THIS IS CONCRETE

THE SHAPE OF THINGS TO COME

A voyage of discovery into the future of concrete: LOW-CARBON, DIGITAL, MARTIAN

HOW BIM TURNED KENGO KUMA'S DUNDEE ROCK INTO REALITY

NASA'S MISSION TO LAND CONCRETE MIXERS ON MARS

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mpa The Concrete Centre

The Concrete Centre provides design guidance, seminars, courses, online resources and industry research to the design community. Our aim is to enable all those involved in the design, use and performance of concrete to realise the potential of the material.

The Concrete Centre is supported by industry to inform, educate and inspire. Our members are Aggregate Industries, Allen Newport, Breedon Aggregates, Brett Group, Britannia Aggregates, British Precast, Cemex Materials, Deme Building, Euro Min, F M Conway, Gallagher Aggregates, GRS Roadstone, Grundon Waste M'ment, Hanson Aggregates, Harleyford Aggregates, HH and HE Drew, Hills Minerals, Ingrebourne Valley Aggregates, J & J Franks, J Clubb, Marshalls Group, Moorhouse Sand & Gravel Pits, Moreton C Cullimore, Morris & Perry, Myers Group, Quattro UK, Rotherham Sand & Gravel, Smith & Sons, Springfield Farm, SSG Quarries (formerly Salop), Tarmac, Trefigin, Tudor Griffiths, Volker Dredging.

The Concrete Centre is part of the Mineral Products Association, the trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries.

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this is concrete

This is Concrete shares interesting facts about concrete and showcases amazing projects via our website, blogs, twitter feed and our project and fact adverts. Our mission is to engage the design community and share the endless possibilities of concrete.
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Cover photo: Digital Building Technologies (dbt), ETH Zürich/ Demetris Shammas

WELCOME

Much has been made of society's dependence on concrete in recent months. It's true that a lot of concrete is poured around the world – because concrete performs so many functions to ensure our quality of life. Concrete is essential for infrastructure projects such as the Thames Tideway Tunnel, to prevent river pollution in London, and the Crossrail line that will cut journey times for millions of commuters. Concrete provides non-combustible structures for our homes, schools, hospitals and offices, and the thermal mass to cool them in warmer summers without energy-intensive cooling systems.

Concrete is a hotbed of innovation – as our exhibition feature on "Concrete Futures" at Futurebuild will show. In laboratories around the world, innovators are reformulating cement to be less energy-intensive or replacing it completely, devising alternatives to fine aggregate such as waste plastic and inventing new types of reinforcement that can bend, be 3D-printed in fibre form or even transmit light.

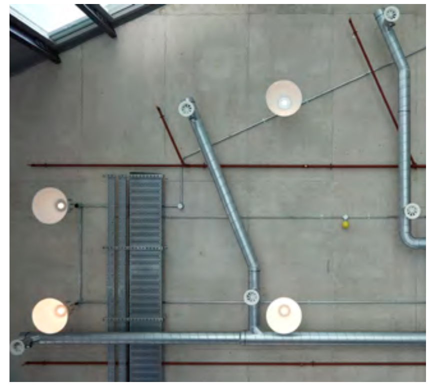
Sustainability has been one of the biggest drivers for this innovation – Futurebuild was of course itself known as "Ecobuild" until this year. The embodied carbon of UK concrete has reduced by 29% since 1990 under the Concrete Industry Sustainable Construction Strategy, which has been collecting detailed data on progress over the last decade (see pages 20-23).

No development happens without environmental impact, so the use of any resource is an investment. Every structure should be designed to get the maximum benefits from that resource for the longest possible time, as well as ensuring that it can eventually be reused to avoid the need to use more primary resources. Concrete ticks all of those boxes and more.

Claire Ackerman, director, The Concrete Centre

SUSTAINABILITY IS ONE OF THE BIGGEST DRIVERS OF INNOVATION. UK CONCRETE'S EMBODIED CARBON HAS REDUCED BY 29% SINCE 1990

THE CONCRETE CENTRE AT FUTUREBUILD



Photos: Marcos Cruz, Rob Parrish, Concrete Centre

Concrete Futures exhibit

The Concrete Futures exhibit at Futurebuild 2019 will feature examples of new and experimental forms of the material, including "living concrete", developed by the Bartlett School of Architecture. Described as an "architectural bark", it can host species such as algaes, mosses and lichens to create more sustainable green walls that require no maintenance and potentially absorb pollution and noise in cities. In 2018, eight prototype panels were installed at St Anne's RC Primary School in London (pictured). The exhibit will also include examples of a smart concrete that could be used to store energy, potentially turning buildings and roads into batteries and enabling much greater use of renewable power by levelling out supply and demand. Potassium-geopolymeric (KGP) composite, invented by researchers at Lancaster University, is made from fly ash and an alkaline solution, and could store and discharge 200-500W/m^2.

Futurebuild takes place at London's ExCeL on 5–7 March. Concrete Futures will be on stand E80in the Materials Hub. More details at concretecentre.com/events

Thermal mass video

By 2060, the amount of energy used for cooling worldwide will exceed energy used for heating. Ensuring buildings have sufficient thermal mass can help to future-proof them against the effects of a changing climate.

Our new video, shot at White Collar Factory in London by AHMM, helps to explain how thermal mass works. thisisconcrete.co.uk

New cements in BS 8500

BS 8500, the British standard for the specification of concrete, has been updated and now permits the use of composite cements. The Concrete Centre's updated guide, Specifying Sustainable Concrete, details the changes and provides information about the sustainability of concrete and its constituent materials. concretecentre.com/publications

Seminar programme

The Concrete Centre will be presenting seminars throughout Futurebuild in the Materials Hub Theatre
concretecentre.com/events

Tuesday 5 March
16.30 – 17.40
Innovations in concrete
An overview of the many exciting innovations being used to lower carbon, reduce waste, improve communications and enhance quality and performance.

Wednesday 6 March
10.30 – 11.40
Circular economy of concrete
Guidance on best practice in material efficiency, exploring the reduction of embedded materials, designing for reuse and recycling at end-of-life, with case studies including the recently completed Royal College of Pathologists HQ by Bennetts Associates.

Wednesday 6 March
12.00 – 13.10
Higher level housing
Guidance on designing and constructing homes for long-term resilience using concrete and masonry, considering practical strategies for addressing climate change impacts such as overheating and flooding.

Thursday 7 March
13.30 – 14.40
Fit for the future
Explore how structural materials help to ensure buildings are fit for the future: resilient to climate change, low carbon, material efficient, robust, fire resistant, secure and built to last, including a case study of AHMM's White Collar Factory.

FORMULATING THE FUTURE

Tony Whitehead reports on the latest innovations in mixes and methodologies – from carbon-storing concrete to cracks that heal themselves

Considering concrete has been around for thousands of years, there is an astonishing amount of research and innovation currently underway to improve the product to adapt to the changing needs of society. Around the world concrete is being made stronger, its carbon footprint is being reduced, and robotics and digitalisation are changing the way concrete structures are built.

Concrete is even getting smarter – able to self-diagnose and self-repair problems such as cracks. And in addition to all this, it is now being recruited in a drive to solve environmental problems unrelated to its primary construction purposes – in particular by using it to "store" waste by incorporating recyclates into the mix.

But when you consider how much concrete is used around the world – some 10 billion tonnes every year – this quest for innovation is easy to understand. Even small refinements could have huge implications, for contractors, designers, the built environment they create and the wider environment they seek to protect.

Take, for example, the impact already made by the availability of stronger concrete. Only 15 years ago, 55MPa concrete was considered high strength. Now most new tall projects in the US incorporate 70-100MPa concrete into their design thanks to the development of reliable water-reducing admixtures.

The effect has been dramatic. The tallest building in the US, One World Trade Center, completed in 2015, used a 100MPa mix to facilitate a less bulky core. This resulted in more lettable space, less gravitational load and therefore less concrete required for the foundations. High-strength mixes enable greater material efficiency, and therefore lower embodied carbon in building structures.

High-strength concrete mixes like this have also played an enabling role in the recent trend for super-skinny residential skyscrapers: many in the US and Middle East are over 300m tall.

So how much stronger can concrete get? We may be approaching the limit for traditional Portland cement (PC)-based concrete, as Professor Leon Black at the University of Leeds explains: "Better plasticisers have allowed us to reduce the water content of concrete so that the cement particles are closer together, resulting in lower porosity and higher strength. But cement has to hydrate to react, so for most practical applications it will not be possible to go much below a 0.3 water:cement ratio."

