion ft^2) of buildings by

LEARNING OBJECTIVES

1. Understand the basics of embodied carbon of concrete.
2. Evaluate the immediate steps that can be taken to reduce carbon footprint when specifying concrete.
3. Prioritize design strategies to get the greatest reductions in carbon footprint using current technologies and design tools.
4. Explore how innovative technologies will result in zero carbon concrete in the future.

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2060. That's an area equal to 1.4 times the entire current global building stock. The UN report urges building designers and owners to design disaster-resilient buildings for the future, with zero-energy consumption. Because of its thermal mass, concrete has long been the material of choice for energy efficiency, and because of its strength and durability, it has been the material of choice for disaster resilience. However, the UN report also urges the building industry to reduce the embodied impacts of building materials.

This article will discuss how design and construction teams can implement ten simple strategies to reduce concrete's carbon footprint today. The recommendations are listed broadly in order of priority, but not in order of impact reduction. All are important and should be implemented. In addition, the strategies are meant to achieve a lower carbon footprint without impacting other traditional performance criteria for concrete.

THE TOP 10 LIST

1. Communicate carbon reduction goals
2. Ensure good quality control and assurance
3. Optimize concrete volume
4. Use alternative cements
5. Use supplementary cementitious materials
6. Use admixtures
7. Don't limit ingredients
8. Set targets for carbon footprint
9. Sequester carbon dioxide in concrete
10. Encourage innovation

IMPLEMENTING THE TOP 10 CARBON REDUCTION STRATEGIES

1. COMMUNICATE CARBON REDUCTION GOALS

One of the basic tenets of achieving a goal is to effectively communicate that goal to everyone on the team. For concrete, that is especially important because there are so many parameters and criteria for concrete mixtures that the goal of reducing embodied carbon may get lost in the clutter.

Drawings and specifications are the primary means through which project goals are communicated to the owner, contractor, and product suppliers. When it comes to embodied carbon, product manufacturing is paramount. Therefore, sustainability goals should be communicated to product manufacturers. This not only applies to concrete but to the majority of building products.

Most product manufacturers bid on a project armed with a set of drawings and are often only provided the section of the specification affecting their work. For concrete, that is section 03300. However, in many instances the sustainability related requirements are placed in section 01000. If a concrete contractor and product manufacturer do not see Section 1 of the specification, then they will be unaware of any carbon reduction goals regarding concrete.

Recommendations

Collaborate

Collaborate with concrete producers and contractors. Invite them in for a meeting or charrette with your design team. Understand what technologies and concrete ingredients are available locally. Just because a product (slag cement for example) isn't generally used in a market, it doesn't mean you should not specify or prohibit its use. Generally, the reason a product is not used is because there is no demand for it. You need to create the demand by permitting and encouraging its use.

Specification

SECTION 03300—CAST-IN-PLACE CONCRETE
PART 1—GENERAL
1.1 SUSTAINABILITY GOALS

A. This project has a goal of reducing the embodied carbon footprint over a typical project by 20%*. To accomplish this goal, we are targeting a carbon footprint reduction for concrete of 35%* over benchmark established in the concrete industry's Cradle-to-Gate Life Cycle Assessment Version 3.[1] Specific targets for Global Warming Potential (GWP) are provided in Section 2, CONCRETE MIXTURES. To accomplish this goal, we are encouraging the use of innovative products and processes for manufactured concrete and will consider proposals for mix designs that can demonstrate they meet all performance criteria for strength, durability, constructability, and cost in addition to reducing carbon footprint.

* These values are for demonstration purposes only.

GLOSSARY

Blended cements—combine ordinary portland cement (OPC) with other materials; the most common is portland limestone cement (PLC).

Environmental Product Declaration (EPD)—an independently verified and registered document that communicates transparent and comparable information about the life-cycle environmental impact of products.

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

Portland-Limestone Cement—blended cement combines up to 15% limestone interground with OPC to make a cement with a carbon footprint that is up to 10% lower than OPC with performance that is identical to—and in some cases better than—OPC.

Supplementary Cementitious Materials (SCMs)—can be used for improved concrete performance in its fresh and hardened state. They are primarily used for improved workability, durability, and strength. These materials allow the concrete producer to design and modify the concrete mixture to suit the desired application.

Sustainable Development—meeting the needs of the present without compromising the needs of future generations

Type IL (X)—portland-limestone cement where "X" can be between 5 and 15% limestone.

Type IS (X)—portland-slag cement where "X" can be up to 70% slag.

Type IP (X)—portland-pozzolan cement where "X" can e up to 40% pozzolan (fly ash is the most common).

Type IT (X) (X)—ternary blended cement where "X" can be up to 70% of pozzolan +limestone + slag, with pozzolan being no more than 40% and limestone no more than 15%.

Pre-bid Meeting

It is also important to communicate carbon reduction goals in other ways. Most projects have pre-bid meetings, which can be opportunities to communicate carbon reduction goals for all products to all potential bidders.

2. ENSURE GOOD QUALITY CONTROL AND ASSURANCE

This is important for all products, but it's especially critical for concrete. Concrete is made from local materials and its performance can be affected by weather conditions, variability of materials, delivery, placing, handling, and testing. Although the materials used to make concrete meet rigorous standards, the variability can be quite high.

