CONCRETE QUARTERLY

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HOME EXPERIMENTS
The disruptive concrete technologies that built a dream home for a deep-sea diver

PROOF POSITIVE
Snøhetta's pioneering office produces more energy than it uses over its entire lifecycle

56 DAYS LATER
Why reaching net zero means rethinking the way we specify strength gain

CASTING OFF

INSPIRATION

APPLICATION

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On the cover:
Concrete House, East Sussex, by Raw Architecture Workshop. Photo by Tarry + Perry

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Jenny Burridge
Head of structural engineering,
The Concrete Centre

Binding targets

Concrete mix design is an art, a science – and one of the keys to a zero-carbon built environment. When construction materials are ranked in order of their embodied carbon, people are often surprised to see how low down the list concrete is. The reason its global carbon cost is so significant is that it is used in such enormous quantities. There are good reasons for this. Apart from the fact that its raw materials are available close to every building site in the world, concrete performs in ways that no other material yet discovered can. As we work to reduce its embodied carbon still further, what we don't want to do is lose the properties that make it – in the words of Bill Gates – an "amazing material".

Concrete's embodied carbon lies predominantly in the Portland cement that makes up 10-15% of the mix. Fortunately, there are already proven ways to specify low-carbon concrete, by replacing a proportion of that cement with fly ash or ground granulated blast-furnace slag (GGBS), waste products of the coal and steel industries respectively. They have been used for 50 years or so, and we know exactly how they perform and the very useful roles they can play. We also know that they can be stronger than conventional mixes but that they achieve strength more slowly – so one very simple step specifiers can take to lower the carbon bill of a project is to specify strength at 56 days for elements such as foundations, rather than 28 (see page 19).

The proportions of the typical mix will continue to evolve over the coming decades. In the UK, we are only just catching on to the potential of powdered limestone, a lower carbon alternative that can replace up to 20% of the Portland cement. It is used as standard widely across Europe – an Irish producer told me that it's in every mix that leaves his plant. This can be specified in the UK as part of what's called a ternary blend, as a second replacement alongside GGBS or fly ash. There is also a growing range of other cements. Some of these are covered by a publicly available specification, but the industry is working to get them fully incorporated into British Standards.

In the UK, the cement industry is trialling fuel switching using hydrogen, and globally it is piloting carbon capture, use and storage technologies, which are at the heart of its roadmap to reach zero carbon emissions by 2050. As this comes onstream, the embodied carbon of Portland cement will fall and it will be able to account for a higher proportion of the mix again. GGBS and fly ash will continue to play a role for the special performance properties they offer, and there will no doubt be many more innovative products coming on to the market as concrete science continues to push the boundaries.

The take-home message for the specifier of today is that concrete can already be a low-carbon material and it's heading for zero – and that wherever you can specify 56-day strength, you should.

ONE VERY SIMPLE STEP SPECIFIERS CAN TAKE IS TO SPECIFY STRENGTH AT 56 DAYS, RATHER THAN 28

The next Futurebuild Game Changers LIVE event on 22 April will focus on low-carbon concrete, with sessions on design and specification and one-to-one technical insights. It will also explore the innovations that will take concrete to zero carbon and beyond – such as cement replacements, as seen at Loyn & Co's Stormy Castle (right). For more information, see **concretecentre.com/events**

Photo: Charles Hosea

INNOVATION: TWO-STOREY 3D PRINTING

"We printed the entire envelope in one piece, on site, in three weeks"

After 20 years working in building control, civil engineer Marijke Aerts thought it was time to do something a bit different: "In particular, I wanted to help construction become more sustainable through the use of transformative technology," she says.

As it turned out, her career change proved dramatic. As project manager for Kamp C, a centre for innovation in construction in Belgium, Aerts (pictured below) has just overseen the construction of Europe's first two-storey printed concrete house."This is not printing components for assembly on site," explains Aerts. "We printed the entire building envelope in one piece, on site, in just three weeks."

Kamp C constructed the 8m-tall house using Europe's largest concrete printer – a fixed gantry system device made by COBOD. "You erect it in just one day, like a crane," says Aerts. "Working with printed concrete is a completely different way of building. There's been a lot to learn, but it's exciting work."

The construction of the cavity walls is ingenious: an external layer comprises an outer skin some 40mm thick supported by a zig-zag inner skin to provide structural strength and stiffness. The inner layer of the wall is made in the same way and the 160mm gap between the two zig-zags is filled with insulation.

Operating the machine is the easy part: "The printer will put concrete exactly where you want it, when you want it." More challenging, she says, is the handling of the geopolymer fibre-reinforced concrete: "When it's cold you have to add a little more water as the all-important consistency depends on temperature and humidity. We also did a lot of tests to optimise the time between layers. Too soon and the previous layer will be too soft; too late and the layers will not bond well. We found eight minutes to be about right – depending on the weather!"

Another challenge is rethinking the design to suit the printer: "The architect's vision has to be translated in such a way that the printer can understand it. Once you have done that, the machine's ability is impressive. Our house features curved walls and overhangs which would be hard to build traditionally."

And of course Aerts is enthusiastic about the environmental benefits: "There is hardly any waste of building material, and no formwork. I like the look of it too. We could have smoothed out the grooved finish, but we wanted people to be able to see and understand how this house was made."

Photos: Kamp C & Jasmien Smets

Kamp C built this house as a demonstration project: "To show what is possible," says Aerts. "But for the next one, we will be working with developers, investigating how we can bring this technology to the market. Meanwhile, another COBOD printer is creating a three-storey house in Germany."

Slowly but surely, and layer by layer, it seems printed concrete technology is moving out of the laboratory, and on to site.

Interview by Tony Whitehead

LASTING IMPRESSION

SIMON HENLEY

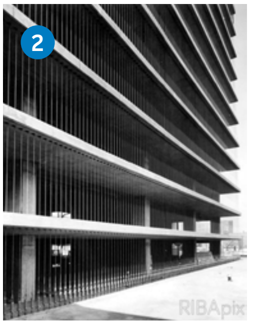
THE GOLDEN AGE OF PARKING, AND POLITICS WITH THE PAULISTAS

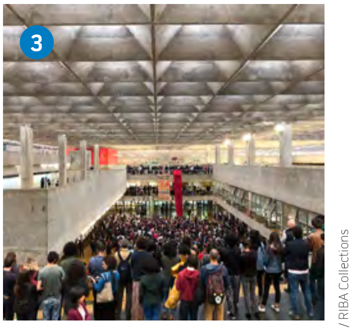
I once took my family on a European tour of car parks. I think they are fascinating, like a primer for buildings. As driving became more popular after the Second World War, the economics of parking changed radically, so they stripped out all of the detail and just left these skeletons. But they are also buildings for wheels rather than feet, with their oblique angles and the fluid surfaces of the ramps.

My favourite car parks are in Chicago. The Marina City towers 1 (Bertrand Goldberg, 1961-68), were once the two tallest residential buildings in the world. The bottom 19 floors of each tower are for parking, and the ramp unwinds like a corkscrew – if you were to unravel it, it would be a kilometre long. It's just a lovely idea, that it's like a spring, with 40 storeys of apartments above. Immediately across the Chicago river stood Parking Facility No 1 2 (Shaw, Metz & Dolio, 1953, demolished 1983). Graphically it's the most elementary structure: a series of concrete slabs with vertical cables to stop the cars falling off the edge. The elevation is simply thick horizontal lines and thin vertical lines. For me, these are two extremes of the quintessential car park: one all about fluidity, the other rigidity.

