The Concrete Centre

CONCRETE QUARTERLY

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Elaine Toogood
Head of architecture, The Concrete Centre

Highs and lows

The UK was the scene of a world-first last month, when a cement kiln at Hanson's Ribblesdale plant in Lancashire was operated using a wholly net-zero fuel mix. During the demonstration, the proportion of fuels in the kiln's main burner was gradually switched over until it was entirely powered by biofuels and hydrogen.

This is a significant milestone on the route to net-zero carbon, and a microcosm of what the UK's cement manufacturers have been doing for some time: replacing fossil fuels with waste-derived alternatives has contributed to a 53% fall in the carbon impact of UK concrete against a 1990 baseline. Concrete doesn't tend to travel so this local context matters: globally, cement production accounts for 8% of carbon emissions, but the equivalent figure for the UK is 1.5%.

There is still a lot to do before cement and concrete achieve decarbonisation on an industrial scale, but we don't have to wait for other people to innovate: there is an enormous amount that architects, engineers and constructors can already do to reduce the embodied carbon of concrete buildings, within current standards and with tried-and-tested ingredients.

At The Concrete Centre, we're receiving a great number of enquiries on this, from specifiers who have decided that concrete is the most appropriate choice – for reasons of fire safety, climate change resilience, or reducing and shifting peak loads in energy consumption – and who want to use it in the most sustainable way. It's heartening to see people challenging even recent guidance on low-carbon mixes, seeking to push it as far as they can.

Designing structures to use materials more efficiently is one part of it. For example, simply by challenging the norm that a building has to have a 9m span, and going for 6m instead would save about one-third of the carbon footprint of the structure, before even considering the concrete itself.

RATHER THAN STIPULATE A CERTAIN PROPORTION OF GGBS, SAY, ASK FOR THE LOWEST CARBON MIX FOR YOUR PARTICULAR APPLICATION

When it comes to the mix, the best-known method is to replace some of the cement with secondary cementitious by-products from industrial processes, such as GGBS or fly ash, but the British Standard is evolving to allow greater use of powdered limestone or other natural pozzolans.

Concrete specification can be a complex art, especially with so many innovative products reaching the mainstream, so unfortunately there isn't always the same right answer. The industry is working on helping to make the process simpler, but right now the best guidance is still to engage early with suppliers. Rather than stipulating a certain proportion of GGBS, say, ask for the lowest carbon concrete for your particular application, because there may be other ways to achieve it. There's no such thing as a single "low-carbon concrete" – there are many different lower-carbon concretes, with different properties, and the key is establishing the mix with the lowest possible carbon for the job that you want it to do. ■

CONCRETE QUARTERLY

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On the cover:
Narbo Via Roman museum, Narbonne by Foster + Partners. Photo by Philippe Chancel

INNOVATION

STRIATUS

ZHA AND ETH REVISIT A ROMAN CONSTRUCTION TECHNIQUE WITH THE LATEST 3D-PRINTING TECHNOLOGIES – USING LESS MATERIAL TO DO MUCH MORE

As any arch-building Roman could tell you, compression in structural design can support the same loads with much less material than deploying the brute strength of a horizontal beam.

This is the principle at work in Striatus, an arched footbridge composed of 53 printed concrete blocks and assembled without mortar or reinforcement. Combining traditional techniques with advanced computational design and robotic manufacturing, the 16m x 12m footbridge is a joint development by the Block Research Group (BRG) at ETH Zurich and Zaha Hadid Architects Computation and Design Group (ZHACODE).

"Before strong, long-span beams were available, people used to make use of compression in structures a lot more," says Shajay Bhooshan, co-founder of ZHACODE. "Roman arches are well-known, but the Mexicans and Nubians also used compression very skilfully in creating vaulted ceilings. Compression makes very efficient use of materials – and less material usually means a lower carbon footprint and a better overall environmental performance."