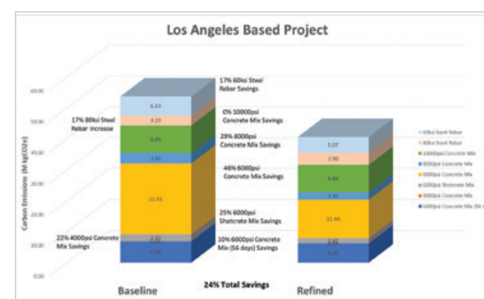
Quality Control

Almost all concrete has compressive strength as one performance criterion. Concrete producers design concrete mixtures to meet the needs of the contractor in terms of workability (flowability, pumpability, finishability, etc.) based on their local aggregates, and then using sufficient quantity of cementitious materials—usually a combination of portland cement and supplementary cementitious materials—to achieve the required compressive strength, which is higher than the specified compressive strength. The "overdesign" (the difference between the actual average compressive strength and the specified compressive strength) is based on well-established statistical methods described in the codes and standards for concrete. If a concrete producer has a good quality control process and a history of consistent test results for a mix design, the overdesign can be relatively small, say 400 to 600 psi for 4,000 psi concrete. But if quality control is poor, or there is no history of test results, then the overdesign can be much higher: 1,200 psi or higher for 4,000 psi concrete.

Lower overdesign means lower cementitious materials content. For example, going from 1,200 psi to 600 psi overdesign would likely require 60 lbs less cementitious material, potentially an 8% decrease in embodied CO_2. The key here is to minimize the overdesign through good quality control. Having manufacturing equipment in good working order, using proven quality

CASE STUDY: 960 W. 7TH STREET, LOS ANGELES

Developer: Brookfield Properties
Design Architect: Marmol Radziner
Executive Architect: Large Architecture
Structural Engineer: MKA
Contractor: Webcor
Concrete Supplier: National Ready Mixed Concrete Company
Photo: Courtesy of Brookfield Properties



Background

960 W. 7th Street is a distinctive multifamily high-rise development located in the heart of downtown Los Angeles. This 64-story tower has 780 residential units totaling 807,000 square feet.

Challenges

Projects of this magnitude have challenges when it comes to balancing cost, long term value, energy efficiency, occupant comfort and sustainability. The design team, developer, contractor and product suppliers need to have the same goals in mind when it comes to reducing environmental impact, including carbon footprint.

Sustainable Solutions

Structural engineers play a key role in selecting the structural system for most buildings, especially for a high-rise in a high seismic zone. In working with the design team to best meet project goals, the engineering firm proposed cast-in-place post-tensioned slabs, with a centralized buttressed concrete core that tapered with height. This system optimized floor to floor heights, eliminated transfers, and worked with unit and public spaces to optimize net/gross floor ratios while preserving unobstructed views at the building perimeter. The firm's optimization also included Performance Based Seismic Design, and 80 ksi rebar wherever it led to a material reduction.

They also developed a low carbon performance-based specification and procurement strategy with the architect and developer, which worked closely with the use of the new Embodied Carbon Construction Calculator (EC3) tool. They used BIM to quantify material quantities and to estimate the embodied carbon of those materials, which were measured using industry average EPDs during design, and product specific EPDs whenever possible after product suppliers became known. "After you know your quantities, the math for performance oriented like material comparisons is simple," states Don Davies, president of the engineering firm. "It's as straight forward as multiplying material quantities by their carbon footprint from comparable EPDs and adding it up. This is becoming increasingly easier for concrete, where today there are over 23,000 EPDs within the EC3 tool database. That the EC3 tool assesses the variability of those EPDs to make like comparisons more reliable is a big key to the credibility of what we then report."

Engagement with the contractor and concrete supplier early on also helped "tighten-up" the mix designs, where the single change of the aggregate being used, moving to imported and higher quality aggregates, improved quality control and variation in the mix performance, allowing the same specified compressive strength reliability to be achieved with a lower quantity of cementitious materials. They worked with the contractor to determine where faster strength gain was really needed and adjusted testing age accordingly to accommodate higher volumes of SCMs.

"We reduced 24% of the total project embodied carbon footprint, at no cost add, that's after accounting for the carbon from barging rock from the Pacific NW down to LA," says Davies. "On the PT slab mixes alone, we reduced the carbon footprint of that mix by 47%."

"Asking targeted questions and measuring the carbon data at the time of procurement can have significant impacts," adds Davies. "Just remember you can't manage what you don't measure."

management principles, and qualified personnel who can design, manage, and manufacture quality concrete consistently equate to good quality control.

Quality Assurance

Testing concrete is not an exact science. Every project has specifications that require independent testing laboratories to ensure that concrete meets the specified performance criteria. Placing concrete is a dynamic process and thus sampling concrete for testing can be challenging. There are well established procedures for taking concrete samples, preparing test specimens, storing them on site, transporting them to a laboratory, and finally testing them in a compression testing machine or other apparatus. If sampled and prepared incorrectly, stored incorrectly, transported incorrectly, and tested incorrectly, the results are meaningless. This also impacts the perceived variability that impacts the overdesign the producer is permitted for future projects.

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QUIZ

1. According to UN Environment, Global Status Report 2017, the world is projected to add 320 billion m^2 (3.4 trillion ft^2) of buildings by_____. That's an area equal to 1.4 times the entire current global building stock.
   a. 2060 b. 2070
   c. 2080 d. 2090

2. According to the course material, which of the following is part of the Top 10 List in the course?
   a. Communicate carbon reduction goals b. Don't limit ingredients
   c. Encourage innovation d. All of the above

3. In the case study that examines 960 W. 7th Street in Los Angeles, ____of the total project embodied carbon footprint was reduced through the use of SCMs.
   a. 10% b. 12%
   c. 19% d. 24%

4. Type IL cement, portland-limestone cement, can be between 5 and ____ limestone.
   a. 15% b. 25%
   c. 35% d. 50%

5. Type IL blended portland-limestone cement with _____ limestone was used on the North Torrey Pines Living and Learning Neighborhood project.
   a. 5% b. 10%
   c. 13% d. 15%

6. Which of the following is the most commonly used supplementary cementitious material?
   a. Slag cement b. Fly ash
   c. Silica fume d. None of the above