A few years ago, I took my students to São Paulo to see the work of the Paulista school, particularly Paulo Mendes da Rocha, Lina Bo Bardi and João Batista Vilanova Artigas. We landed the day that Jair Bolsonaro won the presidential election, and we went to Artigas' FAU-USP architecture school 3 (1969). It's a big block building, elevated off the ground, and the outside flows directly into a covered central space – you can't lock people in or out. I think in some respects it was designed as a protest against Brazil's military dictatorship. That afternoon we watched hundreds of people fill the building and hold a spontaneous protest, unfurling banners, singing and chanting. Mendes da Rocha's Mube sculpture museum 4 (1988) is another example of how the Paulista school make something powerful simply by covering outside space. A lot of it is underground so it's really just a landscape of concrete strata, but one extraordinary bridge spans most of the site. While we were in São Paulo, we met someone who had collaborated with Mendes da Rocha, and it was like turning the clock back 60 years to a more ambitious, socially motivated architecture. That seems to be a consistent theme with good concrete architecture – it has served societies at a point of change very well.

Simon Henley is principal at Henley Halebrown, and author of *The Architecture of Parking* (Thames & Hudson, 2007) and *Redefining Brutalism* (RIBA Publishing, 2017)





Photos: 1, 3, 4, Simon Henley; 2, Architectural Press Archive / RIBA Collections

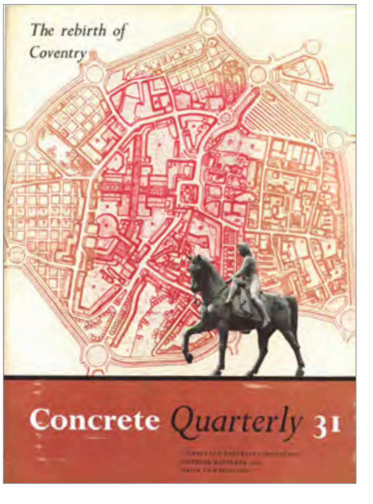
FROM THE ARCHIVE: WINTER 1956

COVENTRY AND THE ART OF REBUILDING

On 14 November 1940, medieval Coventry was reduced to rubble in a single night of heavy German bombing. More than eight decades on, the city is still shaped by that night of desolation, but also by the response of its postwar architects and planners. As the UK City of Culture for 2021, its manifesto describes it as "turning flames into hope and ruin into beauty".

Concrete Quarterly bore witness to the birth of this brave new world with a special issue in winter 1956, exploring everything from housing and schools to the trailblazing shopping precinct. "As the first project of its kind in Britain every detail of the precinct has been studied with minute care," CQ observed, singling out the trees and flower beds for bringing "the freshness and green without which the English are rarely happy".

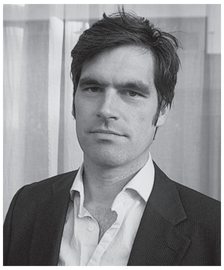
But the reconstruction of an entire city also found Coventry's architects and their critics asking questions of urban space that we are still pondering today. While admiring the city's new housing estates, CQ wondered about the ramifications of decentralisation, as well as the possible benefits of "high flats" brought about by new structural methods. "Much more needs doing … if the town is not to sprawl disastrously over the pleasant countryside. Would it not be wise to make a start, while the space is there, in building one or two tall blocks within the central area? Quite apart from the vital saving of space, there is, after all, a large population that enjoys the urban life and its amenities … not everyone is a gardener."



ORIGIN STORY

WOHNREGAL, BERLIN

MARC FROHN RECASTS AN INDUSTRIAL PREFAB SYSTEM AS FLEXIBLE HOUSING FOR MODERN LIFESTYLES



Photos: David von Becker; Guy Wenborne

It seems like there's an inherent contradiction when it comes to prefabricated housing. On the one hand, it has traditionally been based around a standardised plan, with the wall as the basic unit. But at the same time, there's no single way in which people want to inhabit spaces and the ways we want to live are getting ever broader.

This is the challenge we explored at Wohnregal, a six-storey building of apartments and workspaces in the Moabit district of Berlin. How could we rethink prefabrication, exploiting benefits such as cost savings and shorter construction timelines, but make it more relevant to current lifestyles?

In Berlin, we have a long history of prefabrication, particularly in the east. We visited several factories in the early stages of the project – some of them were revamped East German prefabrication facilities, originally built for massive housing projects in the 1970s and 80s. After a little research, we discovered a modular system for warehouses, based not on walls but on interconnecting precast-concrete beams, columns and slabs. It's a system that has been optimised from an engineering and efficiency point of view – to an extent that an architect would never usually consider.

It appealed to us because warehouses are based on the very idea of flexibility, with open spaces that can be adapted to new uses. The crucial component of the system is the double-T slab – a flat concrete element with two 300mm-deep downstands, designed for long-span construction. With this system we could span the 12m depth of the site very efficiently, giving us complete flexibility over the floorplans. All internal walls are plasterboard and have the services channelled through them, so the possible variations are almost endless.

We didn't soften the visual quality of the concrete at all – it's the same finish you would get in industrial construction. We also kept the rough joints you would get in a warehouse, with 2.5cm tolerances, which is unheard of in residential architecture. But actually it creates a curious aesthetic. Within the apartments, if you look towards the facade, you see huge gaps between the columns and beams. You can't see the actual connections, so these 5 or 10-tonne elements appear to contradict their weight, as if gravity doesn't apply. To me, it is an unexpected discovery: you would never have designed it this way if you were using a conventional building process.

It would have seemed odd to completely negate this structure by hiding it behind a facade, so we gave the east and west elevations a curtain wall of full-height, triple-glazed sliding doors. In the hot Berlin summers, these can be opened on both sides, drawing in fresh air and turning the interior space into a kind of loggia. And with the 2.9m ceiling heights, you get the sense of quite a spacious interior. The glazing also allows light to pierce the rough structural joints behind, adding to the sense that the concrete is floating.

Berlin is an expensive city to build in, but the construction costs of this development compare favourably with the city's main public housing agencies. Currently, Wohnregal provides a mix of apartments and workspaces, two per floor ranging from 35m² to 110m². But of course, this can change at any time. This building provides longevity and flexibility, which is critical in a circular economy, and because the concrete is mechanically connected you can separate everything by material, which is also useful. No one knows what our requirements are going to be in a generation and a half, so we need structures like this, capable of being reappropriated in ways that aren't yet clear.

Marc Frohn is a partner at FAR frohn&rojas in Berlin


REAL
ROLL FOREVER
OAKLEY
birdhouse

DRAMATIC POURS

Adrian Corrigall's self-built house is part film set, part adventure playground – but all concrete. Tony Whitehead explores the 'disruptive' technologies behind a unique dream home

Even by the standards of Channel Four's Grand Designs, the house built by deep-sea diver Adrian Corrigall was, to say the least, unusual. Nobody else, even on a programme that showcases the ambitions of mavericks and outliers, had ever tried to construct a home entirely from rough-finish, exposed, in-situ concrete.

The result attracted an enormous amount of media interest. Even now, two years on, internet opinion rages as to whether the house is a triumph or a monstrosity. Presenter Kevin McCloud plans to revisit the project for a 'what happened next' episode; meanwhile, Corrigall and his wife Megan are fielding calls from filmmakers wanting to use their extraordinary home as a set.