Black, who runs the university's MSc in advanced concrete technology, says that concrete can be made stronger in other ways – for example, by nano-engineering cement via the addition of admixtures and silica fume. But although concrete with strengths of up to 200MPa has already been produced this way, and some bridges in the US have even been built with it, such super-strength mixes are still rare because of high costs and the limited availability of plant capable of producing and handling them. Similarly, experimental concrete comprising less than 1% graphene platelets has shown marked strength and durability improvements but, as Black says: "With graphene costing around £100 per gram, you can forget it for the foreseeable future."

If the quest for strength may have already delivered on much of its potential, another area of research, the effort to decarbonise concrete production, has increased massively in recent years. Specifiers in the UK now routinely choose mixes with a proportion of the PC content replaced by industrial by-products such as GGBS (slag) or FA (fly ash). A 30% FA content, for example, reduces concrete's carbon footprint by around 25%.

Much attention is focused on the development of novel or alternative cements, such as alkali-

"PORTLAND CEMENT IS TOO USEFUL TO BE COMPLETELY REPLACED. RATHER I SEE A KIT-OF-PARTS APPROACH WHERE MANY DIFFERENT SUBSTITUTES ARE USED"

DR SUSAN BERNAL-LOPEZ, UNIVERSITY OF LEEDS

All images: Researchers at ETH Zürich have 3D-printed formwork for a ceiling slab from sand. The resulting 80m^2 lightweight slab is just 20mm thick at its thinnest point

Photos: Digital Building Technologies (dbt), ETH Zürich / Andrei Jipa, Tom Mundy activated geopolymer concrete that uses no PC at all. Comprising 100% cementitious replacement, this was used in the former Soviet Union and, more recently, to create the runways and pavement for an airport in Australia. As the availability of such cement substitutes varies around the world, potentially limiting their use, the search is on for other products that can deliver low-carbon concrete. One promising possibility involves using calcined clays, which work in a similar way to GGBS. Northern Irish firm Banah already produces such a cement replacement and claims it produces a strong and durable concrete.

Black's colleague, Dr Susan Bernal-Lopez, is a specialist in such alternatives. "There are different cementitious substitutes available in different parts of the world and we try to apply the right chemistry to whatever is available," she says. "PC is too useful to be completely replaced. Rather I see a kit-of-parts approach where many different substitutes are used. The choice would depend on local supply, and also the application, since different substitutes result in concretes with different, often desirable, qualities."

Meanwhile, the University of Leeds is among a number of organisations researching ternary blends – cements that contain a third ingredient, further cutting carbon content. "For example, a mix that is 20% limestone and 30% FA enables clinker content to be reduced to 50%," says Black. "Our work is concerned with which proportions and fineness of the limestone content produce the best concrete."

Results are promising: adding limestone appears to decrease porosity and improve durability. "We have to check whether additives like plasticisers still work with the added limestone present – but most do seem to behave similarly," says Black.

Not all ternary blends are covered by British or EU standards, he adds, but "industry is pushing the standards committees to have them included". The recent amendment to BS 8500:2015 introduced ternary blends with a minimum of 65% PC clinker and either 6-35% limestone and pozzolana, 6-35% limestone and fly-ash, or 6-35% limestone and GGBS.

The question of standards is an important one. It is no use having a clever new sustainable concrete if its use is not sanctioned – and to this end Leeds is setting up a National Centre for Infrastructure Materials to speed the testing of new products. "Industry can't afford to wait decades to find out if their new mix will last," says Black. "So

Above: At the super-skinny 432 Park Avenue in New York, a 111MPa mix enabled a height-to-width ratio of 15:1
Right: 100MPa concrete was used for the core of One World Trade Center

Photos: Shutterstock.com

"PERHAPS, IN THE SAME WAY THAT OUR BODIES RELEASE FLUIDS TO REPAIR INJURY, CONCRETE TOO COULD RELEASE REPAIR COMPOUNDS WHEN NEEDED"
DR KEVIN PAINE, UNIVERSITY OF BATH

we look at accelerated ageing of materials. By understanding the chemistry, and using computer modelling, we can help industry and standards committees to have confidence in a new product sooner."

This, of course, is only one of many ways in which computer technology is impacting on concrete innovation. The 3D printing of concrete, for example, has achieved fame on YouTube – with videos of entire houses being 3D-printed by gantry-mounted robotic concrete extruders attracting millions of views.

However, researchers in this field at Loughborough University, working in conjunction with commercial organisations including Tarmac and Skanska, see a subtler future for 3D-printed concrete. "There are a number of ambitious teams in Europe and elsewhere with design proposals for new modern homes and some prototyping, but at the moment it is rarely clear exactly what the construction method is and how much will be printed," says Simon Austin, Loughborough's professor of structural engineering. "On the other hand, printing building components where a variety of geometries is sought is an attractive approach. We are continuing down the component

Photos: roger parkes / Alamy Stock Photo

IN PRACTICE

A role for waste plastic

Scientists at the University of Bath have found waste plastic could be a viable partial replacement for sand in structural concrete.

The research, in partnership with Goa Engineering College in India, has shown how replacing 10% of sand in concrete with waste plastic may help to reduce the vast amounts of plastic waste on India's streets, and deal with its national sand shortage.

The team looked at various types of plastic to see if they could be crushed and used as a replacement for sand, which typically accounts for 30% of a concrete mixture. "We found plastic bottle waste worked quite well," says Dr Richard Ball, reader at Bath's Department of Architecture and Civil Engineering. "Tensile strength was increased a little, though compressive strength was reduced. Characteristics of the waste, particularly the size and shape of the particles, influence the final concrete properties. But even when the reduction in performance prohibits structural applications, lower tech uses such as paving slabs may be viable."

India's sand shortage follows a crackdown on environmentally damaging sand extraction. At the same time, the country's rapid development has led to waste plastic becoming a significant problem – due to a lack of suitable recycling facilities, 15,000 tonnes of plastic is dumped in the streets every day.

There's no reason why replacing sand with plastic could not be a viable option in the UK, adds Ball. "Where the plastic is an industrial by-product, or where it results from existing recycling activity, you actually end up with a more predictable replacement than, say, bottles which are made from a variety of different plastic types. In the UK, for example, we are currently looking at uPVC window recyclate as a potentially reliable source of plastic to put into concrete."

Ball says more work is required before plastic replacement can become routine: "We need to establish how different plastics perform, the effect on fire resistance, and what happens when you want to recycle concrete with a plastic content. Probably the best approach is to look at what plastic is available in a particular instance, and design forwards from there."

The research follows a similar study at University of Sheffield which found that all the main components of waste tyres – crumb rubber, steel wire and polymer fibres could also be incorporated into concrete.

Photos: Solidia Technologies

IN PRACTICE

Carbon-storing concrete

After spending US$100 million on research, a US company based in New Jersey is launching a radically reformulated cement and concrete process which it claims can reduce the carbon footprint of concrete by 70%.

Made by Solidia Technologies, the concrete has already been tested and produced in precast form in the UK at a plant in Leighton Buzzard owned by Solidia's European partner, Lafarge Holcim.

Nicholas DeCristofaro, Solidia's chief technical officer, explains: "We have reformulated cement so that it contains less calcium. This reduces CO_2 emissions at the cement kiln – both because less CO_2 is released from the decomposition of calcium carbonate during clinkering and also because the cement can be produced at lower temperatures, so less energy is required."

Solidia's cement is non-hydraulic, meaning it does not react with water. "Portland cement-based concrete reacts with water to produce calcium silicon hydrate – the glue that binds it together," says DeCristofaro. "But concrete that uses our low-calcium cement is bound together by calcium silicon carbonate after being activated by the addition of warm CO_2 gas.

By activating the concrete with CO_2 recovered from power stations and industrial processes (potentially including cement manufacture itself), it is incorporated permanently into the concrete. This means that the carbon footprint of the finished product is reduced still further to around 30% that of traditional concrete. Solidia hopes that if CO_2-cured concrete succeeds in gaining traction around the world, it could provide a way of binding up large quantities of CO_2 in roads and other structures.

"Existing plants can handle most of the new process," says DeCristofaro. "The concrete is still mixed with water in order to provide the flow properties it requires. The only difference is that after being mixed, the concrete is arranged in blocks and placed into airtight tanks a little like transport containers. The CO_2 is then pumped in, causing the concrete to set."

A key advantage is that the concrete reaches full strength within 24 hours – unlike traditional precast which can take longer to reach its application strength: "That hugely reduces the amount of inventory producers need to have in their yard."

Other advantages include less need to stop production to clean out mixers (as no concrete hardens within them) and a lower risk of efflorescence spoiling the finished product.

It is not yet clear whether these potential cost savings will fully compensate for the additional cost of adding CO_2. Industry will have a more definite idea about price following full commercial roll-out of the product, planned for this year.