7. A 10% increase in cementitious materials content for 4000 psi air entrained concrete compared to non air-entrained concrete of the same strength would roughly translate to a _____ increase in carbon footprint for the concrete.
   a. 8% b. 9%
   c. 10% d. 11%

8. In the Oracle case study, the project reduced Global Warming Potential by _____ from baseline.
   a. 9% b. 10%
   c. 11% d. 12%

9. Research conducted by Possan, et al., indicates that during its lifetime, concrete can uptake anywhere from 40 to 90% of CO_2 emitted in its manufacturing process. In some cases, considering a structure's demolition (leaving crushed concrete exposed to air), its uptake can approach _____.
   a. 95% b. 96%
   c. 98% d. 100%

10. The rates of CO_2 uptake in concrete is greatest when:
    a. Concrete is painted b. Concrete is crushed and exposed to air
    c. Concrete is sprayed with water d. Concrete is post-tensioned

11. The term, ____, is defined as a naturally occurring process which CO_2 penetrates the surface of hardened concrete and chemically reacts with cement hydration products to form carbonates.
    a. Carbonation b. Oxygenation
    c. Deterioration d. Fenestration

12. According to the course's Top Ten Ways, which is cited by the author as the most difficult?
    a. 2—Ensure good quality control and assurance b. 5—Use supplementary cementitious materials
    c. 9—Sequester carbon dioxide in concrete d. 10—Encourage innovation

Concrete rarely tests well when testing protocols are not followed. If test results constantly show lower strength, then the only way to overcome that is to increase overdesign which generally raises cementitious material content. For example, if poor testing increased the overdesign from 600 to 1000 psi the cementitious materials content would increase by roughly 40 lbs for 4,000 psi concrete, increasing the embodied carbon footprint by as much as 6%.

Recommendation

One way to provide some assurance that a concrete producer has good quality control is to require certifications for their manufacturing facilities (plants), mixer trucks, concrete technicians, and plant operators. The same can be said for installers and independent testing laboratories and their personnel.

Include the following in your project specification:

SECTION 03300—CAST-IN-PLACE CONCRETE

PART 1—GENERAL

1. QUALITY ASSURANCE

A. Installer Qualifications: At least one person on the finishing crew must be certified as an ACI Flatwork Finisher, or equivalent.

B. Manufacturer Qualifications:

1. Concrete shall be supplied from concrete plants with Ready Mixed Concrete Production Facilities Certification[2] or equivalent. Criteria of equivalent certification shall be included in the submittal.
2. Quality Control personnel with responsibility for concrete mixtures shall be certified as a Concrete Technologist Level 2[3], or equivalent. Criteria of equivalent certification shall be included in the submittal.

C. Testing Agency Qualifications: Independent testing agency shall meet the requirements of ASTM C1077.

1. Personnel conducting field tests for acceptance shall be certified as ACI Concrete Field Testing Technician Grade I, or equivalent.
2. Personnel conducting laboratory tests for acceptance shall be certified as ACI Concrete Strength Testing Technician or ACI Concrete Laboratory Testing Technician Level I, or equivalent.
3. Test results for the purpose of acceptance shall be certified by a registered design professional employed with the Testing Agency.

3. OPTIMIZE CONCRETE VOLUME

This strategy is just about employing good design practices. If a structural element such as a column or beam is designed larger than required, then excessive concrete is being used which increases embodied carbon. Alternatively, for a high-rise building, reducing the size of the columns might be critical to keeping the rentable space to a maximum. That means using high strength concrete which generally means higher carbon footprint.

However, higher strength concrete does not always mean the concrete has to have a high carbon footprint. Most high strength concrete uses considerable amounts of supplementary cementitious materials (SCMs) such as fly ash, slag cement, and silica fume to achieve high strength. Since those materials have relatively low footprints, they help lower the embodied carbon of concrete. Regarding carbon footprint, however, lower strength is usually better.

Recommendations

Use life cycle analysis software to quickly calculate the embodied carbon of concrete elements (structural or architectural).

Consider exposing concrete wherever possible. Finish materials have a considerable carbon footprint, and since exposed concrete can be attractive and is fire resistant without the need for additional protection, this is an excellent strategy for reducing the carbon footprint of the building.

The other benefit of leaving concrete exposed is that concrete absorbs carbon over time through a process called carbonation. Carbon dioxide from the atmosphere combines with the cement hydration products to form calcium carbonate (limestone) which permanently sequesters carbon dioxide.

4. USE ALTERNATIVE CEMENTS

There are several alternatives to ordinary portland cement (OPC), but the most common are called blended cements. These combine OPC with other materials. The most common type of blended cement is portland-limestone cement (PLC) or, technically, ASTM C595 Type IL (pronounce "one el") cement. This blended cement combines up to 15% limestone interground with OPC to make a cement with a carbon footprint that is up to 10% lower than OPC with performance that is identical to—and in some cases better than—OPC.

There are four types of blended cements in ASTM C595:

Cement Type	Description	Notes
Type IL (X)	Portland-Limestone Cement	Where X can be between 5 and 15% limestone
Type IS (X)	Portland-Slag Cement	Where X can be up to 70% slag cement
Type IP (X)	Portland-Pozzolan Cement	Where X can be up to 40% pozzolan (fly ash is the most common)
Type IT (X)(X)	Ternary Blended Cement	Where X can be up to 70% of pozzolan + limestone + slag, with pozzolan being no more than 40% and limestone no more than 15%

There is also another standard, ASTM C1157, for performance based blended cements with no limits on cement composition which allows considerably more flexibility. There are rigorous testing standards by which manufacturers demonstrate they meet the performance criteria but are not limited to certain percentages of OPC substitution.