COMPRESSION MAKES VERY EFFICIENT USE OF MATERIALS – AND LESS MATERIAL USUALLY MEANS A LOWER CARBON FOOTPRINT

The bridge is made from printed concrete blocks that are partially hollow and weigh between 200 and 700kg. They were assembled on a temporary sculpted board support structure, and arranged in such a way that they are pushed towards each other by their own weight. With the temporary support removed, the structure uses only compression to hold itself together without the need for mortar or steel connections.

The principles of compression have also been put to work in the blocks themselves to maximise the

effectiveness of the 3D-printed concrete manufacturing process. Each was formed by up to 500 layers of printed concrete using a two-part mix in which a bead of concrete "ink" is printed together with an accelerator that causes it to set almost immediately.

"The accelerator is important because, unlike most concrete printing, the beads vary in thickness, and are not all laid down horizontally," explains Bhooshan. "They are at varying angles so, without the accelerator, the sloping nature of the layers would cause the concrete to slip."

The unusual expedient of printing sloping layers allows them to be aligned at right angles to the expected flow of forces through the bridge: "The result is that the printed concrete is more stable because the layers are compressed together. That means shearing is avoided, and the blocks can be lighter because, like the bridge itself, they too benefit from the strength of compression."

The Striatus project stemmed from the PhD that Bhooshan is undertaking with the BRG at ETH Zurich. "I am looking at how you can design effectively with 3D printing in concrete. BRG had worked with Zaha Hadid Architects before, then more PhD students became involved, along with 3D printing firm incremental3d, and concrete supplier Holcim. So it has been a real team effort."

Striatus is much more than an academic exercise, he stresses: "We see real environmental benefits from this approach. As well as minimising material, our blocks are free from steel reinforcement and connections – the mix does not include fibre reinforcement either. So as well as using less steel, it would be easy to take apart and reassemble at a new location. Alternatively, it would be straightforward to recycle the concrete itself as there is no need to remove any steel first."

The bridge is currently exhibited at the Giardini della Marinaressa park for the Venice Architecture Biennale. ■

Interview by Tony Whitehead

TOP
An accelerator makes the concrete set almost immediately, enabling the beads to be printed at varying thicknesses and angles

ABOVE
The blocks are partially hollow and weigh between 200 and 700kg

LASTING IMPRESSION

JOHN PUTTICK

A LANCASHIRE BUS STATION AND AN ALPINE SWIMMING POOL OFFER LESSONS IN THE LIGHTNESS OF CONCRETE

The refurbishment of Preston Bus Station (Building Design Partnership and Ove Arup and Partners, 1968-69) was the project that really got our practice started. Everybody knows it as an example of brutalism, but it's not just uniform concrete – it's used in a variety of ways. There are the big columns that hold up the car park above the main bus concourse, which are exposed with rough shale aggregate, and bring a very warm, monumental character to the space. But then the ribbed concrete decks above are lighter and more defined. The ribs create longer spans with less material and were cast in glass-reinforced plastic shuttering, which was quite innovative. It's quite different to concrete buildings of the same era because the finish has a smoother, tighter quality.

The part of the building that everybody knows is the facade, with its the curving slab edges. They set up a mini factory to cast it on site, which was possible because of the scale and the number of repeated elements – it's a very modular building in a way. I heard a story that for a long time during the design stage, the balustrade on the edge of the car park was simply a vertical concrete upstand. The problem was that this put too much weight on the edge of the slab, so Arup

Photo: Gareth Gardner

ABOVE
Preston Bus Station, refurbished by John Puttick Associates, 2018

Photo: Cjp95 / Justacoté

had to eliminate it and instead came up with this curving leaf-like form that was physically lighter and gave a far more delicate appearance. And that became the iconic image of the building for the city.

A lot of recent concrete architecture approaches the material as fundamentally a heavy, sculptural mass, but the leaf-like elements at Preston got me thinking about concrete shell structures, which are all about lightness. I was in Chamonix a couple of years ago and there's a sports centre in the middle of the town designed by the structural engineer Heinz Isler (with architect Roger Taillibert, 1971). It has this extraordinary shell arching over the swimming pool. It's really light and very, very beautiful, and it's the opposite of the concrete-as-mass approach. As we are becoming more conscious about the environmental impact of materials, this very economical way of achieving very large spans could have a lot of significance.