But the East Sussex house is at least as interesting for the technology it contains as for its uncompromising design. It contains no fewer than five different concrete mixes – the result of Adrian's desire to create his dream home with the help of disruptive technologies. The formwork, too, was cutting edge: reusable and made from recyclable plastic (see box, overleaf).

It was as a skateboarding teenager that Adrian discovered a fascination with concrete: "I loved the shapes and textures of the skateboard park," he says, "the way you could see, just by looking, how it had been made, how it had been poured into existence."

This interest matured into a keen appreciation of concrete architecture, including the work of Louis Kahn, Peter Zumthor and John Lautner, designer of the futuristic concrete villa that features in the Bond film, Diamonds are Forever. "These guys were adventurous," says Corrigall. "They were optimistic, pushing the boundaries and creating exciting stuff. That's what I wanted to do too."

It was the boundary-pushing that led Corrigall and his architect, Graeme Laughlan of Raw Architecture Workshop, to Switzerland and the laboratories of Cemex Research Group. By allowing Cemex to showcase innovative products in his design, Corrigall won both concrete and expertise at favourable rates.

"Adrian wanted to over-achieve on cost," explains Laughlan. "So when Cemex proposed mixes which could reduce or even remove the need for rebar, we were immediately interested. It not only cuts the cost of the reinforcement itself, but also the labour costs of fixing it and the need for a crane on site to place it."

Corrigall's concrete home may be a small building by commercial standards, but at 260m^2 it is a large house and technically quite demanding. And though a bungalow, it does in fact contain seven levels. The entrance is 1.2m below ground, and this rises through a series of steps to the sleeping quarters which are at a similar level above ground.

"We wanted the house to be an adventure," explains Laughlan. "So as you move through, there are these changing floor levels, changing ceiling heights, and changing light levels. In the darker areas you see light coming round the corner from lighter spaces. You want to explore."

Cemex proposed its proprietary fibre-reinforced concrete for the floor and roof slabs – a mix which potentially requires no reinforcement at all. But local conditions prevented this, explains structural engineer Adam Redgrove, director at engineersHRW. "The ground was clay with potential for heave, so we specified trench footings of standard concrete, mainly under the walls, and the slab spanned some 3.5m between these. The span meant we had to have a reinforcement mat, but because of the extra strength provided by the fibre reinforcement we were able to reduce it to one mat rather than the usual two. We did the same for the roof slabs."

Around 120m^3 of fibre-reinforced concrete was supplied to form the ground slabs and the upstands between level changes. Once this had been poured, it was time to deploy another specialist concrete, a proprietary thermal insulating mix called Insularis. "There was concern over the thermal performance at the joints between the slab and the walls, and the walls and the roof," says Laughlan. "So the walls sit on kickers made from Insularis. We looked at prefabbing this

WE WANTED THE HOUSE TO BE AN ADVENTURE. SO THERE ARE CHANGING FLOOR LEVELS, CHANGING CEILING HEIGHTS, AND CHANGING LIGHT LEVELS ... YOU WANT TO EXPLORE

LEFT The house reflects owner Adrian Corrigall's love of concrete architecture by the likes of Peter Zumthor and John Lautner

RIGHT The walls use a self-compacting, high-performance mix with very little reinforcement

BOTTOM RIGHT The bungalow is split across several levels

element, but in the event it was all done in situ with Insularis."

This concrete gets its insulating qualities from a blend of 8mm coarse and 1mm fine lightweight aggregate, but the mix is unusual and initially caused the pump to block. Channel Four's cameras captured the tense moments when site workers struggled to fill the forms with shovels and wheelbarrows before the concrete went off. Fortunately, the kickers are only 175mm high, and were successfully constructed. When the time came to deploy more of the insulating concrete, at the junctions between the walls and ceilings, adjustments to the mix allowed it to be to pump-placed without mishap.

But perhaps the most unusual feature of the construction are the walls themselves. "These don't have any reinforcement at all except for a single line of connecting rods that run from the slab through the kickers," says Laughlan. "They comprise a slender outer skin just 100mm thick, 150mm of insulation and a 125mm-thick inner skin."

While the thinness of these sandwich layers was in part facilitated by the lack of reinforcement, and the obviated need for cover, it is also extraordinary that concrete walls several metres high can be structurally sound and yet so slender.

The secret of course is in the mix, as Richard Kershaw, national technical manager with Cemex UK, explains. "Like the Resilia Conventional we used

Life in the Concrete House

A house made from rough exposed concrete might be an interesting idea, but what is it really like to live in? Having occupied his unusual home for more than two years now, does self-builder Adrian Corrigall have any regrets about his adventure to the extremes of residential architecture?

"Absolutely not," he says. "I really love it. I think people got the wrong idea about the house when they saw it on television. The cameras were there when it was still really a building site. There were grout runs and wet stains. It's not like that any more. When it's fully dried, the concrete calms down and the look becomes … I call it 'considered imperfection'."

Corrigall is constantly amused by the way his home confounds the expectations of visitors: "It's odd, people actually think it's going to be cold and damp. Why would I live in a house like that? In fact, the thermal mass of the exposed concrete retains heat really well and the insulation works brilliantly. In two years we have only used the heating once – and that was this winter after a period of sustained freezing weather. The previous winter we only needed our NVHR [natural ventilation and heat recycling unit]."

The thermal mass effect is only one of several ways the Concrete House performs well environmentally. "One of the advantages of pouring a house is that it's naturally very airtight," says Corrigall. "We pressure-tested it and it's near Passivhaus standard. It's great, too, that the formwork was reusable as well as being made from 100% recyclable plastic. And my house will easily last a lot longer than the average new home being built today – potentially for centuries."

The house's final surprise is the way it behaves acoustically: "It is not at all echoey as people expect," says Corrigall. "The solidity of the walls, and the roughness of the surfaces, seem to dampen rather than reflect noise. And when you find it's acoustically how you wanted it to be, just how you planned it, that's fantastic."

Architect Graeme Laughlan agrees, describing the acoustics as "almost monastic – it's a house to pad about in", and an object lesson in how exposed concrete's reputation for echoes is at least partly due to its usual deployment in larger, more open-plan buildings.

for the slabs, the Resilia HP [High Performance] we supplied for the walls contains a mixture of steel fibres and glass fibres of different lengths. The proportions of steel and glass, together with the different lengths of fibres used, are key to the products' strength."

For the high-performance mix, they used a higher dosage of fibres, the details of which must remain confidential, he adds. "The trick is to use exactly the right amount of paste in combination with just the right aggregate size to keep the fibres suspended and well distributed. Get this wrong and you risk the fibres 'dropping out'."

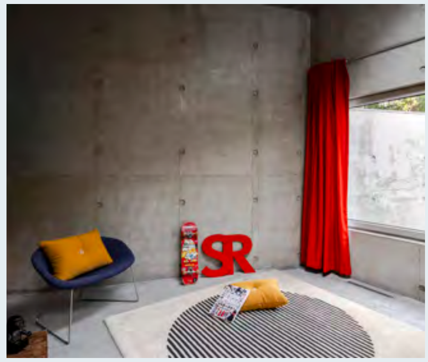
Since the high-performance mix was self-compacting, it was also highly ductile, allowing it to be poured into slim forms with no need for vibration. Pouring the walls was not without its share of drama, however. When one delivery vehicle suffered a puncture, the resulting delay in getting the mix to site caused a pour-line along an external courtyard wall. Fortunately, the high-performance mix had four hours of consistence retention, so the material was able to be placed after the short delay with only an aesthetic line on the wall.

