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BUILD WITH STRENGTH

CONCRETE INNOVATIONS

The Jubilee Church. Photo: Elio Lombardo / Alamy Stock Photo

LEARNING OBJECTIVES

1. Understand new technologies used in concrete manufacturing.
2. Discover how innovative concrete products can improve project performance.
3. Learn how to implement the latest concrete innovations in building and infrastructure projects.
4. Demonstrate the importance of incorporating new technologies to enhance resilience and sustainability in the built environment.

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INTRODUCTION

What do the Jubilee Church and the Pantheon have in common? They are both places of worship in Rome, but besides that, they are both built with innovative concrete. The Romans mastered the use of concrete 2,000 years ago to build some of the most iconic structures ever built. Although different than today's concrete, Roman concrete used the same principles, combining aggregate with a hydraulic binder. The aggregate included pieces of rock, ceramic tile and brick rubble often recycled from demolished buildings. Volcanic ash, called pozzolana, was the favored binder where it was available, but gypsum and quicklime were used as binders also. Even 3,000 years before, the Egyptians used a form of concrete made with mud and straw to build the pyramids. Today, most concrete is made with portland cement, invented in 1824, and combined with high quality quarried aggregate. Most modern concrete is augmented with innovative products and additives to enhance both plastic and hardened properties.

Innovative supplementary cementitious materials (SCMs) such as fly ash, slag cement and silica fume are used to increase strength, durability and workability. Chemical admixtures affect set time, freeze-thaw resistance and flowability. Tiny fibers are added to increase ductility and control cracking. Carbon dioxide is injected into concrete to improve strength and capture greenhouse gasses. Some enhancements actually scrub pollutants from the surface of concrete and from the surrounding atmosphere, which is what makes the concrete on the Jubilee Church so innovative. The exterior curved

The Pantheon. Photo: Hercules Milas / Alamy Stock Photo surfaces are coated with titanium dioxide (TiO_2) cement which eats smog, helping to keep the surface clean.

Concrete is the most widely used building product in the world. For the most part, concrete is made locally with local materials. It is cost effective, readily available, strong and durable. Although conventional concrete can tackle most jobs, it is also the material of choice for the tallest buildings in the world and infrastructure designed to last centuries. New concrete products and manufacturing methods are enhancing concrete's performance to tackle modern challenges. This article explores some of these latest innovations.

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

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

3. **Photocatalysis**—the acceleration of a photoreaction in the presence of a catalys

4. **Graphene concrete**—made by suspending flakes of graphene in water, then mixing that water with traditional concrete ingredients such as cement and aggregate

5. **Carbonation**—Naturally occurring process by which carbon dioxide (CO_2) penetrates the surface of hardened concrete and chemically reacts with cement hydration products to form carbonates

6. **Self-consolidating concrete (SCC)**—Non-segregating concrete that can flow into place, fill formwork and encapsulate reinforcement without any mechanical vibration

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

8. **Blast furnace slag**—Waste byproduct of iron manufacture, used as an SCM or lightweight aggregate in concrete.

9. **Coal ash**—Waste byproduct of burning coal in electric power plants

10. **Beneficiation**—Taking coal ash from landfills and processing it so it meets the necessary standards for beneficial use

11. **Bendable concrete**—Concrete containing fiber additives to enhance ductility and crack control

12. **Geopolymer concrete**—Concrete made with fly ash and/or slag cement combined with an alkaline activator as the binder.