Both ASTM C595 and ASTM C1157 have been permitted in national standards such as ACI 318 and 301, ASTM C94 (ready mixed concrete), and MasterSpec for at least two decades, but most project specifications inadvertently prohibit their use by not listing them in the specification. Many legacy project specifications only list ASTM C150 (portland cement) and don't list ASTM C595 and ASTM C1157, mainly because project specification are rarely updated.

CASE STUDY: UNIVERSITY OF CALIFORNIA SAN DIEGO, NORTH TORREY PINES LIVING AND LEARNING NEIGHBORHOOD

Contractor: Clark Construction

Architects: HKS in association with Safdie Rabines Architects

Concrete Specialists: CalPortland and California Nevada Cement Association (CNCA)

Photo: Courtesy of Walter Kanzler

Background

The founders of the University of California San Diego had one stipulation for the campus: "it must be distinctive."[4] Currently, UC San Diego is fulfilling its founders' early vision "through innovative design" and "transformational projects [that] inspire."[5] One of the latest works in progress at the university is the North Torrey Pines Living and Learning Neighborhood. The neighborhood will be 10 acres of academic, residential, commercial, and cultural buildings. Set for completion in late 2020, part of the neighborhood will include an Arts and Humanities Building, Craft Center with classrooms and specialized facilities, a Social Sciences Public Engagement Building, and four residential buildings that will house 2,000 students.

Challenges

One of the biggest challenges faced for those constructing new buildings on the UC San Diego campus is the university's sustainability policy. Walter Kanzler, Senior Director, Design & Development Services, AIA LEED BD+C, states, "System-wide at the University of California, we have something called the Sustainable Practices

ENVIRONMENTAL PRODUCT DECLARATION FOR UCSD NORTH TORREY PINES LIVING AND LEARNING NEIGHBORHOOD

Global Warming Potential of Portland Limestone Cement

Table 3: LCA Results – 1 metric ton Type IL cement

CATEGORY INDICATOR	UNIT	TOTAL A1-A3
TRACI 2.1 impact categories		
Global warming potential (GWP)	Kg CO_2eq.	871
Acidification potential	Kg SO_2eq.	1.56
Eutrophication potential	Kg N eq.	0.0739
Smog creation potential	Kg O_3eq.	34.8
Ozone depletion potential	Kg CFC-11eq.	1.09E-06
Total primary energy consumption		
Non-renewable fossil	MJ (HHV)	5,010
Non-renewable nuclear	MJ (HHV)	136
Renewable (solar, wind, hydroelectric, and geothermal)	MJ (HHV)	136
Renewable (biomass)	MJ (HHV)	0.883
Material resources consumption		
Non-renewable material resources	Kg	1,530
Renewable material resources	Kg	0.0282
Net fresh water (inputs minus outputs)	l	335
Waste generated		
Non-hazardous waste generated	Kg	2.59
Hazardous waste generated	Kg	0.00658

Global Warming Potential of Typical Type I/II/V Portland Cement

Tables S2: LCA Results (A1-A3) – 1 metric ton Riverside cements

ENVIRONMENTAL INDICATOR	UNIT	RIVERSIDE TYPE I/II/V
TRACI 2.1 impact categories		
Global warming potential (GWP)	Kg CO_2eq.	969
Acidification potential	Kg SO_2eq.	1.70
Eutrophication potential	Kg N eq.	0.0874
Smog creation potential	Kg O_3eq.	38.6
Ozone depletion potential	Kg CFC-11eq.	9.82E-07
Total primary energy consumption		
Non-renewable fossil	MJ (HHV)	5,502
Non-renewable nuclear	MJ (HHV)	142
Renewable (solar, wind, hydroelectric, and geothermal)	MJ (HHV)	143
Renewable (biomass)	MJ (HHV)	0.92
Material resources consumption		
Non-renewable material resources	Kg	1,599
Renewable material resources	Kg	0.0291
Net fresh water (inputs minus outputs)	l	666
Waste generated		
Non-hazardous waste generated	Kg	2.75
Hazardous waste generated	Kg	0.00709

Policy. That policy requires that all new buildings are minimum LEED Silver; in most cases they're recommended to be LEED Gold, and North Torrey Pines Living and Learning Neighborhood is actually set to achieve LEED Platinum."[6]

Sustainable Solutions

Life Cycle Analyses (LCAs) were used by teams bidding on the North Torrey Pines project to demonstrate sustainable design and outcomes. Kanzler notes, "The concrete subcontractor, his affiliation with the industry players, and just having an open dialogue about why we make certain choices [regarding sustainability] were helpful. The conversations also exposed concrete as an 'unknown' benefit around embodied carbon. I think once more people in the [AEC] industry recognize that, they might choose the same products based on similar criteria." Through collaboration and open discussion, project teams were able to determine the aesthetic, structural, and environmental benefits of the concrete specified.[7]

Type IL blended portland-limestone cement with 13% limestone was used on the project. Bill Larson, Vice President of Marketing at the oldest portland cement company west of the Rocky Mountains which has also been an industry leader in energy conservation and environmental quality, agrees with Kanzler's observation about the "unknown benefits" of different types of cement and concrete. While portland-limestone cement has been used in Europe for the past 30 years and in Canada since 2008, the U.S. has been slow to adopt it. "I think what we're seeing here," says Larson, "as we look at the Paris Accord and different climate action plans and at the concrete and cement industry in regard to the amount of CO_2 that's produced—we're seeing a great opportunity to make a change. To make a change today."[8]

This project could use up to 31,170 metric tonnes of Type IL portland-limestone cement which could save 3,055 metric tonnes of CO_2—the equivalent of 664 cars removed from the road for one year.[9]

In addition to CO_2 reduction, the use of portland-limestone cement were a co-benefit along with its appearance. "That campus has a very rich tradition of exposed architectural concrete. As materials have evolved over time, there is now an option to reduce embodied carbon while maintaining a high-quality appearance with portland-limestone cement."[10]

Larson, too, maintains, "In Southern California we have a history of using architectural, aesthetically pleasing cement. A lot of architects incorporate it into their specifications for that reason. It's a very light-colored cement. UC San Diego is a very concrete-conscious campus. They utilize concrete in many different ways, but their buildings and their structures are architecturally pleasing."[11]

Importantly, Larson points out, the real "beauty of portland-limestone cement is that it's available right now."[12] Aesthetic and sustainability priorities need not conflict as more and more environmentally conscious building owners and specifiers seek to use innovative concrete solutions to achieve global CO_2 reduction goals.

