The Jubilee Church in Rome was built with innovative concrete in the early 2000s.

Photo: Elio Lombardo/Alamy Stock Photo

Concrete Innovations

New products, manufacturing methods, and research are developing creative concretes to meet today's challenges

Sponsored by Build with Strength, a coalition of the National Ready Mixed Concrete Association

What do the Jubilee Church and the Pantheon have in common? They are both places of worship in Rome. But besides this, they are also 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 principals, 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. Gypsum and quicklime were used as binders also. And even 3,000 years before, the Egyptians used a form of concrete made with mud and straw to build the pyramids. Today of course, 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 performance, both during its plastic and hardened states.

Innovative supplementary cementitious materials (SCMs) such as fly ash, slag cement, and silica fume are used to increase strength, durability, and workability.

CONTINUING EDUCATION

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Learning Objectives
After reading this article, you should be able to:

1. Understand new technologies used in concrete manufacturing.
2. Discover how innovative concrete products can improve project performance.
3. 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.

To receive AIA credit, you are required to read the entire article and pass the quiz. Visit **ce.architecturalrecord.com** for the complete text and to take the quiz for free.

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The historic Pantheon was built with Roman concrete hundreds of years ago.

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 the surrounding atmosphere, which is what makes the concrete used to build the Jubilee Church so innovative. The exterior curved surfaces are coated with titanium dioxide (TiO_2) cement that eats smog, helping to keep the surface clean.

Concrete is the most widely used building product in the world. It is mostly made locally with local materials. Concrete is cost-effective, available everywhere, strong, and durable. While 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. Although concrete is not always synonymous with innovation, new products and manufacturing methods are enhancing concrete's performance to tackle modern challenges. This course explores some of these latest innovations.

SELF-CLEANING CONCRETE

Imagine concrete that can clean itself and even the surrounding air of harmful pollutants. This is what concrete made with 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 the TiO_2 that is added to the cement during its production. This 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 both organic and inorganic pollutants. It is intended for use in urban centers, where air pollution and poor air quality are most pronounced.

An example of how TiO_2 cement breaks 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. NO_2 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 that 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 United States indicates that "up to 50 percent of these atmospheric pollutants could be reduced in some cities if only 15 percent 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 both urban life and the environment.[1]

BENDABLE CONCRETE

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 that 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

GLOSSARY

Portland cement: This is the most common type of cement in general use around the world as a basic ingredient of concrete, mortar, stucco, and non-specialty grout.
Supplementary cementitious materials (SCMs): Fly ash, slag cement, and silica fume are used to increase strength, durability, and workability.
Photocatalysis: This is the acceleration of a photoreaction in the presence of a catalys.
Graphene concrete: This is made by suspending flakes of graphene in water and then mixing the water with traditional concrete ingredients, such as cement and aggregate.
Carbonation: This 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.
Self-consolidating concrete (SCC): This is non-segregating concrete that can flow into place, fill formwork, and encapsulate reinforcement without any mechanical vibration.
Silica fume: This is a waste byproduct of processing quartz into silicon or ferro-silicon metals in an electric arc furnace, used as an SCM in concrete.
Blast furnace slag: This is a waste byproduct of iron manufacture, used as an SCM or lightweight aggregate in concrete.
Coal ash: This is a waste byproduct of burning coal in electric power plants.
Beneficiation: This is the act of taking coal ash from landfills and processing it so it meets the necessary standards for beneficial use.
Bendable concrete: This is concrete containing fiber additives to enhance ductility and crack control.
Geopolymer concrete: This is concrete made with fly ash and/or slag cement combined with an alkaline activator as the binder.
Fly ash: This is one component of coal ash that is used as an SCM in concrete.

Photo: Elio Lombardo/Alamy Stock Photo

CASE STUDY: JUBILEE CHURCH, ROME, ITALY

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 that which are meant to represent the Holy Trinity. Given the symbolic importance of the shells, their appearance is an absolute priority. Thus, due to the fact that 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.

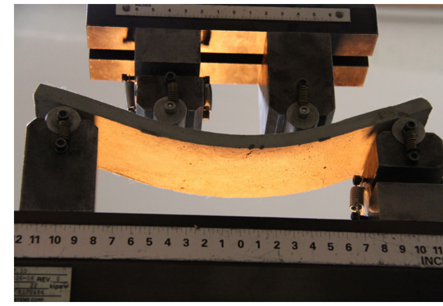
Michigan, where ECC was first researched and invented, states that bendable concrete "can deform up to 3 to 5 percent in tension before it fails, which gives it 300 to 500 times more tensile strain capacity than normal concrete." It is this ability to tolerate tensile strain that makes bendable concrete unique.