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

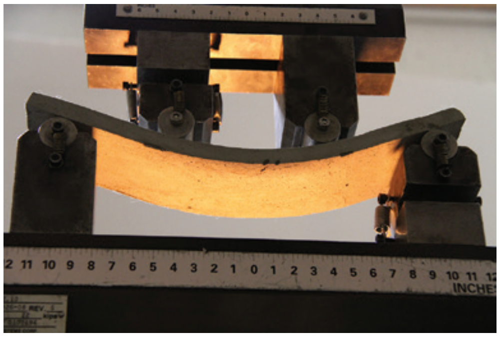
SELF-CLEANING CONCRETE

Imagine concrete that can clean itself and even the surrounding air of harmful pollutants. That's what concrete made with titanium dioxide (TiO_2) can do. The function of TiO_2 cement is to break down harmful pollutants in the air via a reaction catalyzed by light, or photocatalysis, due to titanium dioxide which is added to the cement during its production. This capability of TiO_2 cements was inspired by the ability of certain microbes to break down harmful chemicals by modifying their oxidation state, also through photocatalysis. However, in photocatylitic cements, the reaction is carried out by the titanium whereas microbes rely on natural enzymes. The cement breaks down organic, as well as inorganic pollutants. It is intended to be used for projects in urban centers where air pollution and poor air quality are most pronounced.

An example of how TiO_2 cements break down pollutants can be seen in its conversion of nitrogen dioxide (NO_2), a harmful compound mostly produced by burning fuels in cars and trucks. Nitrogen dioxide is one of the compounds responsible for acid rain, smog, respiratory problems and staining of buildings and pavements. The reaction with sunlight produces hydroxyl radicals which react with NO_2 to produce NO_3 which is dissolved by water after reacting with the cement surface.

Research data of a TiO_2 cement manufacturer in the US, indicates that "up to 50% of these atmospheric pollutants could be reduced in some cities if only 15% of the buildings and roads were resurfaced with a TiO_2 cement." A TiO_2 cement was first used for the curved panels on the Jubilee church (also known as Dives in Misericordia Church) in Rome, which used the photocatalytic cement panels for its stylistic shells. Since then an Italian company has dedicated decades of research to photocatalytic cement products. This cement is promising in its potential to greatly improve urban life and the environment.[1]

BENDABLE CONCRETE



Bendable concrete is 300–500 times more ductile than conventional concrete. Photo: Victor C. Li

Bendable concrete presents an efficient alternative primarily in the construction and maintenance of infrastructure, where concrete is subject to harsh weather conditions and extreme loading. The design which gives bendable concrete, or engineered cementitious composite (ECC), its impressive ductility is based off nacre, the substance that coats the inside of abalone shells. Nacre is composed of small aragonite platelets that are held together by natural polymers, allowing it to be both hard and flexible as platelets are free to slide from side to side under stress. This effect is mimicked in bendable concrete by dispersing tiny fibers throughout. Victor C. Li of the University of Michigan, where ECC was first researched and

CASE STUDY: JUBILEE CHURCH, ROME, ITALY

Photo: Edmund Sumner-VIEW / Alamy Stock Photo

According to architects Richard Meier and partners, the Jubilee Church in Rome was "conceived as part of Pope John Paul II's millennium initiative to rejuvenate parish life within Italy." The project consists of the church itself as well as both secular housing and housing for the clergy. The church is most easily distinguished by the three large concrete shells which are meant to represent the Holy Trinity. Given the symbolic importance of the shells, their appearance is a priority. Because the shells need to remain in pristine condition, it was only natural that "self-cleaning" photocatalytic concrete was used to ensure that the shells would not accumulate stains due to smog. Completed in 2003, the photocatalytic shells have notably remained clean and white, performing constant self-maintenance.

invented, states that bendable concrete "can deform up to 3 to 5 percent in tension before it fails, which gives it 300 to 500 times more tensile strain capacity than normal concrete." It is the incredible ability to tolerate tensile strain that makes bendable concrete unique.

This enormous increase in ductility suggests various potential applications. Firstly, in roads as well as other paved surfaces which must bear repeated loading of heavy vehicles, bendable concrete would crack less often, preventing further weathering primarily from road salts which corrode steel reinforcement. Further, due to ECC's capacity to absorb greater quantities of energy without being damaged, it can be used to make reinforcing elements such as the dampers on the Seisho Bypass Viaduct in Japan, which is roughly 28 kilometers long. Dr. Li states that ECC has been employed as earthquake resistance in tall buildings in Tokyo and Osaka and further suggests that ECC would be useful in underground construction as well as the construction of water infrastructure.