Recommendation

Include the following in your project specifications:

PART 2—PRODUCTS

2.5 CONCRETE MATERIALS

A. Cementitious Materials: use materials meeting the following requirements.

1. Hydraulic Cement: ASTM C150, ASTM C595, or ASTM C1157

5. USE SUPPLEMENTARY CEMENTITIOUS MATERIALS

Nearly all concrete used today has some amount of supplementary cementitious material. The most common are fly ash, slag cement, and silica fume in that order. However, there are others, such as metakaolin, volcanic ash, rice husk ash, and ground glass, just to name a few. Some are waste by-products of other industrial processes and others are naturally occurring materials that require little processing and therefore have small carbon footprints. All enhance the performance of concrete when combined with portland cement, including increased strength, increased durability and enhanced workability. There is a complex chemical process that occurs between the SCMs and the portland cement hydration by-products which contributes to these enhanced properties.

In the U.S., it is the general practice that the concrete producer combines SCMs with portland cement at the batch plant, but in some cases, a producer can use a blended cement (see previous section) and combine additional SCMs at the batch plant. For example, if a producer is using an ASTM C595 Type IP (30), which contains 30% pozzolan, then he may be able to add more fly ash, slag, or other SCM, if the mix meets all the performance criteria.

SCMs offer the greatest opportunity for the reduction of carbon footprint today. In theory, concrete can be made with certain SCMs (slag cement for example) or geopolymer concrete which uses fly ash and alkaline activator, without any portland cement. This is unlikely, mainly because of the available supply of these SCMs and cost. Fly ash is relatively abundant, with some fly ash going unused each year. Slag cement is the second most abundant but is only a fraction of the fly ash available. Others have even less supply. Hence, they are used mainly when concrete performance needs to be enhanced.

To give an idea of how effective the use of SCMs are in reducing carbon footprint, going from a 100% portland cement mix to a 50% fly ash/slag cement mix can reduce carbon footprint by roughly 40%.

Recommendation

Include the following in your project specification:

PART 2—PRODUCTS

2.5 CONCRETE MATERIALS

A. Cementitious Materials: use materials meeting the following requirements.

1. Hydraulic Cement: ASTM C150, ASTM C595, or ASTM C1157
2. Fly Ash or Natural Pozzolan: ASTM C618
3. Slag Cement: ASTM C989
4. Silica Fume: ASTM C1240
5. Glass Pozzolan: ASTM C1866

Do not place any additional limits on the amounts of SCMs (maximum fly ash replacement of 25% for example) and hydraulic cements (see previous section on blended cements). This will result in concrete with the best performance and lowest carbon footprint.

CASE STUDY: GUOCO TOWER, SINGAPORE

Developers: GuocoLand and the Singapore Urban Redevelopment Authority
Architects: Skidmore, Owings & Merrill LLP
Concrete Specialists: GCP Applied Technologies (GCP) and Pan-United Concrete (PanU)
Photo: Courtesy of Michael Fletcher

Background

Located in Singapore's bustling business district is Guoco Tower, Singapore's tallest building. Formerly known as Tanjong Pagar Center, the 64-story tower rises to 290 meters and is accompanied by a freestanding 20-story structure. Comprised of 890,000 sq. ft. of office space, 181 residences, a 150,000 sq. ft. park, the highest 50m pool in the country, as well as a fitness center and myriad retail and hospitality spaces, Guoco Tower is seen by some as an "urban sanctuary."[13] Ultimately, the Tower is a "holistic work-play-live experience" that won numerous awards, including the 2014 World Architecture Award for Mixed-Use Future Projects and the 2019 AIA International Region Design Award.[14]

Challenges

A major challenge for those working on the project was its location in a congested business and tourist district. In order to "expedite construction time and limit disruption," project teams decided to use the top-down construction method. To accomplish this, the project required concrete that possessed high flow, long slump retention, and good rheology properties."[15] Meeting these criteria would not only allow for the top-down construction method, but it would help to create the Tower's 13,500 cubic meter raft foundation.[16]

Sustainable Solutions

A team of scientists, engineers, and materials and logistics specialists from two different concrete manufacturers collaborated on the project. Understanding site conditions, material requirements, delivery timelines, regulations, and safety guidelines was key to selecting a relatively new product, referred to as control flow concrete, which is achieved mainly through admixtures.[17]

Michael Fletcher, Director, Account Management of Admixtures, and LEED BD+C, discusses the decision to use control flow concrete rather than self-consolidating concrete (SCC) at the Tower, both in terms of strength and sustainability. Fletcher states, "It was a 64-story pump job, and control flow concrete can be a drop in solution. It can do a lot of the same things as SCC. SCC mixes were traditionally very high cement content, generally speaking, whereas control flow really fills the gap between regular concrete and SCC."[18]

Guoco Tower required 14,000 psi concrete, and 18,000 psi was achieved. Fletcher states, "In order to get those strengths, maintain slump, be able to pump it—all those great things—anything you can do to enhance properties without going full SCC makes a big difference [to sustainability efforts]."[19] Because control flow concrete does not require the use of mechanical compactors as irregular voids fill automatically, noise pollution was also reduced on site.