Once structurally complete, one more specialist mix was needed to finish the floors. These featured underfloor heating pipes to be laid beneath a finished screed. A bespoke version of a proprietary self-compacting concrete was designed to allow a power-floated finish. The mix contained a maximum 6mm aggregate (smaller than usual) to allow for thin, smooth layering, and a range of admixtures provided a two-hour flow retention to allow the contractor time to work with the material.

Aesthetically, Corrigall's house will always have detractors: Kevin McCloud is among those who have voiced doubts about its raw design. Few would dispute, though, that its use of "disruptive" construction techniques has been a success. Some of the technology involved has already found its way into other developments. Indeed, Resilia was recently specified for a boutique residential project in London designed by 1200 Works – an architectural practice founded by one Hugo McCloud, Kevin's son.

PROJECT TEAM

Architect Graeme Laughlan and David Mulligan of Raw Architecture Workshop
Structural engineer engineersHRW
Concrete supplier Cemex
Formwork supplier Peri



Formwork: casting light

Adrian Corrigall discovered Peri Duo formwork in 2017 at its UK Concrete Show launch. The system comprises plastic forms and formliners locked together by integrated levers and, since each form weighs no more than 25kg, Duo can be used without the need for a crane.

Each Duo panel typically measures 900mm x 1,100mm, and three lorryloads, amounting to 355 panels, were used to construct the entire building. The panels can be used horizontally or vertically, up to 35 times. All walls were completed in 29 pours, with pour heights varying from 2.3m to 3.8m. ALPHA props provided direct support for 345m^2 of concrete slabs, which were completed in five pours.

Originally designed with small projects and developing countries in mind, the Duo formwork requires relatively little expertise to use. The plastic formliners are easily replaced and striking simply involves loosening the levers and pulling hard. "Adrian and Megan basically just ripped the forms down whenever they had time," says architect Graeme Laughlan. "It meant the curing times were not as consistent as they might have been. Nevertheless, I think the Duo system is a good one and I'd be happy to use it on other projects."

Though Duo is simple to erect and strike, Peri used augmented reality software and produced drawings in 3D to facilitate the design stage. This was particularly important at the Concrete House as, due to its fluidity, the self-compacting concrete mix exerts a higher pressure than conventional concrete. Panels were limited to a maximum pressure of 50 kN/m^2.

Despite the sophistication of the design approach, it was not proof against site slip-ups. While Channel Four's cameras were filming, an incorrectly secured Duo panel caused the formwork to rupture on one pour, and the wall section involved had to be remade. The embarrassing error does not seem to have harmed the Duo brand: it has since been used on a variety of residential schemes worldwide, including projects in Brazil, Singapore and India.

Photos: Tarry + Perry

MUSICAL INTERLUDE

The Laidlaw Music Centre's crafted concrete foyer offers a moment of repose between some very noisy spaces, writes Nick Jones

Flanagan Lawrence is well-versed in the interplay between concrete and music. The architect's previous projects include the Royal Welsh College of Music and Drama, which boasts an exposed concrete and timber auditorium, and the concrete-sprayed Acoustic Shells, a crustaceous bandstand on Littlehampton beach. "Concrete always plays a huge part in the projects that we do for music," says practice founder Jason Flanagan. "When you're dealing with a natural acoustic, you want a very hard, reflective, monolithic surface. Then you've got the flexibility to bring in softer materials to deaden and tune the space."

For the Laidlaw Music Centre at the University of St Andrews, however, it is concrete's other acoustic strength that is to the fore. This is a building that contains an awful lot of music, often at the same time. Organised as a series of clearly defined boxes, the southern wing contains a recital hall – capable of hosting a 200-strong choir – and percussion studios, while the north end houses smaller practice rooms, office spaces and a top-floor music library. "From the outset, we knew this was going to have a concrete frame," says Flanagan, "because we needed to keep each space isolated acoustically from its neighbour." When a building contains both a library and a drum studio, you need solid walls.

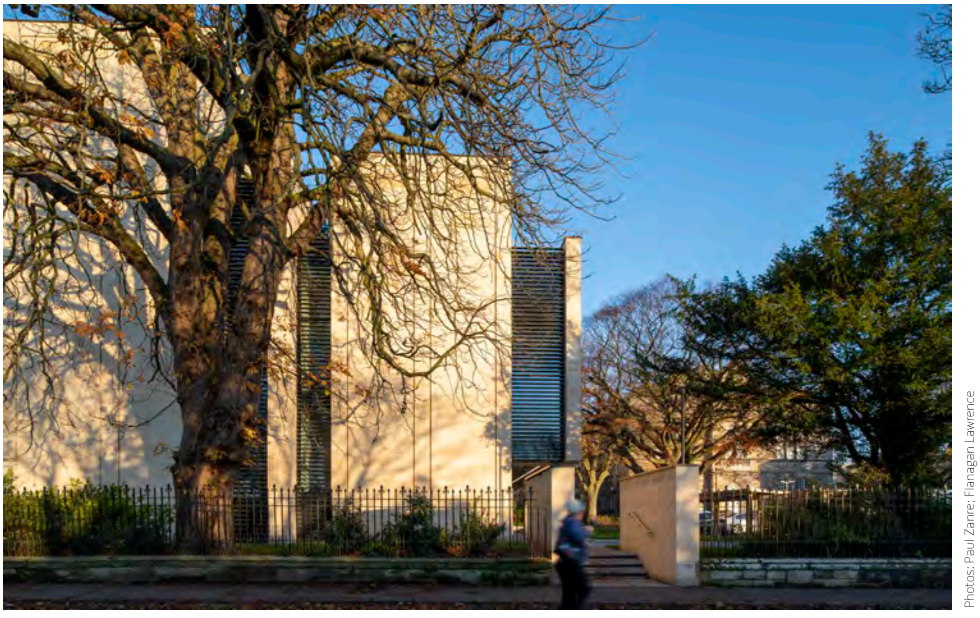
If the building's function dictated the structural material, its unique situation determined the plan and elevations. The Laidlaw Music Centre occupies the western side of St Mary's quad, one of the oldest parts of the university. It is flanked by sandstone buildings and surrounded by mature specimen trees, many of which were planted by the school of biology more than a century ago. "The building literally fits into the available space between the tree canopies and roots," says Flanagan. The stone planes of the main facade, meanwhile, were partly conceived as a backdrop to this greenery. "It's beyond lush. There are times in summer when parts of the building are completely obscured."

Concrete may act as an acoustic separator, but visually it's used as a connector, mediating between the trees, the sandstone and the music facilities themselves. A colonnade of slender, polished in-situ columns softens the transition from greenery to stone, while the entrance foyer transposes the trees into the textured grain of boardmarked concrete. "You get this progression from the trees outside to the concrete foyer to the wood-panelled recital hall beyond," Flanagan says.

The foyer, which slices through the building between its two wings, is largely stripped back to its concrete frame, with exposed soffits, side walls, staircase and footbridges on levels one and two. In addition to its visual qualities, this has a double sustainability benefit, reducing unnecessary

finishes and helping to stabilise the temperature in the naturally ventilated circulation areas.