In a similar vein, the Teshima Art Museum (Ryue Nishizawa, 2010) on Japan's Seto Inland Sea is a building I would love to visit. It's very pure: a 40m x 60m shell with a single permanent installation of water droplets that coalesce beneath an opening in the structure. Again, it's not about mass and weight. It's only 4.3m high, which strikes me as very shallow for a shell of that size. I'd be fascinated to see how it works technically. ■

John Puttick is director of John Puttick Associates

ABOVE
Richard Bozon Sports Centre, Chamonix, by Roger Taillibert and Heinz Isler, 1971

BELOW
Teshima Art Museum, Kagawa, by Ryue Nishizawa, 2010

Photo: Nathan Willock/VIEW

FROM THE ARCHIVE: SPRING 1954

THE ARCHITECTURE OF BUSES

Thirteen years before Preston (see previous page), Ove Arup had designed an equally groundbreaking bus station in Dublin. A mixed-use building that contained offices for the Department of Social Welfare above the two-storey concourse, Busáras was proclaimed at the time as both Ireland's first modernist masterpiece and Europe's first post-war office building.

Concrete Quarterly's reviewer certainly thought it possessed a degree of finesse and technological prowess that set it apart from most contemporary infrastructure projects. "[Architect] Michael Scott has designed the structure entirely in reinforced concrete and has given it a richness of finish, both inside and out, that is uncommon in these days," CQ wrote. "There is much glass, and facings of Portland stone, of brick and of colourful mosaic, bronze fittings, and polished woods." Of particular note was a cantilevered canopy, covered in a multicoloured, diamond-patterned Italian mosaic, with its sides "uptilted like the wings of some great bird alighting on the roof". Arup also designed another canopy, to announce the entrance of the bus station itself. This undulating structure was just 7cm thick and projected more than 6m, and its shell concrete design reduced the need for supporting columns – a sense of lightness that would be echoed at Preston a decade later. "To Dublin, city of beautiful, dignified architecture, this new building adds both beauty and dignity," said CQ.

It also brought a blast of the future. The offices were air-conditioned and double-glazed, and the space between the window panes could be heated to eliminate condensation. Suspended ceilings concealed ductwork and sprinkler heads. The message was clear: with its flagship bus station, post-war Ireland was changing gear. ■

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DUBLIN'S NEW BUS STATION

adds a building which has both beauty and dignity to a city already famous for beautiful and dignified architecture

THE BUS STATION which was started in Dublin in 1946 was eventually opened for use in October 1953. Politics, government decisions and indecisions, changes of administration, changes of purpose, delayed its completion, but the building was worth waiting for. To Dublin, city of beautiful, dignified architecture, this new building adds both beauty and dignity. Michael Scott, F.R.I.A.I., has designed the structure entirely in reinforced concrete, and has given it a richness of finish, both inside and out, that is uncommon in these days. There is much glass, and facings of Portland stone, of brick and of colourful mosaic, bronze fittings, and polished woods.

The building, with its two wings at right angles, occupies a fan-shaped site, with the concourse and parking yard occupying the segment within the angle of the wings. The two wings are of the same width—55 ft.—but of unequal length and height. The main (north) wing is seven storeys high and 242 ft. long; the smaller is four storeys high and 200 ft. long.

Designed originally for Coras Iompair Eireann (the Irish Transport Company) as a bus station and offices for the company, it is now shared between them and the Irish Government's Department of Social Welfare, who occupy the upper floors. The open yard is still occupied by buses, and the basement, ground and mezzanine floors are devoted to the Company's activities—they include restaurants, cloakrooms, lavatories, the waiting concourse with enquiry offices and shops, and a news theatre.

The offices on the upper floors have had to be slightly altered for their new tenants but structurally the building is as it was first designed eight years ago by Michael Scott.