However, before it can be more widely commercialized for such large-scale projects, bendable concrete must become more readily available. To be economically viable, it must be supplied efficiently and not overused on projects. It is paramount that design professionals be made aware of the product and its potential as they might otherwise overlook a promising concrete option for structures that require the ability to deal with considerable tensile strain.

Bendable concrete also has self-healing capabilities. Because bendable concrete keeps cracks relatively small, natural reactions within the hardened concrete generate "healing" through carbon mineralization and continuous hydration which repairs the cracks and restores the durability of the concrete. Bendable concrete is a promising technology that already has proven itself through commercialization by several companies.

In fact, fiber reinforced concrete is not new. Many companies supply fibers for use in concrete with the objective of improving the strength and durability of the concrete in some way. Fiber reinforced concrete accomplishes this by incorporating fibers made of steel, glass or organic polymers (plastics). Sometimes naturally occurring fibers such as sisal and jute have been used as well. These fibers are primarily used to combat plastic shrinkage and drying shrinkage which can otherwise crack and damage the concrete. This resistance to shrinkage and subsequent cracking is the key to extending the lifespan of concrete, decreasing the frequency of costly repairs. Fibers also keep existing cracks from widening and further damaging the concrete when they do appear. More recently, steel fibers have been used in structural applications to reduce the amount of traditional steel reinforcing bars, saving time and labor.

Ultra-High-Performance Concrete (UHPC)

One building product manufacturer became one of the first companies to commercialize bendable concrete with an ultra-high-performance concrete (UHPC) that incorporates fibers into the concrete mixture in order to improve strength and ductility along with a host of other benefits. The manufacturer states that they use "high carbon metallic fibers, stainless fibers, poly-vinyl alcohol (PVA) fibers or glass fibers" to increase the concrete's ability to withstand tensile loads and deformation.

This UHPC is also less porous than conventional concrete, making it more resistant to chlorides,

CASE STUDY: 42 BROAD, FLEETWOOD, NEW YORK

Photo: Bluestone Organization. Photo: ICF Panels, Inc.

42 Broad is a 16-story mixed-use development near New York City being built with Insulating Concrete Forms (ICF). ICF construction is becoming more mainstream with thousands of projects built in the US but is still considered innovative by many. ICFs sandwich a reinforced concrete wall between forms made of rigid polystyrene insulation that stay in place after the concrete hardens. There are several taller ICF buildings in Canada, but at 16 stories, 42 Broad will be the tallest in the US.

The real innovation on this project is panelizing the ICF blocks and using steel fiber reinforcement. The ICFs are assembled off-site in a nearby plant and arrive at the jobsite as custom panels up to 50 feet long, which results in labor and time savings on the job site and means the owner can occupy the building earlier. Part of what makes this process possible is the use of steel fibers in the ready mixed concrete to replace the horizontal reinforcing steel which eliminates costly horizontal rebar slices.

CASE STUDY: PEREZ ART MUSEUM, MIAMI, FLORIDA

Photo: Ian Dagnall / Alamy Stock Photo

The Perez Art Museum in downtown Miami is notable largely for its application of an ultra-high-performance concrete (UHPC). The museum houses roughly 200,000 square feet of indoor and outdoor space for the presentation of modern and contemporary art. However, the property comes with one significant challenge: The museum is built on Biscayne Bay where it is subject to sea air and salt. Additionally, it is at risk of tropical storms and hurricanes and must withstand the forces associated with these extreme weather events. An UHPC was used to produce roughly 100 16-foot-long mullions to support the world's largest impact resistant window at the time of its construction in 2013. The concrete mullions were made to be thin, maximizing visibility, while also meeting the Florida building code for hurricane resistance.

acids, and sulfates. It is also generally much more impermeable to water, making it ideal for roofing as well. In addition, this UHPC has self-healing properties. This bendable concrete has been thoroughly researched and is commercialized.[2]

Graphene Concrete

Graphene concrete is made by suspending flakes of graphene in water, then mixing that water with traditional concrete ingredients such as cement and aggregate. Graphene concrete is concrete reinforced by a single layer of carbon atoms tightly bound in a hexagonal honeycomb lattice. Layers of graphene stacked on top of each other form graphite, a naturally occurring crystalline form of carbon most commonly used in pencils and lubricants. The layers of graphene in graphite can be separated into sheets only one atom thick. Graphene is the thinnest compound known to man, the lightest known material and the strongest compound discovered—over 100 times stronger than steel.