Given the architects' desire for boardmarking, they were keen to pay close attention to the finish, building two 1.5m x 1m test walls on site. "We had to fight quite hard to get sampling incorporated into the programme," says Flanagan's colleague, senior associate director Henrik Lonberg. "But the building doesn't have a basement where we could



Photos: Paul Zanre; Flanagan Lawrence

CLOWISE FROM LEFT

The material-efficient foyer leaves much of its structure exposed; detailed boardmarking on the wall and staircase; the building weaves between mature trees; concrete columns complement the sandstone cladding

PROJECT TEAM

Architect Flanagan Lawrence
Structural engineer Will Rudd Davidson
Main contractor Graham Construction
Concrete frame contractor Stephenson Construction

test things. And because of the sequencing, the first walls to go up were the visual concrete."

The team used both faces of the test walls to explore all aspects of the finish, from types of timber and release agents, to the joints between the boards, to the position of tie holes, the corner details, and even the finish of the nails securing the boards to the formwork. "We also did full elevations of the walls, showing board widths, and setting out of joints and tie holes," says Lonberg. "The one thing we would have liked to have sampled more is the mix, perhaps using GGBS, but we had the constraint of casting in a Scottish winter."

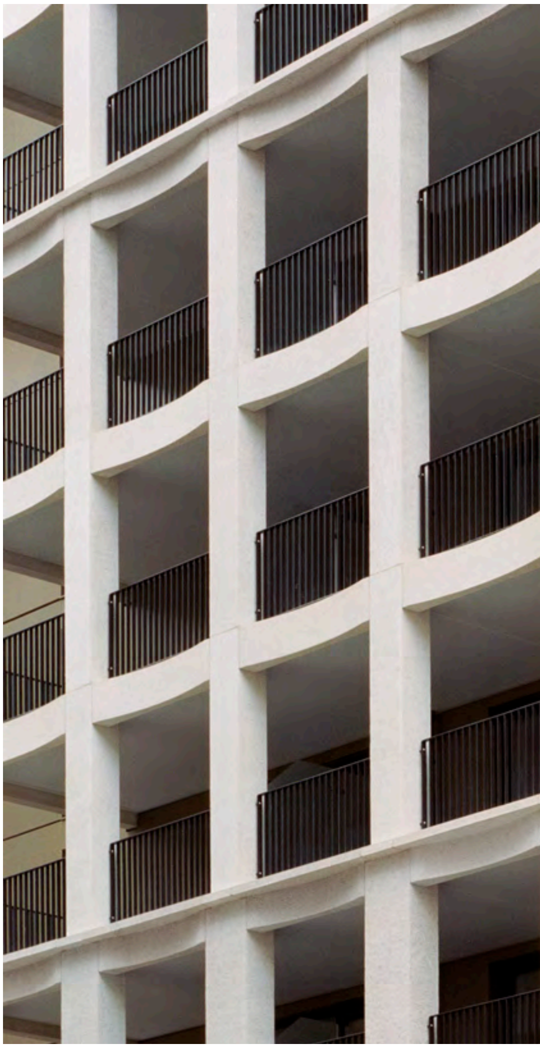
In the end, a CEMI C32/40 concrete with a superplasticiser was specified, cast against Douglas Fir boards. The texture gives the three-storey wall a monolithic quality, says Flanagan: "It's very forgiving in terms of concealing day joints, so you get this sense of a continuous, single entity."

The storey-high formwork was reused three times, mostly in areas intended to be covered in plasterboard. However, in some of the office spaces and parts of the library, the concrete texture was so good that the architects decided to leave it exposed anyway. "We didn't initially specify boardmarked concrete but we got it almost as a bonus," says Lonberg. "Why put a finish on something that looks beautiful in itself?"

The underside of the half-turn staircase extends from the foyer wall with the same rhythmic precision of boards and joints. The flights above are just 150mm deep and the half-landing projects 2.8m from the wall without the aid of columns. The structure is supported via cast-in channels which connect to starter bars cast into the walls, as well as the two bridges. More surprisingly, the stairs also support the foyer wall; the two had to be cast at the same time as the wall has no other lateral support. This is because the recital hall behind is technically a completely independent building, with separate structure and foundations ensuring complete acoustic isolation: "You could drag a cheesewire between the two," says Lonberg.

The glazed east and west elevations of the foyer heighten the effect of the boardmarked concrete: "We really like the way the concrete takes the light," says Flanagan. "The closer you get, the more you see the timber in it, and the similarity to the stone, the trees outside and the timber in the hall. There's a narrative thread that links the whole piece."

WE REALLY LIKE THE WAY THE CONCRETE TAKES THE LIGHT. THE CLOSER YOU GET, THE MORE YOU SEE THE TIMBER IN IT



GLIMMERS OF THE PAST

The scalloped facade and sparkling Dolomite sand of Mæ Architects' Pinnacle House are awash with Thames history, writes Nick Jones

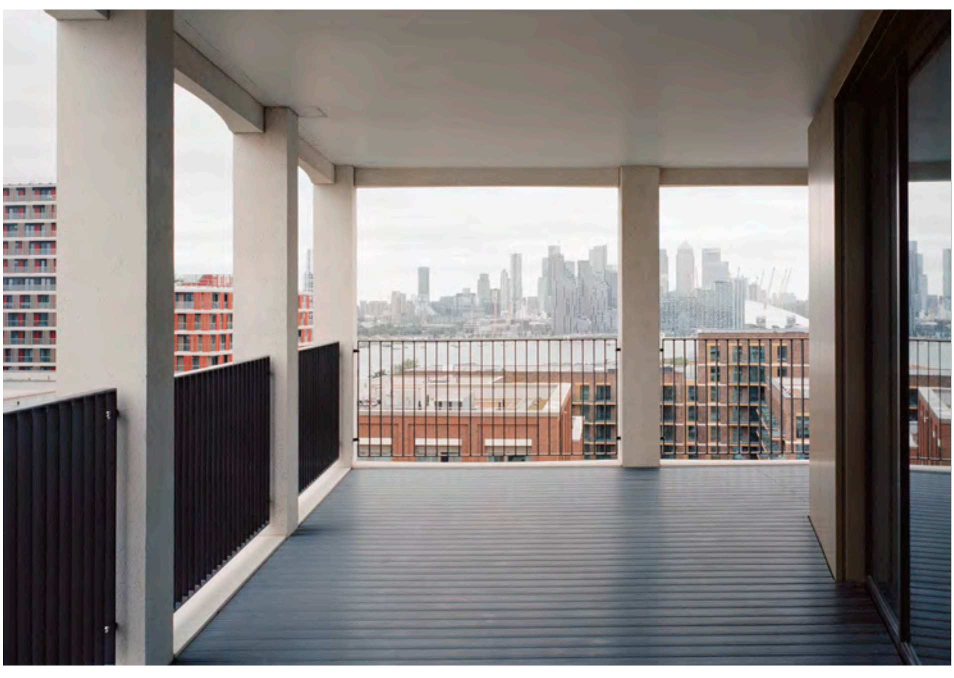
The area of London's docks that used to be known as Minoco Wharf has sharpened up its image in recent years. Once an industrial works, where high explosives were manufactured in the First World War, it is being turned into Royal Wharf, a "riverside neighbourhood" of 3,385 homes, shops and restaurants, masterplanned by Glenn Howells Architects. But with dramatic change comes a desire to connect to the past – and for Royal Wharf's latest apartment building, that connection is expressed via its precast-concrete facade.