Ultimately, the use of control flow concrete along with other sustainability efforts earned the commercial spaces of the Guoco Tower Green Mark Platinum and LEED® Gold certifications.[20]

6. USE ADMIXTURES

Nearly every concrete made today uses some sort of admixture. Most affect the plastic properties in order to make concrete more workable, economical, shorten or lengthen set time, and so on. Without admixtures, concrete could not be pumped hundreds of feet in the air or transported hundreds of miles, and many architectural finishes could not be achieved. There are water reducing admixtures that in effect reduce cement demand, accelerators that improve strength gain, and viscosity modifiers that permit concrete to flow into very tight spaces. All admixtures that meet an ASTM standard should be permitted and those that do not meet a standard should still be considered.

As an example of how effective admixtures can be, using a water reducing admixture that reduces water content in a mixture by 12% will result in a reduction of cement content by 70 lbs for equivalent slump and strength and in a carbon reduction of roughly 10% for 4,000 psi concrete. High-range water reducing admixtures can reduce water content by as much as 40% but the potential reduction in cementitious materials may not be feasible because of constructability needs.

Recommendations

Include the following in the project specification:

PART 2—PRODUCTS

2.5 CONCRETE MATERIALS

F. Chemical Admixtures:

1. Air-Entraining Admixture: ASTM C260/C260M
2. Water-Reducing Admixture ASTM C494/C494M Type A
3. High-Range Water-Reducing Admixture: ASTM C494/C494M Type F or G
4. Accelerating Admixture: ASTM C494/C494M Type C or E
5. Retarding Admixture: ASTM C494/C494M Type B or D
6. Hydration Control Admixture: ASTM C494/C494M Type B or D
7. Workability-Retaining Admixture: ASTM C494/C494M Type S
8. Shrinkage-Reducing Admixture: ASTM C494/C494M Type S
9. Viscosity Modifying Admixtures:

ASTM C494/C494M Type S

10. Alkali-Silica Reaction Inhibiting Admixture: ASTM C494/C494M Type S
11. Corrosion-Inhibiting Admixture: ASTM C1581/C1581M
12. Admixtures for corrosion inhibition: ASTM C1582
13. Admixtures with no standard (ASTM or other) designation shall be used with the permission of the engineer of record when its use for specific properties is required.

7. DON'T LIMIT INGREDIENTS

All too often, there are seemingly random limits on material ingredients in project specifications that limit the concrete producer's ability to meet performance criteria, let alone reduce carbon footprint. Having unnecessary limits on the water to cementitious materials ratio (w/cm) is one example. In most cases, requiring a maximum w/cm is unnecessary and drives up cement content. There are times when a maximum w/cm makes sense, mostly for cases of concrete exposed to freezing and thawing, but it is not necessary to call it out in the specification. Identifying the exposure class of the concrete per ACI 318 and ACI 301 will suffice. The requirements for w/cm for concrete exposed to freezing and thawing are outlined in the specification.

The same is true for air content. There are concretes that must be air entrained, but that is based on the exposure class of the concrete; mainly for concrete exposed to freezing and thawing. Call out the exposure class for each concrete application or class of concrete on the project and that will invoke the necessary air content requirements. Air entraining decreases concrete strength, which means increased cement content to maintain the same strength level. For instance, a 10% increase in cementitious materials content for 4,000 psi air entrained concrete compared to non air-entrained concrete of the same strength would roughly translate to a 9% increase in carbon footprint for the concrete.

Do not list a maximum or minimum cement content, maximum or minimum SCM content, or quantity of admixtures. Do not limit water used for making concrete to potable water (there is an ASTM specification for water used to make concrete). Do not limit the aggregate gradation but do limit the maximum aggregate size based on rebar spacing and member dimensions.

Recommendations

Include the following in the project specification:

PART 2—PRODUCTS

2.12 CONCRETE MIXTURES

A. 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:

Class	Location	Nominal Max. Aggregate Size*	Exposure Class*	f'c, psi @ age*
1	Mat Foundation	3"	F0, S1, W0, C0	6,000 at 90 days***
2	Basement walls	1-1/2"	F0, S1, W0, C0	4,000 at 56 days***
3	Shear walls	3/4"	F0, S0, W0, C0	6,000 at 56 days***
4	Columns level B2-L6	3/4"	F0, S0, W0, C0	6,000 at 28 days
5	Columns level L7-L12	3/4"	F0, S0, W0, C0	4,000 at 28 days
6	Slabs	3/4"	F0, S0, W0, C0	5,000 at 28 days
7**	Exterior pavements	3/4"	F3, S1, W0, C0	4,000 at 28 days

* Values are for demonstration purposes only.
** In the table above, only class 7 concrete (exterior pavements) would have a w/cm and air content limit because of its exposure to freezing and thawing, which is spelled out in ACI 318 and ACI 301.
*** Concrete that will not be stressed for significant time periods can be tested at later ages, which means higher volumes of SCMs can be used, resulting in a lower carbon footprint.

8. SET TARGETS FOR CARBON FOOTPRINT

This strategy is for advanced users only! Some knowledge of life cycle assessment, environmental product declarations, and global warming potential is needed to really implement this strategy. That said, it's not rocket science.

First, resist the temptation to set carbon footprint limits for individual classes of concrete. In effect, this is the same as providing prescriptive limits on materials and leaves little room for the contractor and producer to innovate and meet the project performance requirements, including budget and schedule. The best approach is to use a whole building life cycle assessment to set a carbon budget for all the concrete on the building. It is still necessary to have a general idea of what the carbon footprint of each mix will be to set a carbon budget for the building.

Many concrete companies have published EPDs for concrete, and most would be willing to publish EPDs specifically for a project. A national concrete association has published A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete report1, and Industry Wide EPD21 for concrete. Armed with this information, you can conduct an LCA to determine the embodied impacts of concrete of a benchmark building using typical concrete mixes with typical amounts of SCMs, and a proposed building using concrete mixes with high volumes of fly ash and slag.