This technology's strength largely lies with its accessibility; it is inexpensive and compatible with modern, large-scale manufacturing requirements. According to “Ultrahigh Performance Nanoengineered Graphene–Concrete Composites for Multifunctional Applications,” published in *Advanced Functional Materials*, graphene concrete impressively shows a “146-percent increase in compressive strength as compared to regular concrete, a 79.5-percent increase in flexural strength, and a decrease in water permeability of almost 400 percent.'' In addition to its increased strength, graphene concrete is also more environmentally friendly since it requires less cement than is typically required to produce concrete at a specified strength. Alternatively, higher strength graphene concrete could be used to produce smaller structural elements, thus reducing the amount of material used.

CARBON CAPTURE

Like most manmade materials, concrete is considered a carbon dioxide (CO_2) emitter, mainly due to the cement manufacturing process. However, what if you could reverse that process and capture or sequester CO_2 in concrete through natural processes or carbon capture technologies.

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QUIZ

1. Bendable concrete uses fibers to improve
a. Color
b. Ductility
c. Flowability
d. Slump

2. The primary benefit of concrete made with titanium dioxide cement is
a. Increased strength
b. Improved flowability
c. Staying clean
d. High early strength

3. Steel fibers have been used in concrete to
a. Improve color uniformity
b. Replace steel reinforcing bars
c. Increase set times
d. Improve surface appearance

4. In addition to increased ductility, bendable concrete also has the benefit of
a. Staying clean
b. Resisting extremely high temperatures
c. Reduces surface friction
d. Self-healing

5. Graphene concrete is made by
a. Suspending flakes of graphene in mixing water
b. Wrapping concrete with graphene sheets
c. Recycling pencil lead into concrete
d. Using graphite cement

6. Carbon dioxide is absorbed by concrete in a process called
a. Hydration
b. Carbonation
c. Calcination
d. Photocatalysis

7. Carbonation of concrete is higher when
a. Surface-to-volume ratio is higher
b. Surfaces are painted
c. Concrete is buried
d. Concrete is denser

8. Carbon dioxide injection reduced carbon footprint of concrete in two ways
a. Reduces strength and increase cement demand
b. Sequesters CO_2 and increases strength
c. Eliminates the need for portland cement and increases need for water
d. Reduces labor and set times

9. One company makes artificial limestone by
a. Crushing see shells under high pressure
b. Growing and harvesting coral
c. Mining coal ash from landfills
d. Combining CO_2 with metal oxides

10. Self-consolidating concrete (SCC) is often used to
a. Eliminate mechanical vibration
b. Reduce on-site labor
c. Improve surface appearance
d. All the above

11. Which of the following has NOT been commercialized to any great degree?
a. SCC
b. SCMs
c. Geopolymer concrete
d. Fiber reinforced concrete

12. Beneficiation of fly ash involves
a. Recovering and processing fly ash from landfills
b. Creating fly ash bricks
c. Spreading fly ash on the surface of concrete
d. Converting fly ash to portland cement

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 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.

Carbonation is a naturally occurring process by which carbon dioxide (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 carbonation occurs from the surface inward, creating a tighter matrix at the surface making 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 of the CO_2 emitted from calcination could be sequestered via carbonation. However, real world conditions are usually far from ideal.

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.

In one of the most comprehensive studies, Xi, et al., published a summary of their research "Substantial Global Carbon Uptake by Cement Carbonation," in the journal Nature Geoscience, November 2016. The research quantifies the natural reversal of the calcination process, carbonation. Using analytical modeling of carbonation chemistry, the researchers were able to estimate the regional and global CO_2 uptake between 1930 and 2013. They estimated that the cumulative amount of CO_2 sequestered in concrete was 4.5 Gt during that period. This offsets 43% of the CO_2 emissions from the production of cement caused by the calcination process. Xi et al. conclude that carbonation of cement products represents a substantial carbon sink.