Pinnacle House, designed by Mæ Architects, is the development's tallest building at 14 storeys (the flightpath to City Airport precludes anything higher) and sits at the head of a park that stretches down to the Thames. It comprises a reinforced-concrete tower and a shorter shoulder block to the north, and contains 110 one-, two- and three-bedroom flats, as well as cafes and restaurants at ground level. In the interests of material efficiency, the two parts of the building share a core.

The exterior is wrapped in a grid-like frame that stands up to 2m proud of the building's rainscreen, making a deep two-layer facade with continuous balconies for flats on the east, south and west sides of the tower. This device has as much in common with a Renaissance loggia as a 21st-century London tower – Mæ founder Alex Ely says that the basilica of San Michele in Foro in Tuscany was a reference point. "There's something rather lovely about the depth and shadow you get on a facade like that."

The facade design also had a more local reference point. Each bay is topped by a scalloped beam, adding to the play of light, but also providing a nod to the site's history – specifically the oyster shells unearthed during the excavation of the dock walls. In another classical allusion, the tower has

WE WERE INTERESTED IN HOW FACADES CAN CONTROL CLIMATE – WE SEE THIS AS PART OF THE ECOLOGICAL AMBITION FOR THE BUILDING



Photos: Rory Gardiner

a tripartite structure, with the columns becoming slimmer and the scallops wider as the tower rises. The three distinct sections are marked by a cornice on the third, sixth and ninth levels. "It is open towards the sky, with a bit more privacy towards the ground," says Ely. "It's quite understated but once you draw attention to it, you can't stop spotting it." This subtle variation meant that the precaster needed several bespoke timber moulds per section, covering the changing profiles of the columns and flat and radial beams.

The concrete for the facade is a combination of limestone aggregates and Spanish Dolomite sands, with white cement. Mæ initially explored the idea of adding oyster shells – in the manner of the "tabby concrete" used by early settlers to North America. However, this was deemed out of keeping with the development's other largely precast and brick-clad facades, and it was left to the sands to give a pearl-like iridescence. "You definitely see that little glint in the way you do with oyster shells," says Ely. Again, the mix and the finish change subtly as the tower rises: the lower section is deeply shot-blasted and acid-etched, while the upper levels are smoother and whiter, thanks to a higher proportion of sands. The gentle implication of sedimentary action is another gesture towards the bankside setting. The ability to control the detailing to this degree was a big reason for using precast concrete, Ely adds.

The facades are structural, supporting the reinforced-concrete balconies behind. The balconies were cast in situ with the rest of the concrete frame (with a thermal break at the building perimeter). A system of temporary props was erected to support the projecting balconies until the precast panels, which were cast in one-storey-high, 5m-wide sections, could be retrospectively installed.

The resulting balconies are certainly luxurious for an apartment building, but they also perform an essential function: "We were interested in how facades can control climate, so we see this as part of the ecological ambition for the building. By providing deep shading on the south facade overlooking the river, and also the east and west sides, it is managing the internal climate."

Ely hopes that the ecological ambition will extend to greenery spilling out over the balconies, but the design leaves this in residents' hands. He contrasts this organic approach to The Barbican, where he lives, and where each flat's fixed concrete planters invite a more inflexible response. "The balconies [at Pinnacle House] are just enormous, so you could have a garden on there. It's a very formal piece of architecture, but if someone strung a hammock up, put a shed out or planted it up, I'd love that."

PROJECT TEAM

Architect Mæ Architects
Executive architect Whittam Cox Architects
Structural engineer OCSC
In-situ concrete Henry Construction
Precast concrete Evans Concrete

CLOCKWISE FROM TOP LEFT

The tower looks out over a landscaped park; pronounced cornices separate the facade into three sections, which get smoother and whiter, with slimmer columns, as the tower rises; the balconies are up to 2m deep

EXECUTIVE PRODUCER

Snøhetta's concrete office building will generate more energy than its embodied and operational carbon combined. Nick Jones finds out how

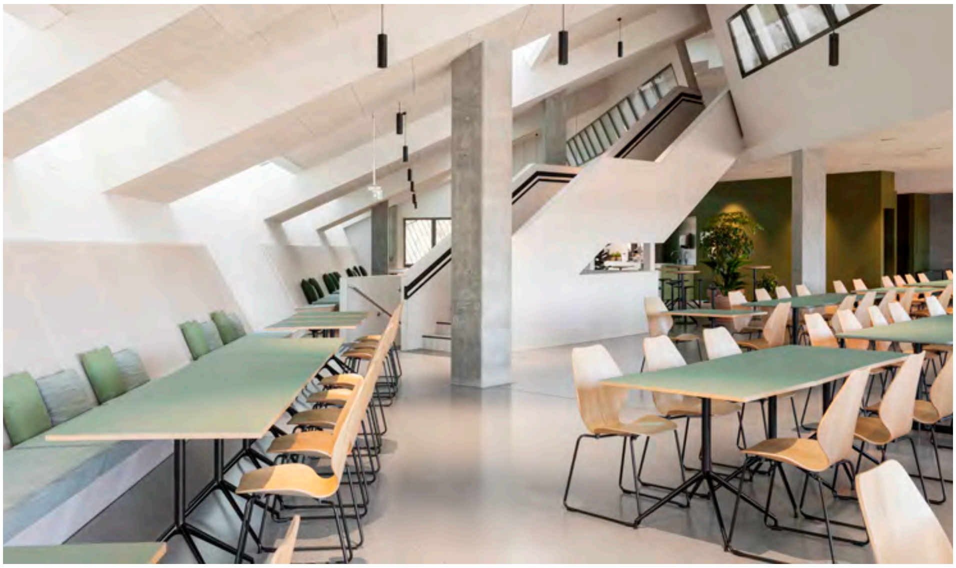
The design for Powerhouse Telemark began with an equation. The team behind this solar-powered office building in the southern Norwegian city of Porsgrunn set out with one golden rule: that it should be "energy positive". This they defined as producing more energy over its designed lifespan than its combined operational energy use and embodied carbon – encompassing the production, transportation, maintenance and even eventual demolition of the building materials. Everything from the 11-storey building's cut-diamond form to its reinforced-concrete structure is designed to make sure there is a surplus in the ledger.

In order to make the power-generation side of the energy-positive equation work, architect Snøhetta needed to squeeze more than 1,400m^2 of solar panels on a plot little more than twice that size. The oblique slices and angles of the building form are all means to this end, creating a roof that is much larger than the building's base and slopes down 24 degrees towards the south-west, maximising the solar-generating area. More panels are squeezed on to the south facade, which includes a sharp cutaway to provide shade to the lower floors. This cat-and-mouse game with the sun continues all the way round the building, with slanted elevations, transparent and opaque facades, triple glazing, automated blinds and wooden shades all part of a carefully controlled solar strategy.

The original plan was to build this complex, overhanging structure in timber, but this proved too expensive, so the team turned to reinforced concrete. Now the task was to make the embodied carbon side of the equation stack up. This involved replacing as much of the cement as possible in the concrete with fly ash – the most common cement substitute in Norway. For the main mix used in the structure, this amounted to about 27%, reducing the carbon emissions by more than a quarter, as well as cutting the energy used in the production of the concrete by about 16%. FA was also used as aggregate, replacing some of the finer grades.