This enormous increase in ductility suggests various potential applications. Firstly, in roads as well as other paved surfaces that must bear repeated loading of heavy vehicles, bendable concrete would crack less often, preventing further weathering primarily from road salts that 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 suggests that it would also be useful in underground and water infrastructure construction.

However, before it can be more widely commercialized for such large-scale projects, bendable concrete must first become more readily available. To be economically viable, it needs to 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

Photo: Victor C. Li



Bendable concrete is 300–500 times more ductile than conventional concrete.

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 to improve its strength and durability 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 to improve strength and ductility, along with a host of other benefits. The manufacturer states that it uses "high-carbon metallic fibers, stainless fibers, polyvinyl 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, acids, and sulfates. It is also

Photos courtesy of The Bluestone Organization

CASE STUDY: 42 BROAD, FLEETWOOD, NEW YORK

42 Broad is a 16-story mixed-use development near New York City being built with insulating concrete forms (ICFs). ICF construction is becoming more mainstream with thousands of projects built in the United States, 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 United States.

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 job site 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.

Photo: Ian Dagnall/Alamy Stock Photo

CASE STUDY: PEREZ ART MUSEUM, MIAMI, FLORIDA

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.

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 and then mixing the water with traditional concrete ingredients, such as cement and aggregate. Graphene concrete is concrete reinforced by graphene. Graphene is 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 separate layers of graphene in graphite can be separated into sheets only one atom thick. Graphene is the thinnest compound known to man, the lightest material known, and the strongest compound discovered—more than 100 times stronger than steel.

This technology's strength largely lies with its accessibility given that it is inexpensive and compatible with modern, large-scale manufacturing requirements. According to a research paper published in the *Advanced Functional Materials* journal titled "Ultrahigh Performance Nanoengineered Graphene – Concrete Composites for Multifunctional Applications," 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.[3]

Photo courtesy of CarbonCure

CASE STUDY: 725 PONCE, ATLANTA, GEORGIA

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 U.S. 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.

CARBON CAPTURE

Like most manmade materials, concrete is considered a carbon dioxide (CO_2) emitter, mainly due to the cement manufacturing process. But what if one could reverse this process and capture or sequester CO_2 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 carbonation occurs from the surface inward, creating a tighter matrix at the surface and 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 the 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.

One of the most comprehensive studies is highlighted in an article titled "Substantial Global Carbon Uptake by Cement Carbonation," which was published in the journal *Nature Geoscience* in 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 estimate that the cumulative amount of CO_2 sequestered in concrete is 4.5 gigatonnes in that period. This offsets 43 percent of the CO_2 emissions from production of cement caused by the calcination process. The researchers 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. This might not be considered innovative since it would simply mean changing the way that demolished concrete is collected and treated before reuse. 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 year or two, and thus leaving crushed concrete exposed to air before reuse would be beneficial.

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, converting the CO_2 into a solid-state mineral within the concrete. The minerals formed enhance compressive strength.[4]

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 equipment and licensing is offset by the reduction in cement. The technology has been installed in more than 100 plants across North America, which have in turn supplied more than 2 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 sector. 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.[5]

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 percent 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 for more precision during the curing process, but the concrete also sequesters CO_2 equal to 5 percent of its weight. Between the combined factors of lower material costs, lower fuel costs, and the CO_2 sequestered during curing, the company claims that concrete's carbon footprint is reduced by 70 percent.

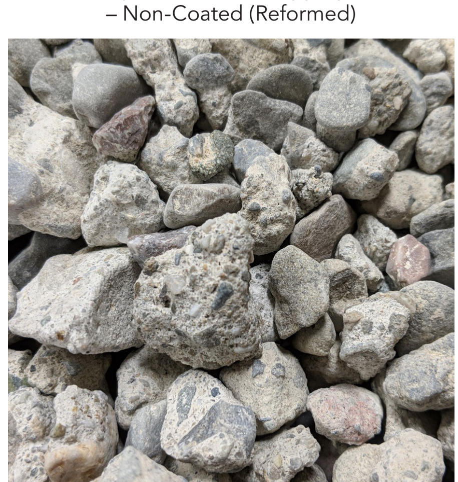
This concrete also offers other practical benefits beyond being environmentally friendly. For example, the company states that its concrete experiences reduced efflorescence, meaning that salt staining will appear less severely and less frequently on the surface when it is exposed to water. Additionally,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

Another company offers a product that "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."

The company states that carbon-negative concrete is achievable by using an artificial limestone in concrete. It estimates that by replacing the conventional aggregate in 1 cubic yard of concrete, typically 3,000 pounds worth, 44 percent 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 lightweight 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

Recycled Concrete Aggregate – Non-Coated (Reformed)



Coated Recycled Concrete Aggregate

Photos courtesy of Blue Planet

Recycled concrete particles are coated with synthetic limestone, forming a coating that is 44 percent by mass CO_2.