Initially, at least, Solidia concrete is likely to be confined to relatively simple, non-structural precast products. However, the process has been proven to work on road pavement, and on elements up to 30m long by surrounding them in tarpaulin to contain the added CO_2.

route with our R&D based on robotic arms."

Felipe Manzatucci, Skanska's director of digitalisation, agrees: "There is more scope for 3D printing to create specific building components – complex shapes that would be hard to make the formwork for."

One problem 3D-printed concrete has yet to solve, however, is its "corduroy" appearance, the result of a process that builds up the element by repeatedly laying down a 12mm-diameter bead of concrete. Another issue is that of reinforcement, with trials stymied by the fibres' tendency to clog the printing nozzle.

Greater potential, perhaps, lies in 3D-printed formwork which allows the shape of the resultant concrete to be far more refined than traditional shuttering. The method was notably demonstrated last year when researchers at ETH Zürich 3D-printed formwork for a ceiling slab from sand. The formwork, which once printed is similar to sandstone, was able to remove all unnecessary volumes, leaving concrete only where it was required by the design.

This resulted in a fantastically shaped formwork of swirls and curves which was then sprayed with high-performance fibre-reinforced concrete. The completed 80m^2 lightweight slab is just 20mm thick at its thinnest point, and at 15 tonnes is less than half the weight of a normal slab. This improves the material efficiency not only of the building components but of the formwork required during construction, reducing waste. ETH Zürich is also leading the field in computer-controlled rheology of concrete to allow a variable slipforming technique known as smart dynamic casting (see right).

Finally, no discussion of concrete's future can be complete without

Photos: Gramazio Kohler Research, ETH Zürich

IN PRACTICE

Smart dynamic casting

A house in Switzerland has become the first in the world to feature structural concrete elements made by smart dynamic casting (SDC). Opened in February this year, the NEST building of the Swiss Federal Laboratories for Materials Science and Technology in Dübendorf uses a digital fabrication process whereby wet concrete is fed into a movable form and hardens almost immediately.

Dr Ena Lloret-Fritschi, postdoctoral researcher at the Swiss Federal Institute of Technology in Zürich, explains that the process uses a type of self-compacting concrete that has been heavily retarded and which is accelerated on demand just before it enters the formwork.

"SDC is a gravity-fed additive manufacturing process that uses a dynamic formwork for the production of structures with variable geometry," she says. "It relies on close control of the concrete's state of hydration which is monitored and used to automatically adjust the slipping speed – the rate at which the concrete exits the moving form. The material is shaped in the delicate phase when it changes from soft to hard, which means that at the moment when it exits the formwork, it is just capable of sustaining its own weight and the weight of the material on top. In that moment, the material is similar to wet clay. It then hardens almost immediately."

The process has produced some startling results. By using a six-axis, robot-controlled revolving rectangular form, the team has produced a continuously twisting column with a corkscrew-like appearance (above). Columns can also be produced with bends, kinks or variable diameters. Concrete strength produced with the SDC technique has been measured at between 80-100MPa in compression.

For the DFAB house, SDC was used to produce 15 load-bearing mullions, each 3m tall, with the concrete being dynamically cast around simple steel reinforcement. "Because the form has an adjustable diameter, the width of the columns varies from 100mm to 180mm, allowing us to put the concrete only where it is needed from a structural point of view," says Lloret-Fritschi.

As SDC is a continuous process, it is potentially faster than 3D-printing, she adds. "We have created columns at a rate of approximately 1m/hour. The surface finish is also very smooth as opposed to being corrugated, an issue 3D printing is still struggling with. We are currently investigating the possibility of producing factory-made precast elements. This opens up new possibilities – in particular with regards to the speed and precision of material processing."

The project is embedded within the Swiss National Centre of Competence in Research (NCCR) Digital Fabrication, and is the result of collaboration between Gramazio Kohler Research and the Physical Chemistry of Building Materials Group of ETH Zürich.

considering smart or "clever concrete" that can diagnose and heal its own cracks. Kevin Paine, reader at the University of Bath and a leading researcher in this field, explains: "We can include capsules of bacteria spores in the concrete mix along with food such as yeast extract. If the concrete cracks, bacteria is released and exposed to oxygen and water. It feeds on the yeast, and turns calcium into calcium carbonate – or limestone – to seal the crack before it has a chance to enlarge."

This could potentially be combined with self-diagnostic technology. "By adding piezo-ceramic material to the concrete mix we can measure the electrical properties of, for example, a bridge. Then by using impedance spectroscopy we can assess any changes in the structure, or this can be done automatically."

Such technology is already available, but Paine sees promise in linking it to self-repair mechanisms. "Imagine a vital structure which is very difficult to access – perhaps something underground or underwater. How would you know if it had started to fail? In the future, you could have concrete that triggered its own repair mechanisms. Perhaps, in the same way that our bodies automatically release fluids to heal injury, concrete too could feature a vascular-style system to release repair compounds when needed."

Bacteria-repaired concrete is still some five to 10 years from the market, says Paine, and intelligent self-repairs lie still further into the future. Whatever that future looks like, it is certain that much of it will be built from concrete. But as the sector continues to innovate, and mixes and methodologies become ever more sophisticated, it could be very different from the concrete we know today.

Photos: seanpollock.com

IN PRACTICE

Bespoke mixes for a unique home

It has always been possible to produce infinite variations of concrete's sand-cement-aggregate mix, but the continuing development of additives means that designers can now, more than ever, specify sophisticated bespoke mixes to perform specific functions within a building.

This was entertainingly demonstrated on Channel 4's Grand Designs, which followed the fortunes of self-builder Adrian Corrigall and his efforts to create an all-concrete house by using "disruptive methodologies". Corrigall and architect Graeme Laughlin of RAW Architecture Workshop worked closely with the CEMEX Research Group in Switzerland which proposed a range of innovative concrete mixes.

The ground slab, for example, was built from CEMEX's Resilia Conventional, a concrete containing fibres that add strength and enable the amount of steel reinforcement to be reduced. A high-performance, self-compacting version of the mix, Resilia HP, was used for the structural walls and horizontal elements – a choice that again reduced the amount of steel reinforcement, this time by some 60%. Being a high-strength and highly ductile mix, a self-compacting concrete allows thinner sections to be cast – particularly appropriate since the structure was made of in-situ concrete sandwich panels comprising two leaves of concrete with a central core of insulating material.

This design choice also accelerated the cycle time between casting of the walls, as there was very little steel to detail and fix. And because it was a self-compacting mix, the material could be placed into forms with little or no vibration, allowing the contractor to complete each element more quickly.

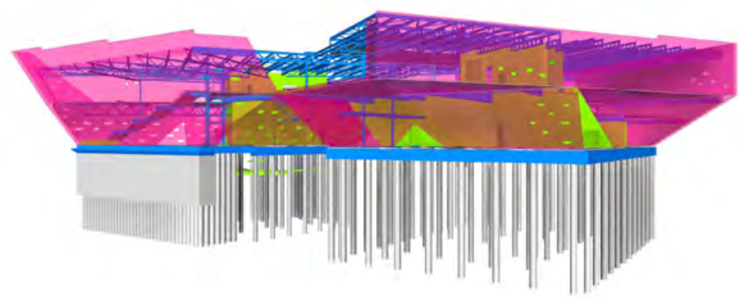
Innovation in any field is not a smooth glide of progress though, as the team discovered when the time came to deploy CEMEX Insularis, an insulating concrete containing polystyrene beads. This had been specified for various slab-wall junctions where cold bridging could be a problem, but when the team attempted to place it, the pump blocked, forcing the contractor to pour the concrete manually. The team discovered that the problem had been caused by variations in the raw material, as well as the configuration of the pump. Following modifications to the mix and adjustments to the pump configuration, the material eventually flowed into place.