While this helped the team to keep within their budget for embodied energy, it did bring challenges on site. FA-based concrete cures more slowly in cold weather, and here temperatures plunged to –13°C while they were casting the ground slab. "We had to use a heater to warm it up, and placed heating cables against the formwork," says Arne Vatnar, senior adviser at contractor Skanska. "We also sometimes added accelerator to the mix." He adds that, despite such minor tribulations, FA continues to gain strength even after it has cured. "It is a two-step process: the cement and water react first, and the FA reacts against this, creating a stronger and more resistant concrete several years after it is cast."

Another key part of the equation involved a simple subtraction: reducing the amount of materials used, both in the structure and the fit-out. The slabs were post-tensioned, enabling



PROJECT TEAM
Architect Snøhetta
Structural engineer
Asplan Viak
Contractor Skanska

CLOCKWISE FROM FAR LEFT
Exposed concrete floors are an integral part of the geothermal heating and cooling system; the building is highly insulated, with triple isolated glazing throughout; the cut-diamond form is designed to optimise daylight and shading; the roof and facades incorporate more than 1,400m² of solar panels

Photos: Ivar Kvaal

their depth to be reduced from 300mm to 240mm. And the interiors use the same robust, durable palette of materials throughout, including carpet tiles created from old fishing nets and parquet floors made from offcuts of ash. It is a guiding Powerhouse principle that even if the tenants change, the interior design remains the same – even down to the signage. "This allows for a certain amount of flexibility in tailoring the visual expression of the different office spaces without creating unnecessary waste that may be generated when brand-specific signage is removed or produced," the architects explain.

As part of this unfussy aesthetic, the structure is used as finish where possible. Almost 90% of the walls and columns are left exposed and untreated, as well as 40% of the soffits. This has brought other benefits when it comes to the building's operational energy. As with all exposed concrete, the slabs help to regulate the internal temperature by acting as a thermal store, but they also play an active role in the geothermal heating and cooling system. This "Lowex" system uses a heat pump to draw water from eight 300m-deep wells on the site up to the building and through a network of pex pipes embedded in the exposed concrete slabs in a 4m-wide strip parallel to the facades. The thermal mass of the concrete helps to distribute the heat, or cooling, throughout the building.

The final part of the equation factors in the demolition of the building, and it is envisaged that the concrete will be crushed and reused as secondary aggregate. A simulation program, SIMIEN v 6.009, was used to evaluate the energy concept, forecasting that the immense photovoltaic array will generate 87.3kWh/m²yr over a 60-year life. The combined embodied carbon and operational energy use, meanwhile, came in at 44.2kWh/m²yr and 41.5kWh/m²yr respectively – a positive result, with 1.6kWh/m²yr to spare.


PROTON BEAM THERAPY CENTRE
THE CHRISTIE

Beyond the binder: How to specify lower carbon concrete

Understanding strength and structure is key to reducing concrete's footprint, writes Jenny Burridge

In October 2020, the UK concrete and cement industry launched its Roadmap to Beyond Net Zero. The roadmap shows how the industry can continue its decarbonisation journey, with the aim of providing net-zero concrete by 2050. The industry has already taken considerable early action, and due to investment in fuel switching, changes in product formulation and energy efficiency, its direct and indirect emissions are 53% lower than 1990. The roadmap shows that the industry could become net negative by 2050, without offsetting, removing more carbon dioxide from the atmosphere than it emits each year.

Although a net-zero concrete is not yet available, significant amounts of carbon can be saved by looking at how we specify concrete and adopting the most appropriate solution for each project. This is not simply a case of selecting the most "low-carbon" mix, but understanding the properties of cement replacements and additions, factoring in considerations such as strength gain, and using materials as efficiently as possible.

Cement replacements

If we consider the different constituents of concrete, around 85-90% of the mix is represented by aggregates and water. These have very low embodied carbon, with locally sourced primary aggregates responsible for about 4kgCO_2/tonne. It is the cement, forming the remaining 10-15%, that leaves the biggest footprint. A critical means of reducing concrete's embodied carbon is therefore to specify low-carbon mixes using cement replacements, or low-carbon cements.

All concretes to British Standard BS 8500 are based on Portland cement, or CEMI, but most contain secondary cementitious materials (SCMs) or additions, such as ground granulated blast-furnace slag (GGBS), fly ash, silica fume, limestone powder and pozzalana. These SCMs have a much lower embodied carbon than CEMI (see table 1).

Since the most recent version of BS 8500, ternary blends of cements have been allowed. Ternary refers to CEMI with two additions, normally limestone fines with either fly ash or GGBS. All of these cements are based on CEMI, but there are also geopolymers or alkali-activated cementitious materials (AACMs) that can be specified using PAS 8820, a publicly available specification produced by standards body BSI. These are normally based on GGBS, activated by a chemical that is added to the mix.

TABLE 1: EMBODIED CO_2 OF UK CONCRETES*

Broad designation of cement type in concrete	Percentage of addition	Embodied CO_2 kgCO^2/m^3 of concrete
CEMI	0%	283
IIA	6-20%	228-277
IIB	21-35%	186-236
IIIA	36-65% GGBS	120-198
IIIB	66-80% GGBS	82-123
IVB	36-65% fly ash or pozzalana	130-188

* Based on a cement content of 320kg/m^3 of concrete

Photos: Interserve

BOTH IMAGES At 12,000m^2, the Christie Proton Beam Center in Manchester is the largest treatment facility of its kind in the world. Its dense heavyweight structure, containing some 17,000m^3 of concrete, is vital for shielding staff and visitors from high levels of radiation. The mix used by contractor Interserve contained 70% GGBS cement replacement, drastically reducing the embodied carbon of the structure and also minimising heat gains and thermal cracking during curing.

Strength gain

One of the things to note with the use of low-carbon concrete is that the higher the proportion of additions, the slower the strength gain. This might not influence the construction programme if the concrete does not need to be struck quickly or to support load shortly after being cast. For example, foundations are frequently cast against the ground and the load is applied only slowly as the project progresses. Although the standard concrete strength is specified at 28 days, a concrete made with CEMIIIB cement will still be gaining strength at that stage and may be a further 40% stronger when it has gained full strength. The designer could take advantage of this by specifying a 56-day strength (see Insights, opposite).

For foundations, cement replacement of up to 80% GGBS may be possible. Elements that need to have a faster strength gain, such as suspended or post-tensioned slabs, can still use additions and do not need to be restricted to using CEMI. There have been several projects that have used CEMIIIB for a post-tensioned suspended slab, and concrete producers can add an accelerant admixture to improve the setting time.

TOP At Nicholas Hare's UCL Student Centre in London, all of the in-situ concrete and some of the precast elements use 50% GGBS cement replacement, as well as high levels of recycled aggregate

ABOVE Nithurst Farm in Kent by Adam Richards Architects also uses 50% GGBS. This both reduces the building's embodied carbon and realises the architects' desired pearl-grey finish

A CONCRETE MADE WITH CEMIIIB CEMENT MAY BECOME 40% STRONGER THAN ITS 28-DAY STRENGTH

Material efficiency

Designers should also be aware that, even where a larger proportion of cement is needed for higher-strength concrete, in some instances this can actually reduce the embodied carbon of a structure, as a smaller volume of concrete is required overall. Alternatively, as the water-cement ratio is key to the strength of concrete, use of superplasticiser admixtures reduces the cement content in the same strength concrete by reducing the water.