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.

The substrate is usually small rock particles or even recycled concrete.[6]

SELF-CONSOLIDATING CONCRETE

Self-consolidating concrete (SCC) is highly flowable, 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 job-site 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 turnaround times of concrete trucks.

SCC was first developed in 1986 by Professor Okamura at Ouchi University in Japan to address shortages in skilled labor. At first, SCC was used in highly specialized projects, such as in repair work or difficult-to-reach areas, 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 that is superior to that of conventional concrete. SCC still has a relatively high cost, but it is gaining popularity where labor is in short supply or smooth, exposed concrete is desired.

One of the highest-profile uses of SCC is in high-rise buildings, proving its commercial viability and success in practical applications. Some considerations to take into 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 job-site 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 job site matches the standards specific to the project itself. SCC is fully commercialized and 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 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 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

Photo: David Pereiras/Shutterstock

CASE STUDY: 432 PARK AVENUE, NEW YORK

432 Park Avenue in New York City is currently the tallest residential structure in the United States. 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 a July 2018 article in *STRUCTURE* magazine. These include "five outriggers, each spanning over two stories, […] devised throughout the height of the tower, […] serving 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. 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.

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 United States, 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 were 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 toward 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 United States, but the use of fly ash in concrete was only started to any significant volume in the late 1900s, it is estimated that about 1.5 billion tons of coal ash has been placed in landfills, of which some is fly ash—and this is where the innovation comes in. Several companies, understanding that 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 necessary standards for beneficial use. For fly ash, this 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 that must be reduced before use in concrete.

Several companies have developed processes for harvesting ash from landfills and reducing the unburned carbon and

Photo: ghornephoto/iStock

CASE STUDY: TRUMP INTERNATIONAL HOTEL AND TOWER, CHICAGO

The Trump International Hotel and Tower in downtown Chicago stands at a stunning 92 stories, made entirely out of reinforced concrete. A total of 194,000 cubic yards of concrete was used on the project. Architect and engineer Skidmore, Owings & Merrill specified high-performance concrete, and the concrete supplier designed 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 the 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, permitting 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.

Photo: Greg Balfour Evans/Alamy Stock Photo

CASE STUDY: 102 RIVONIA, JOHANNESBURG, SOUTH AFRICA

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 percent 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 percent, which also heavily contributed to the project having a lower carbon footprint.

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 the size of particles to make them more uniform, which is a desired characteristic of fly ash.

According to an article titled "Digging Through the Past: Harvesting Legacy Ash Deposits to Meet Future Demand" published in a 2019 issue of *Ash at Work* magazine, author Rafik 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 currently in landfills.

Blended Cements

Most SCMs are added at the concrete plant to supplement portland cement. However, there are several alternatives to portland cement called blended cements. These combine ordinary portland cement (OPC) with other materials at the cement plant. The most common type of blended cement is portland limestone cement (PLC), or technically ASTM C595 Type IL (pronounced "one el") cement. This blended cement combines up to 15 percent limestone interground with OPC to make a cement with a carbon footprint that is up to 10 percent 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:

1. Type IL (X) Portland-Limestone Cement, where X can be between 5 and 15 percent limestone.
2. Type IS (X) Portland-Slag Cement, where X can be up to 95 percent slag cement.
3. Type IP (X) Portland-Pozzolan Cement, where X can be up to 40 percent pozzolan (fly ash is the most common).
4. Type IT (AX)(BY) Ternary Blended Cement, where X and Y are the percentages of slag cement, pozzolan, or limestone, and A and B are the types of ingredients (S, P, or L). The total of X + Y cannot be more than 70 percent, with pozzolan being no more than 40 percent and limestone no more than 15 percent.

Blended cements are accepted in all the concrete standards.

Geopolymer Concrete

Although we are 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 that polymerizes these materials into molecular chains to create a hardened binder. The more common activating solutions include sodium hydroxide or potassium hydroxide, which liberates the silicon and aluminum.

Compressive strength of geopolymer concrete is comparable to portland cement concrete or higher, and 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. And its fire resistance is considerably better than portland cement concrete, 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. A company called Ceratech launched geopolymer concrete in in 2002 but later closed. A product called Pyrament was launched in the 1980s but was not successfully commercialized. Some of the drawbacks include the high cost and energy to produce the chemical activator, the

CONTINUING EDUCATION

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CASE STUDY: GLOBAL CHANGE INSTITUTE, BRISBANE, AUSTRALIA

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, on-site greywater system, solar energy and thermal chimney. And it is the first building to include structural geopolymer precast concrete, significantly reducing the carbon footprint of construction materials.

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 environments, 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 percent 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 percent of global CO_2 emissions primarily due to the cement manufacturing process. The demand for concrete will likely continue to grow as the 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.

END NOTES

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