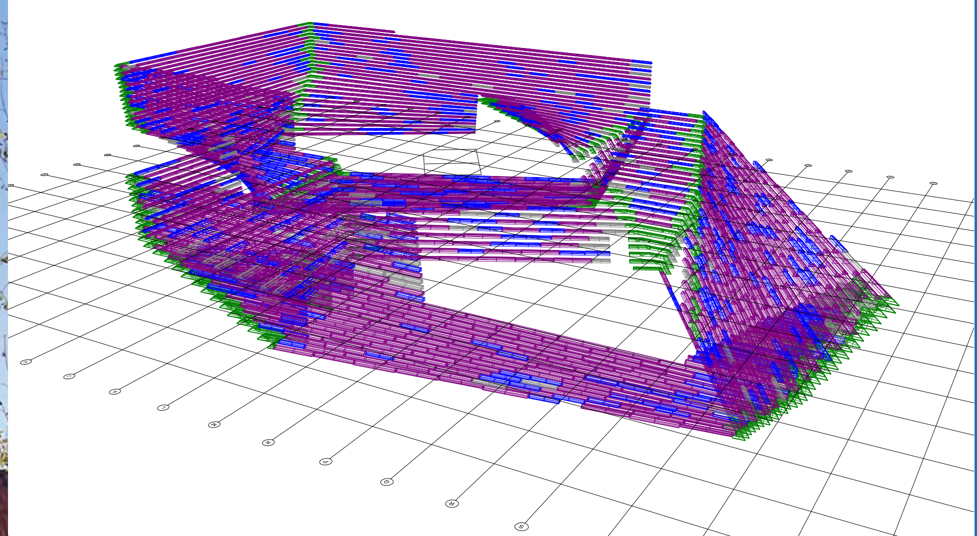
Once structurally complete, one more specialist mix was needed to finish the floors. These featured underfloor heating pipes to be laid beneath a finished concrete or screed floor. A bespoke version of CEMEX's Evolution self-compacting mix was designed to allow a power-floated finish, without compromising on floor levels throughout the build. Dubbed Evolution F, the mix contained a range of admixtures which were added to aid the placement of the concrete by controlling the consistence retention to give the contractor time to work with the material.

THE ROCK THAT BIM BUILT

Paul Wilkinson discovers how collaborative software enabled Kengo Kuma's structurally daring V&A Dundee to become a reality

Photos: Hufton + Crow Models: Arup, KKAA





The £80m, 8,500m² V&A Dundee in Scotland is devoted to design. Fittingly, it is also a triumph of international design cooperation. From some angles, this striking building resembles a ship setting sail on the River Tay; closer inspection suggests stratified rock formations – the original inspiration for Japanese architect Kengo Kuma. The museum was Kuma's first building in the UK and was initially designed as a competition bid. Detailed delivery was managed by a small group of UK and Irish firms who pushed the available technology, including building information modelling (BIM) software, to the limits.

"Work on the project started at the competition stage in 2010 and we were already using 3D software – mainly Rhino3D – to develop our designs," says project architect Maurizio Mucciola, who led the project while at Kengo Kuma & Associates (KKAA), and completed its delivery from London-based PiM.studio Architects which he founded in 2016. "After the competition closed and we started detailed work on

Above: KKAA's parametric model of the external facade

the building, Rhino was used for our detailed architectural design, but we needed to coordinate our work with the structural and M&E services designers at Arup, who were using Autodesk Revit." The team agreed a protocol for exchanging 3D models using basic 3DS and DWG format files, which allowed for easy export and import by the designers, enabling them to check each others' designs.

Accommodating the internal services was relatively straightforward, says Mucciola, but the novel design of the concrete structure and its external facade posed particular challenges. Many of the 21 elevations curve in two directions at once, concrete walls up to 18m high incline outwards, and 2,429 precast-concrete elements weighing up to three tonnes each needed to be attached to these walls. This called for a methodical approach to both architectural and structural design, careful liaison with the specialist subcontractor responsible for delivering the precast panels and other components, and detailed consideration of how these would be lifted and installed.

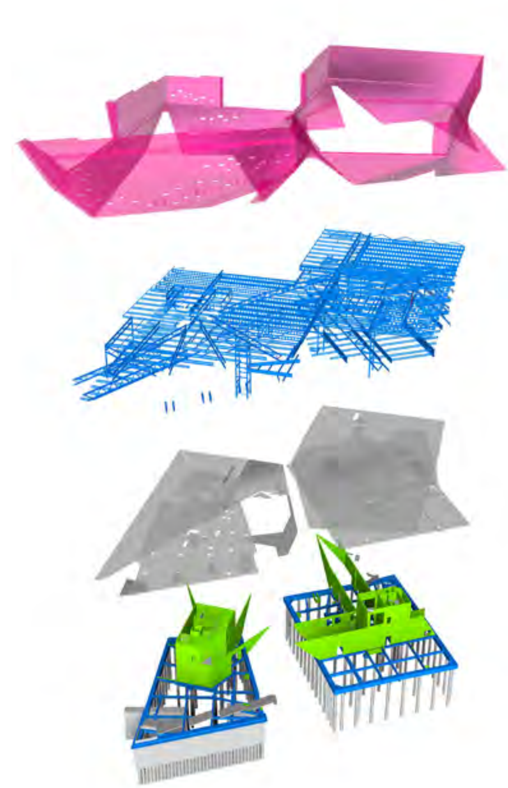
Techrete had provided advice about fabrication and installation during the competition bid and was subsequently appointed by main contractor BAM Construction to provide the concrete facade components. These were produced at Techrete's factory in Brigg, Humberside. Once cast and inspected, units were transported in batches of between six and 10 by road to Dundee.

Detailed design of the facade elements was undertaken at KKAA using Dassault Systèmes' CATIA software, while Techrete deployed Tekla Structures in its detailed panel production design processes.

"The panels were designed to be individually fixed to the wall structure," Mucciola says. "The wall was formed by sections of in-situ concrete, each incorporating a channel to be used for the fixing brackets. We had to be meticulous about the initial setting out of the structure – we used GPS coordinates to support this process – and then carefully coordinated the design of the channels in the structural units so that they corresponded with the brackets incorporated into the concrete plank panels forming the facade."

The complex nature of the design meant that every panel was unique, so the architects created detailed schedules to help guide Techrete's fabrication. Each panel was given a unique ID so its progress from design, through fabrication, inspection, delivery and installation could be monitored. Labels incorporating barcodes were used to help track each item.

Most planks incorporated two channels, but some had three, and the detailed design coordination ensured efficient installation. At the peak of construction, the team were fitting up to 22 precast elements in a day. Mucciola recalls:



Above: An exploded view of Arup's structural model. The engineers employed Autodesk Revit software and exchanged files using 3DS and DWG format files
Top and opposite: The facade includes 2,429 precast-concrete elements

"Out of around 5,000 channels, only two or three were out of place and required some drilling to ensure an accurate fit."

The architects and Techrete also had to be mindful of the overall sequence of construction, says Mucciola. "Initial site preparation had included the construction of a temporary coffer dam on the riverside, and this needed to be removed early to enable completion of hard landscaping on that side of the museum. The panel fabrication programme therefore focused on completing the riverside facade before working around the remaining elevations."

Design of the V&A Dundee helped the architects advance their BIM capabilities. Although already proficient in Rhino3D, they had not previously deployed CATIA, so the project provided the perfect test for Mucciola's team to apply parametric approaches and manage interfaces with other firms' software: "CATIA proved highly compatible with Techrete's Tekla Structures software and we were also able to use the Tekla viewer when checking our model design."

With the UK construction industry being urged to digitise and adopt more manufacturing-led approaches, Mucciola believes PIM.studio and its collaborators on the V&A Dundee are well placed to apply its digital skills on future projects and push the boundaries of collaborative concrete building design still further.

DIGITAL BEYOND DESIGN

New technologies have revolutionised everything from quarrying to maintenance, writes Duncan Reed

It is now eight years since the UK government mandated the adoption of building information modelling (BIM). A lot has happened since then but has it been truly innovative or disruptive? I'd argue that there has been plenty of innovation that relies on new digital technologies, even if it is not thought of as being BIM as originally defined.

In quarries, for example, the use of drones, laser scanning, photogrammetry and 3D modelling gives operators a far better understanding of their assets. Combined with on-board telemetry for quarry vehicles, this provides opportunities to save time and money. Trials are already taking place of both autonomous and electric vehicles to further improve the sustainability of quarrying activities.

At the design and manufacture stage, accurate, constructible models allow architects, engineers and fabricators to create vastly improved details, carry out constructability reviews and clash-detect reinforcement, as well as enabling new methods of creating complex formwork for casting items using 3D-printing techniques.

It is here that information about the product comes into its own in the digital age. This data will allow the industry to create a digital twin – whether at the level of individual products or at a national level, following the Gemini Principles set out by the Cambridge Centre for Digital Built Britain, which would allow such data to be harnessed for the public good. This is where it isn't necessarily the product itself that is more innovative, but the data linked to it that can be used to deliver considerable added value across the lifecycle of the asset. However, data for the public good does not mean data for all – cyber security must remain a key priority for all built assets.

Improvements in sensing technology will yield further innovation in construction. Cheaper equipment can now be fitted to new and existing structures to allow real-time analysis of their behaviour. For asset operators with large portfolios of complex concrete structures, these changes offer the potential for huge amounts of data to be collated and processed for useful real-time analysis. This could allow more efficient maintenance regimes based upon real, documented requirements and help operators to determine performance trends. Targeted predictive maintenance becomes business as usual, enabling operators to deliver more with less.