Structurally efficient sections such as rib or voided slabs, or post-tensioned structures also use less concrete, while foundations can be made more efficient by avoiding standardised sizes across the site.

If in doubt, the simplest way forward, at the moment, is to specify designated or designed concretes with a reduced range of cements. There is also a range of proprietary low-carbon concretes available. It is worth talking to your concrete supplier as early as possible to find out what can be achieved for the location and needs of the project.

Reducing a structure's carbon footprint takes a lot more than simply specifying a material. There is currently no single structural material that can be considered "lowest carbon" across all projects. Instead, we must look closely at its constituents and performance, and its impact on the building as a whole, and specify the most appropriate solution in conjunction with factors such as ground conditions, building height, climatic conditions, floor loading, longevity and opportunities to dematerialize generally. And once material choices have been made, we must redouble our efforts to use them as efficiently as possible.

REFERENCES AND FURTHER READING

Specifying Sustainable Concrete, MPA The Concrete Centre, 2020

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Photos: Brotherton Lock; Alan Williams Photography

TABLE 2: CEMENT CLASSES

EN 1992-1-1 class	Example cement type
R	CEM I
N	GGBS > 35% or fly ash > 20%
S	GGBS > 65% or fly ash > 35%

Note: percentages relate to total cement content
Source: CIRIA 766. Control of cracking caused by restrained deformation in concrete. CIRIA, 2018

Insights: Using 56-day concrete strengths

Tony Jones explains why specifiers should consider slower class cements

Concrete strength is usually specified at 28 days after casting. Striking of formwork normally occurs significantly before this as, in the temporary condition, the full strength is not required. All concretes will gain strength after 28 days but the amount depends on the type of cement used. European Standard EN 1992-1-1 considers three different cement classes: R, N and S (see table 2, above). Concrete with Class R gains strength the quickest, Class S the slowest. However, concretes with slower class cements typically gain more strength overall – which is not accounted for if 28 days is used as the cut-off.

Figure 1 (below) compares three Class S concretes, specified to reach strength at different ages, with a Class R specified at 28 days. The Class S specified at 28 days is 15% stronger after 300 days than the Class R specified at the same time. The Class S specified at 56 days is about 10% weaker than the Class R at 28 days but reaches the same strength at about 180 days, while the Class S specified at 90 days remains weaker than the Class R at 350 days.

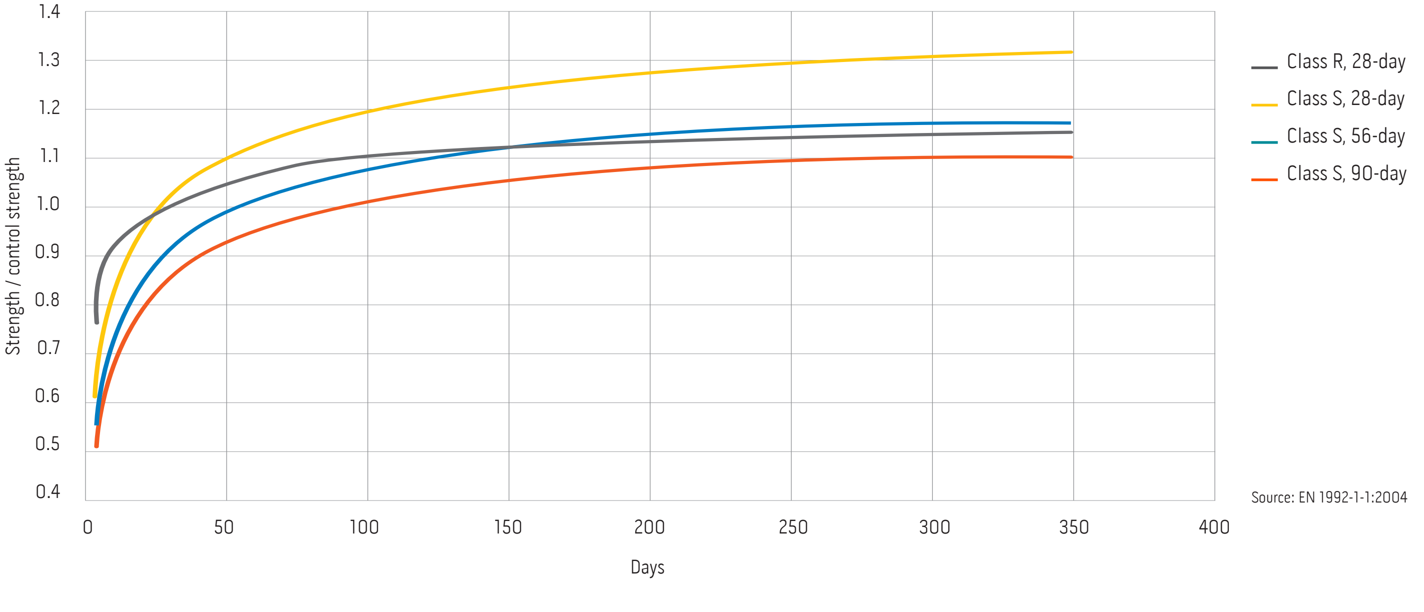
All concretes show some increase beyond the strength of the Class R at 28 days. Structural design codes normally rely on some increase to offset the fact that concrete strength is known to be lower under sustained loads. The default "recommended values" in EN 1992-1-1 imply an increase of between 13 and 18%. Although no precise value is stated in the UK National Annex, historically the long-term strength gain of Class R concrete specified at 28 days has been shown to be adequate. Therefore if, at the time of loading, a concrete is stronger than a 28-day Class R equivalent of the same age, it will be acceptable. As figure 1 shows, the 56-day Class S was stronger than the Class R after about 180 days.

Specifying concrete at 56 days provides an opportunity to reduce cement content and therefore embodied carbon. Although savings will depend on the exact mix used, it is estimated to be up to 10kg/m^3, based on the typical embodied carbon of cement – see "Specifying Sustainable Concrete" (Further Reading). British Standard BS 8500 permits the specification of concrete strength at 56 days, but it is important to discuss the mix with the concrete supplier to ensure that the aim of reducing cement content is met.

Class S concrete will not be appropriate where high early strengths are required. Its need to continue to cure beyond 28 days may be problematic on thin elements such as slabs subject to drying. However, Class S is normally well suited to use in foundations, retaining walls, larger columns and transfer slabs. In such instances, specifying strength at 56 days can be a very effective way of reducing embodied carbon.

■ **Tony Jones is principal structural engineer at The Concrete Centre**

FIGURE 1: STRENGTH GAIN OF CONCRETES MADE FROM DIFFERENT CLASS CEMENTS, NORMALISED TO STRENGTH SPECIFIED AT DIFFERENT AGES



Source: EN 1992-1-1:2004

FINAL FRAME: GOMOS MODULAR HOUSING, PORTUGAL

Porto-based architect Summary has created its own modular housing system inspired by the prefabricated modules used to install sewers. The volumetric "Gomos System" units in Vale de Cambra are made of precast-concrete sections that can be joined together to create a continuous shell of any size. The raw interiors have been left bare to minimise cost, and all internal compartments can be moved or taken out, enabling future adjustments.

Photo: Fernando Guerra / VIEW Pictures