The building is constructed on a reinforced concrete raft generally 18 in. thick and thickened below the columns. As the basement is below tidal water level, the floor and walls are waterproofed with asphalt. A big saving in cost was effected by constructing the foundations and basement without the use of steel sheet piling. This was done by making use of existing retaining walls around the periphery of the site, which were underpinned and strutted; they were then asphalted on the inside and the new retaining wall concreted against them.

The main building is constructed with reinforced concrete columns and hollow-tile slab

23

The north wing: the picture gives an idea of the depth between the double windows, in which the temperature control apparatus is installed.

yellow and white, cantilevers out above each window, 'supported', visually, by harp-string verticals of bronze. A cantilevered canopy the width of the building and T-shaped in plan, juts out at one end. This canopy, which is carried on columns covered in blue mosaic, has its sides up-tilted like the wings of some great bird alighting on the roof. The soffit of the canopy is covered with mosaic in a diamond pattern of red, blue, yellow and white. Above the penthouse, again, the lift and ventilation plant are housed in cubes faced with perforated greyish blue tiles, designed to merge into the colours of the sky.

From first floor upwards, the line of the building overhangs the line of the ground floor columns by the width of the first floor frontal beam. This beam, which is 4 ft. 6 in. wide and 3 ft. 9 in. deep, carries the upper floors on its outer edge, while its inner edge rests on the ground floor columns. The cantilever action thus caused is resisted by transverse beams across the width of the building at each column. These beams are reduced in depth towards the centre, to accommodate ventilation and other services. A false ceiling is hung level with the lowest soffit of the beam.

ORIGIN STORY

THE ROCK HOUSE

GORT SCOTT'S JOE MAC MAHON ON A PROJECT THAT STARTED WITH A WALK IN THE WOODS

We were invited to enter the competition for this private house in 2012. It was the last plot on a development in Whistler, and it was quite a challenging site, on a rocky outcrop overlooking Alta Lake. We really wanted to win the project so Jay [Gort] and Fiona [Scott] took a gamble and flew out to Canada.

Getting to know the site like that was probably what made the difference to us winning the competition. The essence of the design stems from that first visit and the experience of walking up through this rocky promontory. You work your way through the woodland, and there's a series of changing horizons, as different views reveal themselves. There's Whistler Mountain behind you, and Blackcomb Peak and Wedge Mountain through the trees.

ABOVE
The building's complex geometry was set out in increments of 3½ inches, the width of the formwork boards

TOP
The house is positioned on a rocky outcrop over Alta Lake

ABOVE
Deep overhangs shade the extensive glazing from the summer sun

It culminates at the top of the rock where you see Rainbow and Sproatt mountains in front of you across the lake. The design of the home was trying to replicate that journey.

The prow of the rock was absolutely sacrosanct, so we cut down into the ground behind that, excavating by hand. We like to quote Frank Lloyd Wright: "No house should ever be on a hill. It should be of the hill. Hill and house should live together with each the happier for it." Obviously, the best material to achieve that with was concrete. From an early stage we had the idea of a concrete base that would then hold the living spaces floating above. These would be clad in black-painted cedar – a way of connecting it to the surrounding forest.