Finally, the digital record allows for the accurate replacement of parts when they do reach end of life, and a lower impact on users of the assets during these maintenance works. Very soon it could be that the digital record of a concrete asset is as important than the asset itself, if not more so.

Duncan Reed is digital construction process manager at Trimble Solutions

Photo and models: PCE

IN PRACTICE

Project Capella, Cambridge

Set to open in 2019, Project Capella is an £80m, 18,000m² laboratory building for the Cambridge Stem Cell Institute. Located on the University of Cambridge's Biomedical Campus, it brings all of the Institute's research groups under one roof.

Several building projects were being undertaken simultaneously at the campus, which is also the site of Cambridge's main Addenbrooke's Hospital, so a key challenge was to construct Project Capella with as little disruption to the hospital and neighbouring projects as possible.

Tamworth-based concrete fabrication specialist PCE used its "hybrid" DfMA (design for manufacture and assembly) process to deliver the building. Its hybrid approach combines design, fabrication and procurement, mixing different systems and materials – prefabricated concrete components, structural steelwork and in-situ concrete. "We aim to offer alternatives to make construction quicker, more cost-effective, less environmentally intrusive, and safer," says business development director Simon Harold. "Factory-produced components also tend to have a consistently higher quality of finish than those finished by on-site trades."

While vibration-free superstructure designs usually involve an in-situ concrete frame, PCE helped to devise a hybrid of precast and in-situ concrete. Design involved extensive use of Revit and Tekla Structures BIM applications.

Harold divided the project into four main stages: basement, structure, plant room and facade – four-fifths of which were delivered using components fabricated offsite. For the six-storey building's 5m-deep basement, PCE provided prefabricated wall units to form the liner wall before starting on the suspended floors that would be critical for the building's vibration-free requirements. "For laboratory purposes, we need to achieve a very stiff slab," says Harold. "Precast concrete planks alone are not adequate for this purpose, so a deep reinforced structural topping was added to give mass – the floors are 500mm thick overall."

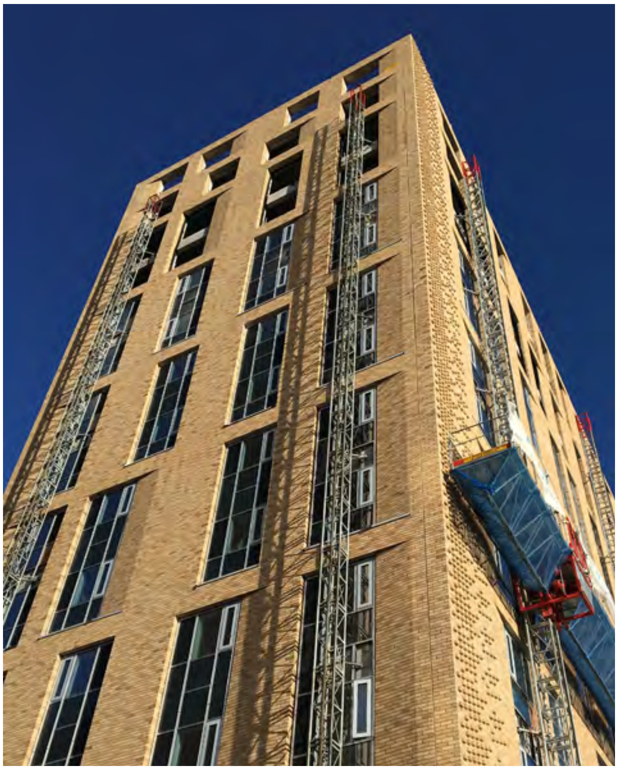
The facade cladding, manufactured by Techrete at Brigg on Humberside, is primarily double-storey-height architectural precast concrete panels, 10m by 3.5m. "The panellised approach allowed us to incorporate the curtain wall and glazing offsite, further streamlining onsite activities," says Harold. "We fabricated the units in 'landscape' format, then transported them to site where we devised a special lifting jig to rotate each unit to its final 'portrait' position."

The pre-glazed facade panels also meant the building became watertight much earlier in the programme, adds Harold. This had significant programme benefits because MEP installation could start much earlier than would be possible with traditional envelope construction, particularly valuable given the complexity and long commissioning time involved in installing the Cambridge Stem Cell Institute's research-grade laboratory systems.

Offsite construction techniques also provided some benefits vital to working within the perimeter of a working hospital, not least a reduced number of deliveries to an already congested site. "With less onsite fabrication, there are fewer vehicle movements, less noise, dust and vibration, and less plant is required – all attractive to the client when we were working next to the hospital's cancer centre," said Harold.

"Our hybrid DfMA approach also has manpower advantages. Fewer personnel are needed on-site – with a corresponding impact on transport and accommodation – while our fabrication team can concentrate their efforts in the design studio and factory environments, leaving installation to our other specialists, and by reducing working at height, we reduce safety risks."

Above: Revit and Tekla Structures BIM applications were used in the DfMA process



IN PRACTICE

The Lansdowne, Birmingham

The Lansdowne is a 206-apartment build-to-rent scheme located close to one of Birmingham's busiest road junctions, Five Ways, and adjacent to two existing tower blocks on Hagley Road. The tightly confined site demanded a creative approach to the 18-storey building's construction. Main contractor Interserve appointed precast concrete specialist FP McCann to manage offsite fabrication and just-in-time delivery of key elements.

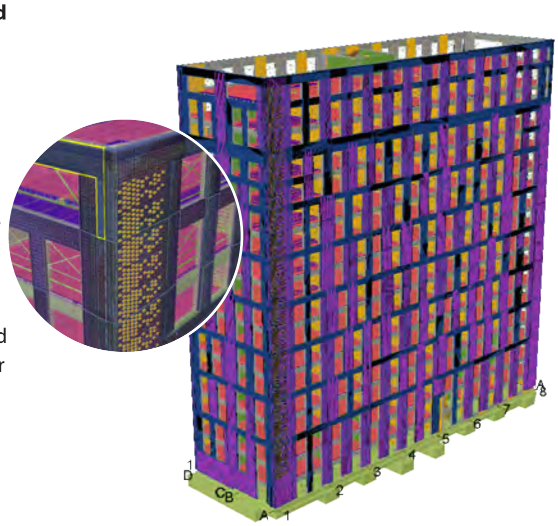
The £26m project provides private rented accommodation in one, two and three-bed configurations over 16 storeys, with car parking, a gym, bike storage and other resident facilities below. "Interserve felt the site justified use of offsite manufacture, and we proposed a solution incorporating precast concrete columns, beams, walling and flooring," says Daniel Westgate, FP McCann's commercial manager for structures. "This would accelerate construction of the structure and building envelope, and minimise disruption to follow-on trades."

FP McCann's in-house designers SRC worked with the client's architect Building Design Group (BDG) and civil and structural engineer CWA to optimise the ground floor and mezzanine level's structural design to incorporate precast concrete floor beams, and to align with the load-bearing elements of the structure above.

The building comprises external and internal precast concrete walls 180mm thick; external precast concrete insulated sandwich panels; precast columns 5550mm high x 800mm wide x 400mm deep; and beams 6,530mm long x 800mm wide x 400mm deep. These products, along with steel beams in the corridors, were used to support 200mm-thick precast hollowcore planks. "The 206 apartments were formed by 396 precast concrete crosswalls and 361 sandwich panels," explains Westgate. "To satisfy Building Regulations Part A, the sandwich panel wall and internal solid walls have continuous vertical ties; all floors were horizontally tied to their supports and fully grouted, providing a three-dimensionally tied structure." BDG had proposed a brickwork finish, so brick slips were incorporated during offsite manufacture of the facade units. This removed the need for scaffolding – instead, mast-climbers were used for jointing and other finishing works.

Gavin Lowe, structures manager at FP McCann, describes some of the factory and site activities: "We were able to take the client's consultants' Revit-based designs and import data from their models into the Tekla Structures software we use for design and fabrication. Every component was uniquely numbered and barcoded so that we could track production, storage, transport and delivery to site. We could also use data about components' sizes and weights so that crane operators knew exactly what to expect. On average, we took nine days to complete each of the 16 apartment floors." The efficiency of the build process meant completion was brought forward from May 2019 to the end of February.

Would the team have done anything differently? Westgate and Lowe both mention the building's two-storey high windows: "With earlier involvement, we may have been able to influence the installation process," says Lowe. "Instead of it being a follow-on process, the windows could have been fitted to the facade units at our factory. That's a lesson we'll all bear in mind for the future."