The first step in the analysis is to identify typical concrete mixtures for the benchmark building. The Benchmark Report lists mix designs and their environmental impacts for eight different regions in the United States.

The next step is to identify mix designs that have significantly lower GWP than the benchmark mixes that will meet the performance criteria (strength, durability, etc.). 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 such as 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 days to account for slower strength gain. High volume SCM mixes can be identified from the Industry-Wide EPD or from published product specific EPDs from different regions.

Sophisticated LCA software can be used for this exercise, which would permit what-if scenarios, or the simple math is as follows:

- Equation 1: $GWP_B = (GWP_{B1})(V_1) + (GWP_{B2})(V_2)...(GWP_{Bn})(V_n)$
- Equation 2: $GWP_P = (GWP_{P1})(V_1) + (GWP_{P2})(V_2)...(GWP_{Pn})(V_n)$

Where:

- GWP_B = Global Warming Potential of Benchmark Building
- GWP_{B1}, GWP_{B2}, etc. = Global Warming Potential of each different concrete mix or class of concrete on the project from the Benchmark Report
- GWP_P = Global Warming Potential of Proposed Building
- GWP_{P1}, GWP_{P2}, etc. = Global Warming Potential of each proposed concrete mix or class of concrete as selected from the Industry-Wide EPD or from product specific EPDs if available at time of design (unlikely).
- V_1, V_2, etc. = Volume of each different concrete mix used on the project.
- n = Number of concrete mix designs or classes of concrete.

Recommendations

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

2.12 CONCRETE MIXTURES

B. 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.

* This value is for demonstration purposes only.

9. SEQUESTER CARBON DIOXIDE IN CONCRETE

Like most manmade materials, concrete is considered a carbon dioxide emitter, mainly due to the cement manufacturing process. However, that process can be reversed: CO_2 can be captured or sequestered in concrete through natural processes or carbon capture technologies.

Carbonation is a naturally occurring process by which CO_2 penetrates the surface of hardened concrete and chemically reacts with cement hydration products to form carbonates. For in-service concrete, carbonation is a slow process with many dependent variables. The rate decreases over time. This is because carbonation decreases permeability and

CASE STUDY: ORACLE WATERFRONT CAMPUS, AUSTIN, TX

Owner: Oracle
Architect: STG Design
Structural Engineer: Walter P Moore
General Contractor: Ryan Companies
Concrete Contactor: Keystone Concrete
Concrete Producer: Centex Materials
Photos: Casey Dunn

Background

The Oracle Waterfront Campus in Austin is a corporate office building with 550,750 square feet of floor space with a 147,000-square-foot attached ground level parking garage and 646,800-square-foot detached parking garage.

Challenges

According to Jim Susman, Principal at the project's architectural firm, "Much more than a corporate campus, the Oracle Waterfront was conceived to serve both existing and incoming talent as well as the community in support of Oracle's project vision: to create a campus resonating from an active core, blending with the surrounding context as it expands from its center."[22] The entire design and construction team was challenged to have the project blur the lines between public and private property and be welcoming to the pedestrian-friendly community that surrounds it while meeting challenging sustainability criteria of LEED and Austin Energy Green Building (AEGB) standards.

Sustainable Solutions

The structural engineers worked closely with the design-build team to meet a demanding schedule, structural challenges, and environmental criteria for this concrete building. The design required over-sized floor plates to accommodate open office spaces, expansive balconies and terraces, and large meeting spaces. "The cantilevered balconies provide exceptional views of the lake and downtown Austin," states Adam Johnson, Principal and Austin Managing Director with the structural engineering firm. They also made the designer's vision for a truly unique lobby space come to life with a floating stair and bridge that lead visitors to large meeting spaces.

To meet their sustainability goals, the structural engineers incorporated several key strategies to help lower carbon footprint. "The story of Oracle is one of getting in early and talking to the concrete sub and the ready-mix supplier to communicate the carbon reduction goals," said Dirk Kestner Principal and Director of Sustainable Design with the structural engineering firm. They discussed optimizing cement content with the supplier and iterated mix designs to lower carbon footprint. "One thing we did was to consider the construction cycle to use different mixes for the floors based on when they were stressing versus using the two-day mix for all floor placements since the strength at stressing was what governed and not 28-day strength." according to Kestner. This permitted lower cementitious materials content than would normally be used for post-tension floor mixes.

Structural engineers conducted an LCA using software which considers the embodied impacts of all materials of the structure and enclosure for the project. Since this was such a concrete intensive project, they focused on improving concrete mix designs to meet the LEED Whole Building LCA criteria for lowering environmental impacts. They created two computer models to compare the proposed building to a baseline building, fully maintaining the functional equivalence of the two buildings but varying the mix designs. "The concrete mixes for the baseline building were chosen from the Life Cycle Assessment

Benchmark Report, as well as from comparable existing projects in Austin. It is essential to measure from an accurate reference, which is usually NOT a straight cement mix" states Kestner.