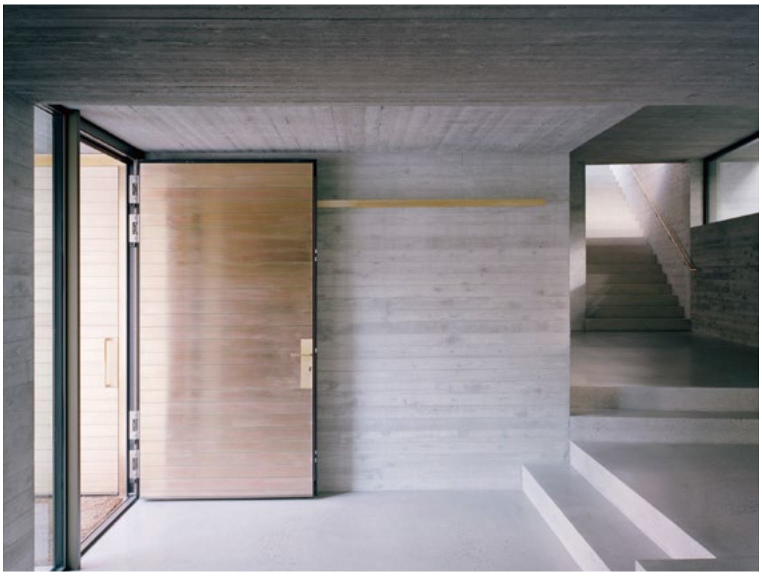
We were really lucky to find a local contractor who loved working with concrete. We worked very closely with them from early on to design the formwork for the whole building. The house has a very complicated geometry so we had to carefully plan out every junction and joint line – we basically drew every single board, so we could get it spot on. We figured out that the most efficient way to set out the building was in increments of 3½ inches, an off-the-shelf size for the cedar planks. (We had to learn how to work in Imperial measurements – a first for me.) This follows through to the stairs, which are 7 inches, and all the way to the tops of the chimneys. We also had to plan all the light fittings and switches at a very early stage as the electrical conduits are cast into the concrete.

It was important that the tone of the concrete fitted in with the rock, so we lightened it with titanium dioxide. Internally, we decided to strike it in such a way that it would leave strands of the cedar in the concrete. We did a test where a little bit of cedar was left behind and we really liked it. It's not very noticeable at first, but at certain angles you just get this golden shimmer. It's especially nice when it catches the light.

The only concrete interior that isn't textured is the double-height basement gallery space, which acts as a hall connecting various parts of the building. Here, we used phenolic ply formwork to give a very smooth finish. All of the walls and the slab were cast at once, with a self-compacting mix pumped from below.

When we started working on the project, low-energy design wasn't high on the agenda in this part of the world, partly because they had such cheap hydroelectric power. But together with the client, we wanted to push it to be as sustainable as we could achieve. We designed the building to Passivhaus principles, but with natural ventilation. Big overhangs shade the windows in summer and a geothermal field under the house supplies hot water and cooling. The concrete structural system has 4 inches of rigid insulation between an 8 inch inner structural leaf and 5½ inch outer leaf. Thermally it's brilliant, it really helps to balance the house – which is a challenge in a climate that gets very, very hot in summer and very cold in winter. On a hot day, when you go down to the lower levels it really feels cooler, like you're in the belly of the rock. ■