Above: FP McCann took consultants' Revit-based designs and imported data from their models into Tekla Structures software

Photo and model: FP McCann

ABOVE Team Zopherus' expandable community of hexagonal pods would be 3D-printed inside the landing vehicle

MIXING IT ON MARS

Marscrete will be mission-critical to any future landing on the Red Planet, writes Nick Jones

Is concrete about to go extraterrestrial? In the past few years, plans to colonise Mars have made, if not giant leaps, at least small steps towards the launchpad. In Los Angeles, serial entrepreneur Elon Musk is busy building a factory for his Big Falcon Rocket, which he hopes will propel people to the Red Planet within six years. Not to be outdone, in December 2017, President Trump signed Space Policy Directive 1, effectively charging NASA with launching a manned Mars mission by 2033.

But one of the curious things about space exploration is that the further it reaches, the more it has to rely on earthbound technologies. Whereas the first Moon landing in 1969 was a mere eight-day trip, it will take astronauts at least seven months to reach Mars, which means they will need places to live and work when they get there. In response, designers are turning to a material they have used on Earth for thousands of years: concrete.

NASA's 3D Printed Habitat Challenge, launched in 2014 to "advance the construction technology needed to create sustainable housing solutions for Earth and beyond", has spent five years exploring the possibilities of Martian concrete. The competition's latest phase challenged design teams to complete a full-scale virtual habitat in BIM software, and the concepts they have come up with are striking for their naturalistic, almost primitive, concrete aesthetics. The overall winner, Arkansas-based Team Zopherus, presented an expandable community of hexagonal pods rising out of the red dust, while fellow finalist Northwestern University from Illinois imagined a parabolic dome not unlike a giant termite mound.

There are several reasons why concrete is the obvious material for Martian architecture. Buildings will need to be strong and durable, to withstand everything from meteor storms to high levels of solar radiation. And they will need to be built using local resources – it costs about US$4,000 to launch a kilogram of material into low Earth orbit, so it won't be viable to take construction supplies 225 million kilometres across space. Researchers believe that Martian rock and soil – or regolith – could act as the concrete's main ingredients. Although no actual samples have returned to Earth, Mars rovers have determined the composition of regolith as mostly silicon dioxide and ferric oxide, with some aluminium oxide, calcium oxide and sulfur oxide.

But perhaps the chief appeal of concrete is that it can be used with the two technologies that have changed the game as far as Martian (and perhaps terrestrial) habitation is concerned: 3D printing and autonomous robotics. Both are already fairly advanced as extraterrestrial construction techniques – Lockheed Martin claims it will 3D-print a satellite within the next decade – and offer the possibility of creating liveable structures before the arrival of humans on Mars' surface. The Zopherus habitat, for example, envisages vast landers that seal to the ground and act as a pressurised environment for concrete-mixing and printing, while rover robots search the surrounding land for materials. Once these have been mixed, the whole hexagonal pod is printed within the lander, with prefabricated components such as airlocks and windows added to the print as needed.

Team Zopherus' mission has been helped by the discovery in 2018 of a 20km-wide subglacial lake – the first known stable body of water on Mars. This allowed it to propose a surprisingly familiar-sounding concrete using crushed ice to hydrate the regolith. "You could use a similar technology to printing with gypsum-based concrete. We liked that it seemed like a low-tech material. I say low-tech – it's taken humans quite a while to get it to this level," says Zopherus architect Trey Lane. Not that this means creating Martian concrete will be straightforward: "You don't really think about it but even sand is different on Mars. It's going to be sharper; on Earth there's more water that wears things down."

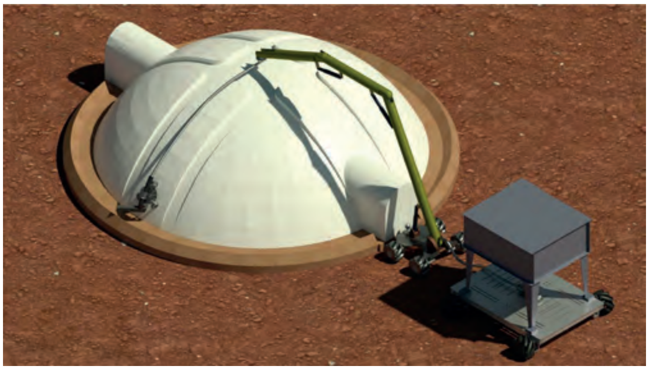
"YOU DON'T REALLY THINK ABOUT IT BUT EVEN SAND IS DIFFERENT ON MARS. IT'S GOING TO BE SHARPER"
TREY LANE, TEAM ZOPHERUS

Other teams have reasoned that even if the landers do find water, it may be required for other uses, such as growing food and sustaining the astronauts. The second phase of NASA's competition challenged teams to 3D-print a series of structural elements from a Martian soil simulant (made from basalt from a volcano in Hawaii) and recycled mission plastics. The winning entry by a Foster + Partners-led team used 30% plastics to bind 70% regolith and was stress-tested at a maximum load of 1,694kg.

Northwestern's scientists, meanwhile, are investigating a formula that needs neither water nor plastic. They have mixed approximately 50% soil simulant with 50% sulfates, readily available on Mars, to create a type of sulfur concrete – the sulfur is melted at about 130-140ºC and hardens around the soil as it cools. While this approach has been used on small-scale terrestrial applications in the past, the Northwestern team have noticed that Martian simulant is more effective than conventional aggregates. "Either there are more metallic bonds taking place, something else is bonding with the sulfur, or it's producing other compounds that we're unaware of," says Dr Matthew Troemner, part of the team. "What we're seeing in compression tests is anywhere from 55 to 65MPa, in the order of a very strong traditional concrete."

ABOVE Northwestern University's Martian soil simulant, which comes from the Mojave desert in California

BELOW Northwestern's proposal involves 3D-printing sulfur concrete over an inflatable inner membrane



Images: NASA, Northwestern University

The other advantage of sulfur concrete is that it hardens as soon as the sulfur dips below its melting point, making it ideal for 3D printing. Northwestern is exploring a robotic extrusion-based system, heating the sulfur and regolith in a screw, before pushing it out "like toothpaste" as a semi-solid. "Depending on the size of bead you're extruding, it could take five to 45 seconds for an outer layer to harden, and so within a couple of minutes you can be printing your next layer," says Troemner.

The Northwestern team envisage printed layers of smooth, orange-red Marscrete built up around an inflatable inner membrane, which would provide tensile strength and fire protection – unlike traditional cement-based mixes, sulfur concrete is not fire resistant. But they also foresee applications closer to home. "Sulfur is a by-product of oil production, so you can basically get it for almost nothing aside from your transport costs," says Troemner. He suggests that it could be used as a cement replacement.

Lane, meanwhile, believes there could be Earthbound applications for the Zopherus robotic lander too, particularly for building in combat or disaster zones. "Being able to put a robot down and come back in a few weeks to find your structure complete could save lives," he suggests.

Even if we don't get to go to Mars, it seems that extraterrestrial thinking is set to transform the world we do live in. "There's a huge benefit to robotic construction," says Lane, "and it's something we're going to see more and more of."

THE WHOLE-LIFE CASE FOR CONCRETE

Whole-life performance takes in a broad range of factors. Here's how concrete stands up

	ENVIRONMENTAL	SOCIAL	ECONOMIC
FIRE RESISTANCE	Concrete is non-combustible, helping to ensure its longevity and avoiding the need for additional fire-proofing materials.	Concrete reduces the spread of fire, helping to provide life safety and property safety. During construction, a concrete frame presents no fire risk to neighbours.	Regulations require the safe evacuation of occupants but do not ensure the survival of property. Concrete structures comply with life safety regulations but also resist fire to enable cost-effective repair and reuse.
THERMAL MASS	Concrete's thermal mass can reduce or avoid the need for mechanical cooling. This inherent property of concrete can save hundreds of kilograms of CO_2 over a building's life.	The thermal mass inherent in concrete provides long-term resilience to the issue of overheating – a growing health and wellbeing issue, particularly among the very young and the elderly.	Using the thermal mass provided by concrete can lower the running costs of a building. It can also reduce the amount of M&E equipment needed, leading to lower operating and maintenance costs.
DURABILITY	The durability of concrete structures helps them to achieve a long life and maximise their performance, keeping their whole-life environmental impact to a minimum.	The durability of concrete structures means that, once built, they are rarely out of use for maintenance and hence cause minimal social disruption.	Concrete is a very stable and durable material with an extremely long life. As a result, maintenance costs are very low.
ACOUSTIC ISOLATION PERFORMANCE	Concrete offers good inherent acoustic performance, requiring very little in the way of additional finishes and materials, which often have a short lifespan. As a result, less material is used and potential waste is avoided over the life of the building.	Concrete's mass provides a good barrier to noise, improving quality of life, particularly in high-density housing or near busy roads.	Concrete provides good inherent acoustic separation. This can result in cost savings because minimal supplementary design measures are required.
ROBUSTNESS AND SECURITY	Concrete can provide a robust, finished surface, avoiding the need for additional materials, which would require maintenance and periodic replacement over a building's lifecycle.	Solid concrete and masonry party walls result in safe, secure buildings, preventing unwelcome intruders.	Concrete structures, particularly those with minimal finishes, will suffer less damage and cost less to repair and maintain.
FLOOD RESILIENCE	Concrete retains its structural integrity, resulting in minimal waste of materials following a flood.	Concrete and masonry structures can be designed to resist water penetration, keeping inconvenience and disruption to businesses, homeowners and the community to a minimum.	Downtime of businesses, homes and essential community services is minimised if flooded buildings have been constructed in concrete, as they will require less repair work.