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 small period, such as one or two years, leaving crushed concrete exposed to air before re-use would be beneficial.

CASE STUDY: 725 PONCE, ATLANTA, GEORGIA

Photo: Courtesy of CarbonCure.

Completed in 2018, the office building at 725 Ponce De Leon Avenue was constructed using 48,000 cubic yards of carbonated concrete. Through their cooperation, the structural engineer Uzun+Case and a concrete supplier were able to greatly reduce the carbon footprint of this project. The concrete sequestered 680 metric tons, or 1.5 million pounds, of CO_2 which is roughly the amount of CO_2 absorbed by 800 acres of US forest each year. The fact that emissions harmful to the environment could be reduced by such a significant factor on this large project, which provides 360,000 square feet of office space, is a perfect example of the viability of carbon capture and sequestration as a sustainable option for concrete construction.

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 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.[3]

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.

The economic viability of this concrete also makes it a particularly attractive innovation. The cost of the equipment and licensing is offset by the reduction in cement. The company has installed its technology in over 100 plants across North America, which have in turn supplied over two million cubic yards of concrete. This product is sufficiently available to be used now and has already been used to great effect in numerous projects.

Use of Carbon Capture Technology

One company offers another carbon capture technology. It combines a specially formulated cement with CO_2 curing to produce concrete, primarily in the precast concrete products industry. This cement is about the same cost as portland cement but significantly reduces CO_2 emissions through reduced production energy. This is primarily because the cement uses all of the same materials that are used to produce portland cement but in a different ratio.[4]

This specially formulated cement uses less limestone than portland cement, which allows it to be fired at lower temperatures in the same rotary kilns in which ordinary portland cement is currently produced. These lower firing temperatures consume less energy and produce 30% less greenhouse gases and other pollutants. Additionally, instead of curing in water like conventional concrete, the concrete cures in contact with a CO_2-containing atmosphere. Not only does this allow more precision during the curing process, but the concrete also sequesters CO_2 equal to 5% of its weight. Between the combined factors of lower material costs, lower fuel costs and the CO_2 sequestered during curing, the company claims concrete's carbon footprint is reduced by 70%.

This concrete also offers other practical benefits beyond being environmentally friendly. For example, the company states that their concrete experiences reduced efflorescence, meaning that salt staining will appear less severely and less frequently on the surface when it is exposed to water. Additionally, the concrete's water absorption is reduced, being less than 2%. It has a compressive strength of about 10,000 psi, and it takes less pigment to color. Finally, this concrete is compatible with non-conventional aggregates and recycled glass. This allows further reduction of material cost and environmental benefits.

Another company offers a product which "combines unpurified CO_2 absorbed directly from power plant flue gas or other industrial CO_2 emission sources with metal oxides to make limestone used to coat a substrate, making CO_2-sequestered construction aggregate. The limestone coating is 44 percent by mass permanently sequestered CO_2 waste."

Recycled concrete particles are coated with synthetic limestone, forming a coating that is 44% by mass CO_2. Photos: Blue Planet Ltd.

The substrate is usually small rock particles or even recycled concrete.[5]

The company states that carbon-negative concrete is achievable by using an artificial limestone in concrete. They estimate that by replacing the conventional aggregate in one cubic yard of concrete, typically 3,000 pounds worth, 44% of its weight would be comprised of sequestered CO_2, roughly 1,320 pounds. This would offset more than the amount of CO_2 generally produced by the same amount of conventional concrete made with portland cement, which is roughly 600 pounds per cubic yard. The limestone-coated light-weight aggregate was specified for the Interim Boarding Area B at San Francisco International Airport in 2016. Concrete testing showed that this concrete met all necessary specifications.

Carbon capture and sequestration technology is a promising solution to reducing the carbon footprint of cement and concrete while improving performance. The possibility of vastly reducing CO_2 emissions associated with the production of concrete or even going beyond by sequestering more CO_2 than is produced during the cement manufacturing process is enticing. Many carbon capture and sequestration technologies are already commercially viable and are currently being used for construction since they can be conveniently produced by existing equipment or by retrofitting existing factories. Overall, carbon capture offers a simple but highly promising solution to reducing the environmental footprint of concrete.