The concrete mixes for the proposed "improved" building were initially chosen from an internal database developed by the engineering firm for low carbon mixes (mixes containing high volumes of SCMs). The improved mixes were analyzed by the software to determine the embodied environmental impacts per cubic yard, and based on that analysis, the concrete mixes were implemented into the Whole Building LCA. They also varied the age for testing concrete to allow for higher volumes of fly ash. For example, since the foundations do not see the full design load until construction is complete, they specified testing concrete at 56 days for the drilled piers. As a result, the project met the rigorous LEED Whole Building LCA credit by showing at least a 10% reduction in Global Warming Potential (12% in this case) along with at least a 10% reduction in at least two other environmental impact categories:

Impact Measure	Units	Estimated % Reduction from Baseline to Proposed
Acidification Potential	kg SO_2eq	13%
Eutrophication Potential	kg Neq	3%
Global Warming Potential	kg CO_2eq	12%
Ozone Depletion Potential	CFC-11eq	11%
Smog Formation Potential	kg O_3eq	12%
Non-Renewable Energy	MJ	6%

The design-build team's work netted several accolades. Austin Business Journal awarded the project The 2019 Commercial Real Estate Award. Other awards included Urban Land Institute Impact Award for the Most Influential Project, a Golden Trowel Award for excellence in the Industrial/Commercial category and an Austin Green Award for outstanding sustainable design and innovation as well as design strategies that respond to rapidly evolving environmental, social, and health imperatives. The project has also been awarded USGBC LEED Gold and an AEGB 4-Star rating.

carbonation occurs from the surface inward, creating a tighter matrix at the surface that makes it more difficult for CO_2 to diffuse further into the concrete. While slow, the carbonation process does result in an uptake of some of the CO_2 emitted from cement manufacturing, a chemical process called calcination. Theoretically, given enough time and ideal conditions, all the CO_2 emitted from calcination could be sequestered via carbonation.

The rate of CO_2 uptake depends on exposure to air, surface orientation, surface-to-volume ratio, binder constituents, surface treatment, porosity, strength, humidity, temperature, and ambient CO_2 concentration. Predicting how much CO_2 is absorbed by in situ concrete is difficult. What is known is that rates of CO_2 uptake are greatest when the surface-to-volume ratio is high, such as when concrete has been crushed and exposed to air.

Two areas of research and commercialization offer considerable enhancements to this CO_2 uptake process. The most basic approach is enhanced carbonation at end-of-life and second-life conditions of concrete. If conditions are right and particle size is small, crushed concrete can potentially absorb significant amounts of CO_2 over a short period, such as one or two years, leaving crushed concrete exposed to air before re-use would be beneficial. Research conducted by Possan, et al., indicates that during its lifetime, concrete can uptake anywhere from 40 to 90% of CO_2 emitted in its manufacturing process. In some cases, considering a structure's demolition (leaving crushed concrete exposed to air), its uptake can approach 100%.[23]

Other commercially viable technologies accelerate carbonation. This is accomplished either by injecting CO_2 into concrete, curing concrete in CO_2, or creating artificial limestone aggregates using CO_2.

One company uses CO_2 captured from industrial emissions, which is then purified, liquefied, and delivered to partner concrete plants in pressurized tanks. This CO_2 is then injected into the concrete while the concrete is being mixed, which converts the CO_2 into a solid-state mineral within the concrete. The minerals formed enhance compressive strength. The process reduces CO_2 emissions in two ways: through direct sequestration of CO_2 injected into the concrete mixture and by reducing cement demand since this concrete requires less cement to produce concrete at a specified strength.

Recommendations

Consider permitting the use of recycled aggregates made of demolished concrete on the project and possibly require that those recycled aggregates be exposed to air for one year before being used. In some cases, a certain percentage of aggregate used in concrete to be recycled can be permitted or it can simply be required that all aggregate base or fill be made of crushed concrete. The use of carbon mineralization processes such as injecting CO_2 into concrete or curing in CO_2 environments should be encouraged as well as the use of artificial limestone aggregates.

It is also worth considering the use of exposed concrete on the project, both on the interior and exterior. This has the added benefit of reducing the amount of finish material in addition to absorbing CO_2 throughout the lifetime of the building. The following are examples of specification language that would encourage carbon sequestering technologies:

PART 2—PRODUCTS
2.5 CONCRETE MATERIALS
A. Normal-weight Aggregate: ASTM C33
B. Lightweight Aggregate: ASTM C330
C. Recycled concrete aggregate (crushed concrete) meeting the requirements of ASTM C33 or ASTM C330 may be used in structural concrete up to 10%* of the total aggregate. Crushed concrete shall have been crushed and exposed to air at least 1 year before use in concrete (to maximize CO_2 sequestration).
D. Artificial limestone aggregate meeting the requirements of ASTM C33 or ASTM C330 is permitted.
E. Carbon mineralization by injecting CO_2 into concrete during manufacturing or curing in CO_2 atmosphere shall be permitted.

* Value is for demonstration purposes only.

10. ENCOURAGE INNOVATION

Of the ten strategies, this is probably the most difficult. Throughout this article, it has been stated not to list specific products or name certain technologies. Instead, simply list the standards that one must meet. The problem with this approach is that it permits innovation but does not necessarily encourage it. If a standard has been met, likely the product is considerably past the innovation stage. The product or process was likely invented, worked within a standard, modified the standard, or modified to meet a standard. All these processes translate to years of research and development work, which means it is difficult and expensive to innovate. For an innovative product or process to be successful, demand must be created, but the current design-bid-build process discourages innovation. However, there are some things that can be done to help create demand for innovative products.

Recommendations

The recommendation here really goes back to Strategy 1. Communicating the carbon reduction goals to contractors and producers during the design process is critical. Let them know that you are looking for innovative solutions. Design charrettes would be a great place to engage engineers, contractors, and concrete producers. Ask them to provide solutions. Most sophisticated producers are experimenting on new formulations all the time. Ask them to discuss some of their low-carbon concretes. Will they meet all the performance criteria set by the design team and the contracting team?

CONCLUSIONS

There is no silver bullet to making concrete with zero carbon footprint. It can be done, but not at the volume and cost demanded by today's building owners. For some concretes on a project, the carbon reduction might be 90%, others closer to 70%, and still others around 30%. All these reductions lead to concrete with a significantly lower footprint than most concrete projects. If you choose to set carbon footprint targets, this will lead to the greatest reduction, but you cannot expect to meet these targets without implementing these top 10 ways to reduce concrete's carbon footprint. ■

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