LESS IS MORE

Guy Thompson explains the many facets of material efficiency, a key focus for the Concrete Industry Sustainable Construction Strategy over the last decade

Material efficiency can be defined simply as doing more with less. The target is to use fewer resources in the most sustainable way, minimising the environmental impact, while extracting maximum value from those resources by providing buildings and infrastructure that will be useful for the long term – and therefore promoting the transition to a circular economy.

So the reduction of waste and the use of recycled content are just two elements of material efficiency in the built environment. Just as embodied CO_2 is not by itself the whole of a carbon footprint, material efficiency assessments should not be limited to a single life-cycle stage.

For the last ten years, the Concrete Industry Sustainable Construction Strategy has been reporting annually on a wide range of metrics that demonstrate sector performance, and many of these relate to material efficiency.

Unless all of these elements are considered holistically, opportunities for whole-life efficiency may be lost or muddled, along with a host of related design criteria such as whole-life carbon and cost, climate change mitigation and adaptation, and fire resistance. As with all materials, the use of concrete must be carefully considered, and an awareness of how to design for long-term efficiency is vital to achieving the greatest benefit from the least amount of resources.

Much is made of the quantities of concrete used around the world to enable societies to achieve their goals and to shelter and protect their citizens. But when you consider the material efficiency that concrete and masonry can offer, and the many opportunities to do more with less, it is hardly surprising that clients and their design and construction teams depend so much on a material that provides such powerful benefits from cradle to grave.

Responsible sourcing

Concrete is an inert material created primarily from natural minerals that can be locally and sustainably sourced throughout the UK, reducing imports, transport costs and carbon emissions.

Recycled/secondary aggregates

Depending on the application and the type of concrete, there is often an opportunity to incorporate recycled aggregates that have been previously used in other projects and secondary aggregates that may be by-products from other industrial processes.

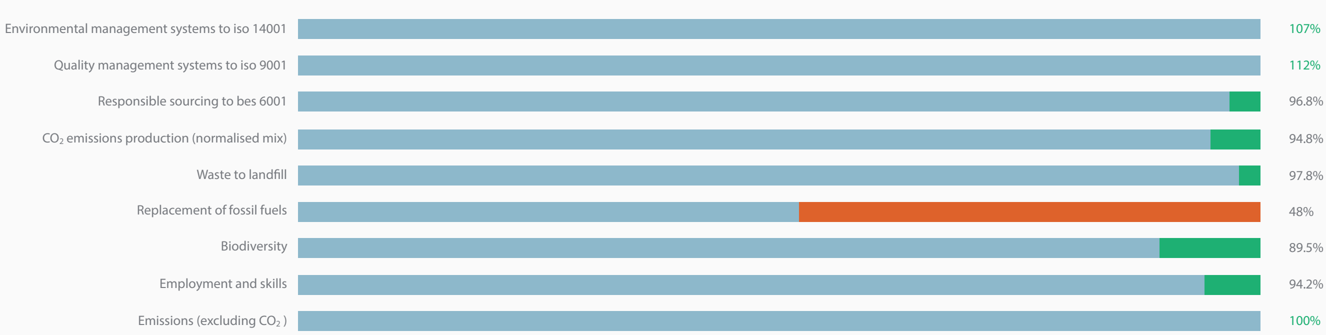
The inclusion of recycled and secondary aggregates in concrete is a balance of resource efficiency, CO_2 emissions from transportation, and the implications for mix design and performance, so they should only be used where it is technically and environmentally beneficial to do so. In 2017, 8.3% of aggregates used in concrete were from recycled or secondary sources. Approximately a third of all aggregates used in the UK for concrete and other applications are either recycled or secondary.

Recycled concrete, as well as being used as an aggregate, is often used at the source of demolition, in new substructures and external landscaping. There are a range of established uses for recovered concrete, with no evidence of any material being sent to landfill.

Cementitious materials

There are significant volumes of by-product materials such as ground granulated blast-furnace slag (GGBS) and fly ash that can act as part of the cementitious binder in concrete. These materials have a lower embodied carbon than cement and can also influence

Progress to 2020 targets based on 2017 performance from a 2008 baseline

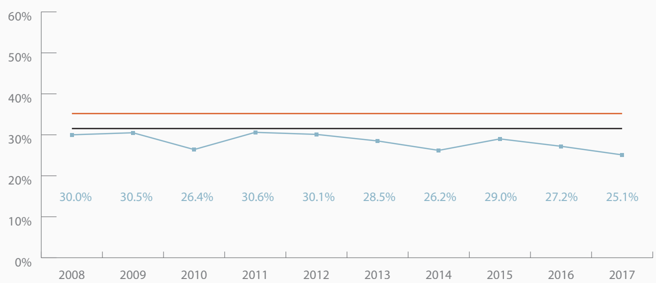


Concrete Industry Sustainable Construction Strategy: **progress on key indicators**

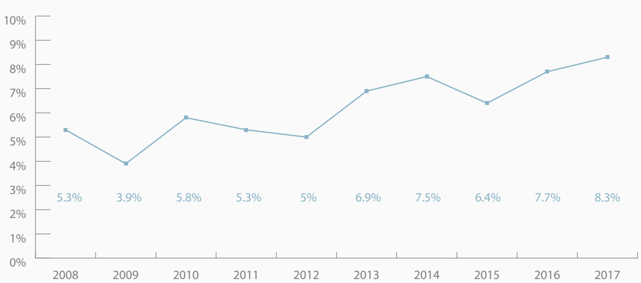
Key

- Concrete
- Concrete plus reinforcement
- 2012 target
- 2020 target

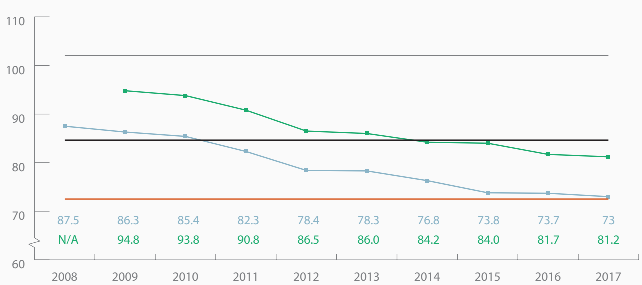
% of additional cementitious materials (GGBS, fly ash etc) as a proportion of total cementitious materials used



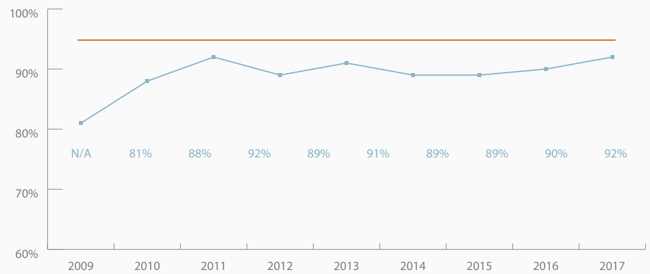
Recycled/secondary aggregates as a proportion of total concrete aggregates



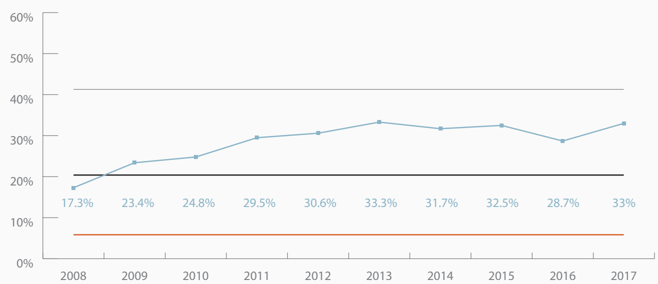
CO_2 emissions as a proportion of production output – normalised mix (kg CO_2/tonne)