SELF-CONSOLIDATING CONCRETE

Self-consolidating concrete (SCC) is a non-segregating concrete that can flow into place, fill formwork and encapsulate reinforcement without any mechanical vibration. SCC relies upon a combination of a high proportion of fine aggregate and admixtures called superplasticizers and viscosity-modifiers to achieve a stable and highly flowable concrete.

The increased ease of use and efficiency of SCC during construction is the basis for many of its principal benefits. First, it can be placed faster than regular concrete while requiring less finishing and no mechanical vibration. It also improves the uniformity of in-place concrete as well as the uniformity of surfaces, reducing or eliminating the need for surface work.

Additionally, using SCC allows for labor savings as well as increased jobsite safety as it does not require workers to travel the surface of slabs or the tops of walls to mechanically vibrate the concrete. SCC saves time during construction, resulting in cost savings, as well as improving the pumpability of the concrete and the turn-around times of concrete trucks.

Prof. Okamura at Ouchi University, Japan, to address shortages in skilled labor, first developed SCC in 1986. At first, SCC was used in highly specialized projects such as repair work or in areas difficult to reach due to its high cost of production and need for high quality control. The first high production use of SCC was in precast applications where concrete is produced and placed in controlled conditions. In ready mixed concrete applications, SCC was used primarily for heavily reinforced sections and where mechanical vibration was difficult. More recently, SCC is being used in architectural concrete since it results in a surface finish superior to that of conventional concrete. SCC still has a relatively high cost but is gaining popularity where labor is in short supply or where smooth exposed concrete is desired.

One of the highest profile uses of SCC is in high-rise building projects, proving its commercial viability and success in practical applications. Some considerations to take into

CASE STUDY: 432 PARK AVENUE, NEW YORK

Photo: David Pereiras / Shutterstock

432 Park Avenue in New York City is currently the tallest residential structure in the US. It is an aesthetically simple building that features exposed white concrete columns that structurally reinforce the structure in addition to providing the building with its most distinctive stylistic attributes. The building is thin for its height, having a width and length of 93.5 feet and a height of 1,396 feet. Multiple innovative structural methods were used to achieve "minimal displacement, accelerations, and vibrations to meet the most stringent standard" according to an article in STRUCTURE magazine, July 2018. These include "five outriggers, each spanning over two stories, […] devised throughout the height of the tower, […] serve as positive linkages between the interior core and the perimeter framing, which enhanced the overall performance of the structure."

Stiffer concrete with higher compressive strength was used on floors above the 38th to further increase resistance to movement in the upper stories. Furthermore, all concrete cast for 432 Park Avenue was designed for enhanced durability by minimizing the ratio of water to cementitious materials to as low as 0.25, and the concrete was required to be pumpable, self-consolidating and have a low heat of hydration to facilitate construction and the appearance of the exposed structural elements.

account regarding this concrete stem from the fact that it is dependent upon flowability, which may be reduced by hot weather, long haul distances or jobsite delays. Specifications required for a given job such as flowability and spread can vary, but mixtures can be tested via methods including the slump flow test to determine the extent of the concrete's plastic properties to ensure that the concrete arriving at a jobsite matches the standards specific to the project itself. SCC is fully commercialized and is used all over the world.

FROM WASTE TO WORTH

Supplementary Cementitious Materials (SCMs), such as fly ash, slag cement and silica fume, are the keys to high performance concretes. What makes these materials so innovative is that most are derived from a waste—byproducts of a manufacturing process that would otherwise end up in landfills. But when these waste materials are combined with portland cement in concrete, they react with certain chemical compounds to produce more binder. As a result, these materials are extremely valuable as SCMs.

Silica Fume, Blast Furnace Slag, and Coal Ash

Silica fume is a waste byproduct of processing quartz into silicon or ferro-silicon metals in an electric arc furnace. Silica fume consists of superfine, spherical particles that when combined with cement significantly increases the strength and durability of concrete. Of the three main SCMs, silica fume has the lowest supply and has the highest cost, usually at least three times that of portland cement. It is used in applications where extremely high strength is needed, such as columns in high-rise buildings, or where extremely low permeability is desired for durability, such as bridge decks and parking decks. It is typically combined with other SCMs to optimize performance and cost.

Blast furnace slag is the waste byproduct of iron manufacture. After quenching and grinding, the blast furnace slag takes on much higher value as an SCM for concrete. Blast furnace slag is used as a partial replacement for cement to impart added strength and durability to concrete. Some slag is used to make lightweight aggregate for concrete. About 16 million tons of slag were produced in the U.S., but less than half that was used in concrete as an SCM. Slag cement costs about the same or slightly more than cement depending on quality and location.

Coal ash is the waste byproduct of burning coal in electric power plants. Fly ash, a common SCM used in concrete, is one component of coal ash. According to the American Coal Ash Association (ACAA), in 2017, 111.4 million tons of coal ash were produced, of which 38.2 million tons was fly ash. Coal ash and fly ash have many uses, ranging from use in concrete as an SCM to synthetic gypsum for wallboard to mining applications. Of the 38.2 million tons of fly ash produced, only 14.1 million tons are used in concrete.

Fly ash is the most plentiful of all SCMs and is roughly half the cost of portland cement; however, because of increased emissions regulations on coal-fired power plants, not nearly as much high-quality fly ash is produced as in the past. In addition, with a move towards renewables and natural gas, coal-fired power plants are closing and thus many cost-effective supplies are diminishing.

Because coal power generation started in the early 1900s in the US, but the use of fly ash in concrete was only started to any significant volume in the late 1,900s, it is estimated that about 1.5 billion tons of coal ash has been placed in landfills, of which some is fly ash. Several companies, understanding the demand for fly ash in concrete is likely to increase, have begun to recover fly ash from landfills and treat it using a process called beneficiation.

Beneficiation simply means taking coal ash from landfills and processing it so it meets the

CASE STUDY: TRUMP TOWER CHICAGO

Photo: ghornephoto / iStock

Chicago Trump Tower and Hotel stands at 92 stories, made entirely out of reinforced concrete. A total of 194,000 cubic yards of concrete was used on the project. Architect/engineer Skidmore, Owings & Merrill specified high-performance concrete, and used a concrete supplier to design the mixes. Columns and walls required 12,000 psi at 90 days up to level 51 with some lateral resisting elements up to 16,000 psi. SCC was specified for many of structural elements because of reinforcement congestion. To reduce heat of hydration, high volumes of SCMs were specified for the mat foundation, which included a combination of slag cement, fly ash and silica fume. At time of construction, the 5,000-cubic-yard mat foundation was the largest single SCC placement in North America.

The high-performance reinforced concrete system helped minimize floor thickness creating higher ceilings. Residential floors also feature open spans up to 30 feet without requiring perimeter spandrel beams, which permits panoramic vistas of Chicago and Lake Michigan. Combining several innovative concrete technologies allowed for quick, efficient construction, as well as new opportunities that are not available with conventional concrete.

CASE STUDY: 102 RIVONIA, JOHANNESBURG, SOUTH AFRICA

Photo: Greg Balfour Evans / Alamy Stock Photo

102 Rivonia Road consists of two main buildings with connected walkways in-between to create a sense of connectedness and encourage collaboration between different areas of the office. It was designed with sustainability in mind, being 50% more sustainable than the average office building with a 4-star Green Star SA (South Africa) rating. Air-cooled chillers and a fire system that recycles used water also contributed to the project's energy efficiency. Notably, the use of fly ash in the concrete reduced the overall material use of the project by 30%, which also heavily contributed to the project having a lower carbon footprint.

necessary standards for beneficial use. For fly ash, beneficiation typically means reducing the amount of unburned carbon in the ash. Carbon tends to have an absorptive quality which inhibits air entraining and water reducing admixtures. There are also other chemicals such as ammonia in some coal ash deposits which must be reduced before use in concrete.