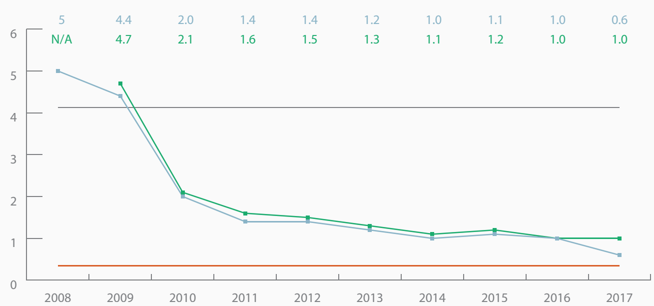
% of production certified to responsible sourcing standard BES 6001



Materials diverted from the waste stream for use as a fuel source, as % of total energy use

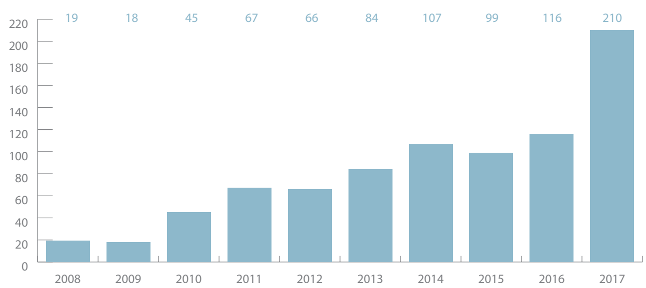


Waste to landfill as a proportion of production output (kg/tonne)

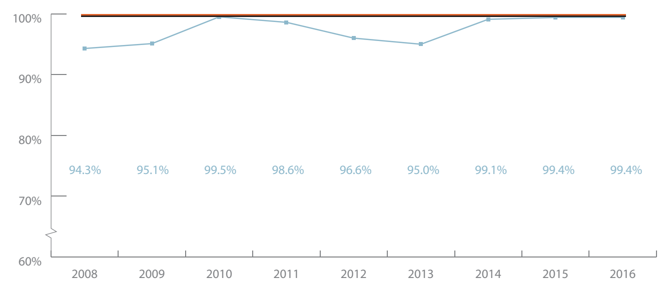


"THE CONCRETE INDUSTRY IS A NET USER OF WASTE – 210 TIMES MORE WASTE IS CONSUMED DURING THE MANUFACTURE OF CONCRETE THAN THE INDUSTRY SENDS TO LANDFILL"

Net waste consumption ratio



% of relevant production sites that have specific biodiversity action plans



the appearance and performance of concrete. In 2017, additional cementitious materials made up 25.1% of the total used.

Recycled steel reinforcement

Members of the British Association of Reinforcement (BAR) that manufacture steel reinforcement used approximately 96% recycled ferrous metal waste as raw materials in their electric arc furnaces (EAF) in 2017. BAR members that fabricate reinforcement used more than 95% EAF material in producing and supplying rebar for use in concrete.

BES 6001

During 2017, certification of concrete products to BES 6001 reached 92% of production tonnage. Over 90% of this certified tonnage achieved a performance rating of "Very Good" or "Excellent". Responsible sourcing is included when calculating credits under BREEAM assessment schemes. Under the Responsible Sourcing Certification Scheme, the majority of certified concrete production attracts a RSCS score of 7.

Waste consumption

Concrete is manufactured using efficient, low-waste processes and can be supplied in the precise quantities required, limiting waste. The concrete industry is a net user of waste – 210 times more waste is consumed during the manufacture of concrete and its constituent materials than the industry sends to landfill.

Waste to landfill

The indicator for waste minimisation relates to landfill disposal per tonne of concrete production and includes waste related to the constituent materials. During 2017, the value was 0.6kg/tonne of concrete produced. This represents significant progress towards the 2020 target of a 90% reduction from the 2008 baseline, equivalent to 0.5kg/tonne. Our longer-term aspiration is for zero waste to landfill.

Replacement of fossil fuel

The industry requires high temperatures for production, primarily in cement manufacture, and this is an opportunity to safely use alternative combustible materials instead of fossil fuels. Where fuels used are recognised as carbon neutral under the EU Emissions Trading Scheme, this has the added benefit of reducing the embodied carbon of cement.

The concrete industry indicator shows the proportion of energy derived from materials diverted from the waste stream as a percentage of total energy use. In 2017, 33% of total energy use was from waste-derived fuels, the highest value recorded since the strategy was launched in 2008. For cement production alone, this increases to 44%.

Design

The use of all construction materials can be optimised through structural design and the selection of construction systems that cut waste on site. Designers can also adopt a strategic design approach to optimise concrete's performance and reduce the need for other materials.

Concrete alone can often meet the performance requirements of structure, fire and acoustic separation, without the need for other finishing materials. A range of design solutions enable designers to improve material efficiency, such as post-tensioned concrete or void formers. Exposed concrete also optimises thermal mass, enabling considerable savings on energy and carbon over a building's life.

The durable finish of concrete offers further lifecycle cost savings through a reduction in maintenance (and replacement) that would be required for other "wearing" finishes. Designing for long-life in most cases is the most efficient investment in resources.

Considering a building's performance in a changing climate is an essential part of designing for the future. Concrete and masonry can be used to provide resilience to overheating, flooding, strong winds and extreme weather events.

The long service life and robust nature of concrete facilitates the reuse of existing concrete frames and foundations, extending a building's life still further. Designers can use space-planning and adaptation strategies to accommodate changes of use and extend the life of a structure.

At end of life, concrete is 100% recyclable. Demolished concrete can be relatively simply segregated and crushed for reuse as a cost-effective material for hard core, fill or in landscaping or used as recycled aggregate in new concrete. Crushed concrete aggregate absorbs up to 20% of the original embodied carbon.

Reusing recovered materials can avoid the use of primary resources, preferably where it is more carbon-efficient to do so.

The graphs here provide a snapshot of the UK concrete sector's performance to date, and the table opposite summarises progress towards all the targets. The full performance report can be downloaded from **sustainableconcrete.org.uk**

Summary of performance indicators

The concrete industry publishes performance data annually. Reports are available at sustainableconcrete.org.uk.
More information about the indicators can be found in the Concrete Industry Guidance Document on Sustainability Performance Indicators.

Performance indicator	Baseline		Performance	Target
	Year	Value	2017	2020
Sustainable consumption and production: action on materials				
% of production sites covered by a UKAS-certified ISO 14001 environmental management system (EMS)	2008	72.3%	96.6%	95.0%
% of production sites covered by a UKAS-certified ISO 9001 quality management system (QMS)	2008	84.2%	96.3%	95.0%
% of additional cementitious materials (GGBS, fly ash etc) as a proportion of total cementitious materials used	2008	30.0%	25.1%	35.0%
Recycled/secondary aggregates as a proportion of total concrete aggregates	2008	5.3%	8.3%	No targets set*
% of production certified to responsible sourcing standard BES 6001	2008	n/a	92.0%	95.0%
Climate change and energy: action on carbon				
Kilowatt hours of energy used in production as a proportion of production output (kWh/tonne)	2008	132.1	154.1	Deliver the industry CO_2 target and sector climate change agreement targets
Energy intensity as a proportion of production output – normalised mix (kWh/tonne)	2008	132.1	122.3	
CO_2 emissions as a proportion of production output – normalised mix (kg CO_2/tonne)	1990	102.6	73.0	Reduce by 30% from 1990 baseline (72.2)
	2008	87.5		
CO_2 emissions from delivery transport through the industry supply chain as a proportion of production output (kg CO_2/tonne)	2009	7.2	8.6	Under review
Natural resource protection and enhancing the environment: action on waste, biodiversity and water				
Materials diverted from the waste stream for use as a fuel source, as % of total energy use	2008	17.3%	33.0%	50.0%
Waste to landfill as a proportion of production output (kg/tonne)	2008	5.0	0.6	90% reduction from 2008 baseline (0.5)
Net waste consumption ratio	2008	19	210	
Mains water consumption as a proportion of production output (litres/tonne)	2008	86.0	69.7	Under review
% of relevant production sites that have specific action plans on biodiversity	2008	94.3%	99.4%	100%
Creating sustainable communities: action on wellbeing				
Reportable injuries per 100,000 direct employees per annum	2008	799	656	
Lost time injuries (LTI) frequency rate for direct employee per 1,000,000 hours worked	2010	6.5	4.0	From 2014-19, reduce LTIs by 65% with an aim of zero harm
% of employees covered by UKAS-certified training and evaluation process	2008	84.4%	99.1%	100%
Number of convictions for air and water emissions per annum	2008	6	0	0
% of relevant sites that have community liaison activities	2008	85.9%	90.3%	100%

* This is because increasing recycled content is not always indicative of sustainable performance

This data is published on behalf of the Sustainable Concrete Forum, and sourced from the following sector associations: British Association of Reinforcement, British Precast, British Ready-Mixed Concrete Association, Cement Admixtures Association, Cementitious Slag Makers Association, Mineral Products Association, MPA Cement, UK Quality Ash Association.