Several companies have developed processes for harvesting ash from landfills and reducing the unburned carbon and ammonia, calcium, sulfur and other impurities. The simplest process is to burn off the excess carbon. Still other methods use chemical treatment to mitigate the effects of carbon and ammonia, and one company uses low-frequency sound to reduce particle size to make them more uniform, a desired characteristic of fly ash.

According an article "Digging Through the Past: Harvesting Legacy Ash Deposits to Meet Future Demand," authored by Rafik Minkara and published in Issue 1 2019 of Ash at Work magazine, Minkara concludes, "While the variety of technologies now exist to beneficiate land-filled and ponded ash, the cost and complexity of doing so can be challenging." He goes on to say, "Beneficiation processes can be as simple as using off-the-shelf equipment or as involved as developing customized solutions with high capex requirements." In the end, it will depend on demand for fly ash. As low-cost supplies diminish over time, the demand is likely to be filled by harvesting and beneficiating the vast supply of coal ash in landfills.

CEMENTLESS CONCRETE

Although cementless concrete is likely years away from widespread commercialization, one of the more interesting areas of research and development is on geopolymer concrete, which uses fly ash and/or slag and chemical activators as the binder in place of portland cement. Geopolymer concrete is made by using a source of silicon and aluminum, usually fly ash or slag, and combining it with an alkaline activating solution, which polymerizes these materials into molecular chains to create a hardened binder. The more common activating solutions include sodium hydroxide or potassium hydroxide, which liberate the silicon and aluminum.

CASE STUDY: GLOBAL CHANGE INSTITUTE, BRISBANE, AUSTRALIA

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As Australia's first carbon neutral building, the Global Change Institute at the University of Queensland was designed to meet the highest level of sustainability. It is one of the first buildings to be registered for The Living Building Challenge. Some of the green building features include operable sun-shading, bio-retention basin, onsite greywater system, solar energy and thermal chimney. It is also the first building to include structural geopolymer precast concrete, significantly reducing the carbon footprint of construction materials.

The compressive strength of geopolymer concrete is comparable to portland cement, or its strength gain is generally faster with strengths of 3,500 psi or higher at 24 hours. Compressive strengths at 28 days have shown to be 8,000 to 10,000 psi. Research shows that geopolymer concrete has lower drying shrinkage, lower heat of hydration, improved chloride permeability and is more resistant to acids. Its fire resistance is also considerably better than portland cement, which is already highly fire resistant, making geopolymer concretes ideal for special high temperature applications.

To date, most of these products have not developed beyond the research and development stage. Some of the drawbacks include the high cost and energy to produce the chemical activator, the difficulty and safety concerns in handling a highly alkaline solution and the need to control temperature during the curing process. In addition, building code approvals are always a hurdle. Currently the most promising applications are in severe environment applications such as precast concrete bridges or other specialty applications such as high acid or high temperature environments or for rapid repair.

The key to geopolymer concrete commercialization will be to develop low cost, easy-to-use activators. One promising development is at Rice University where engineers have developed a geopolymer concrete that requires only a small fraction of the sodium-based activation chemicals used in other geopolymer concretes. According to the researchers, they used sophisticated statistical methods to optimize the mixing strategies for ingredients. This resulted in an optimal balance of calcium-rich fly ash, nanosilica and calcium oxide with less than 5% of the traditional sodium-based activator.

CONCLUSION

More than 20 billion tons of concrete are produced around the world each year. As a result, concrete construction contributes about 5% of global CO_2 emissions primarily due to the cement manufacturing process. The demand for concrete will likely continue to grow as population grows. In addition, the demands on strength, durability and workability will continue to increase. A combination of traditional and advanced technologies will help meet these new demands. Technologies such as TiO_2 cements, SCC, SCMs and fibers are being used now to varying degrees with outstanding results. Carbon capture and sequestration are in their infancy but show great promise. Fly ash beneficiation will help meet the demand for affordable, high performance concretes and geopolymer concretes may one day help make concrete carbon neutral without sacrificing performance. ■

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