Joe Mac Mahon is an associate at Gort Scott



Photos: Rory Gardiner

PROJECT TEAM

Architect Gort Scott

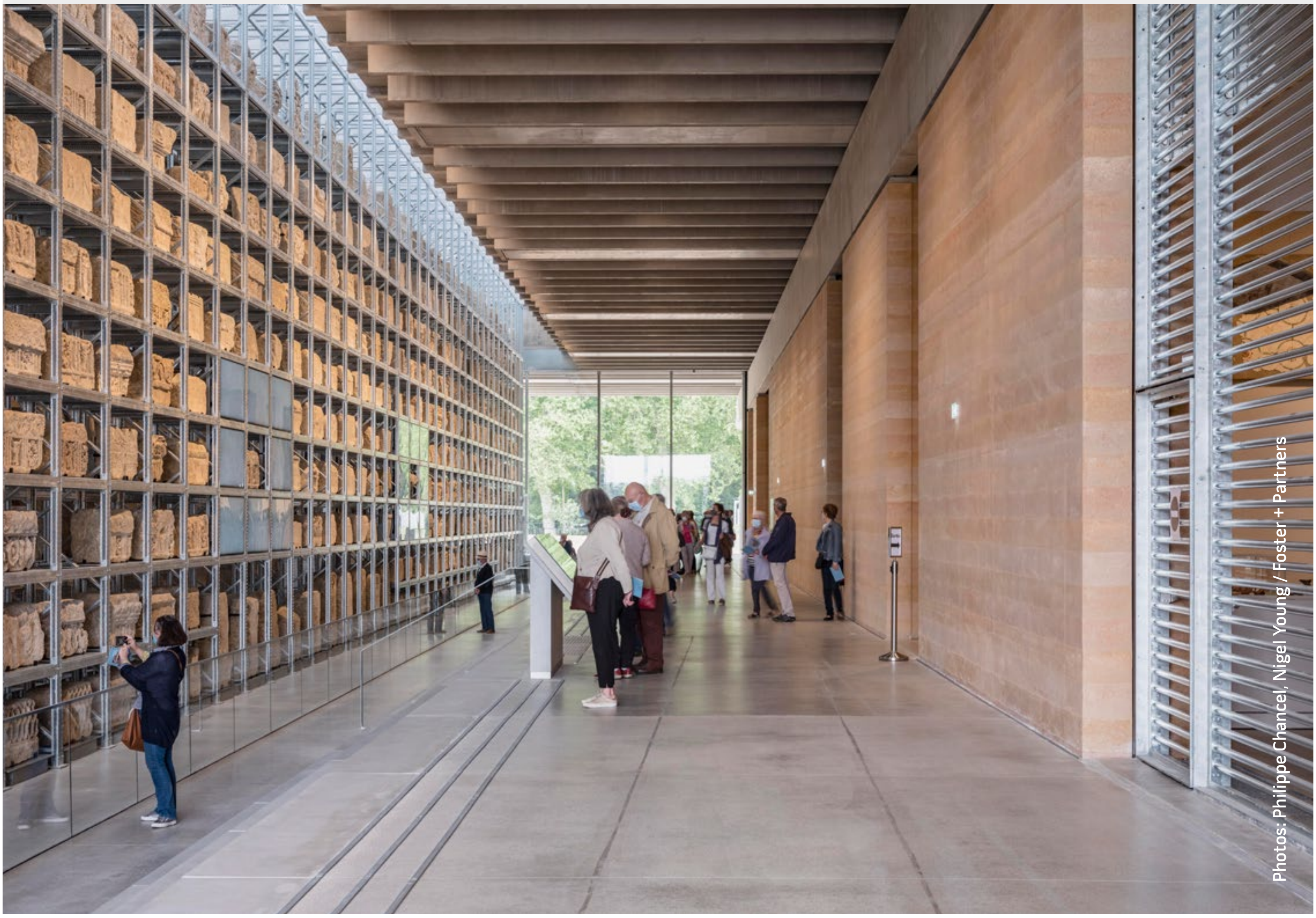
Structural engineer Equilibrium

Contractor Durfeld

Concrete contractor BMak Construction

TOP
A terrace and pool form a bridge to the guest house

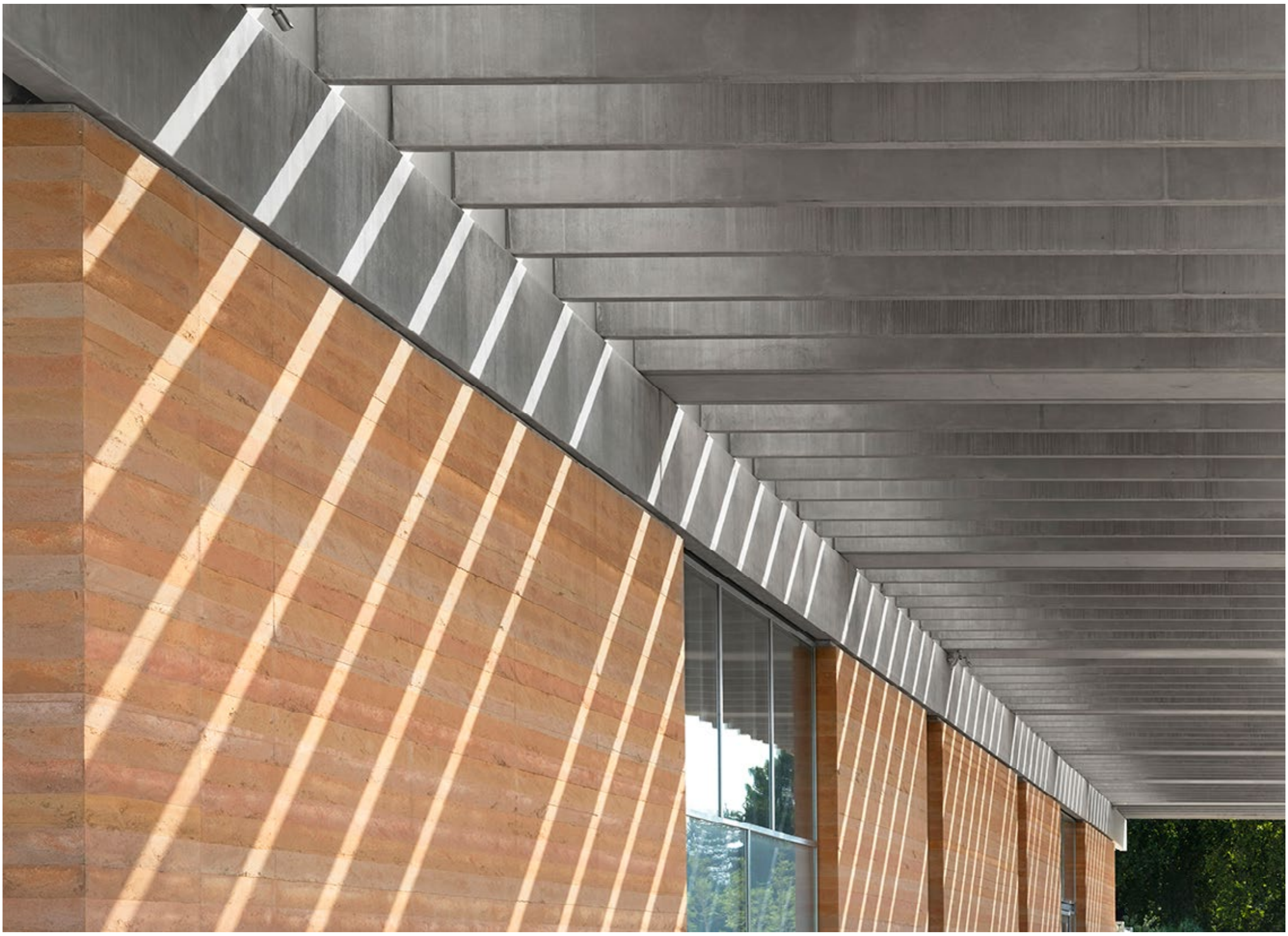
ABOVE
The concrete was lightened with titanium dioxide



Photos: Philippe Chancel, Nigel Young / Foster + Partners

THE BEAUTIFUL AND RAMMED

Foster + Partners brings the layered richness of the southern French soil to precision-engineered concrete at Roman museum Narbo Via, writes Tony Whitehead



ABOVE
Oxide colourants were used to create the varying terracotta-like tone of the layered concrete

Exposed concrete has become a popular choice for designers of prestige museums and galleries: from the spectacular V&A at Dundee, to the equally striking Glassell School of Art in Texas, architects have deployed both in-situ and precast concrete to create buildings that are highly distinctive from the outside, yet appropriately quiet and relaxed once you step inside.

The same can certainly be said of Narbo Via, a new museum of antiquities in the port city of Narbonne in southern France. But this building – not unusually for a Foster + Partners design – has something a little bit different: its massive walls are made from terracotta stripes of rammed concrete.

Made by compressing an almost-dry mix, rammed concrete is still a rare sight anywhere, and tends to feature more in designer homes than civic projects. So how did it come to be used on a major cultural building spanning nearly 9,000m^2?

"We originally envisaged a structure clad in precast concrete," says architect Hugh Stewart, a partner at Fosters. "But as the design developed, we began to favour a more monolithic approach, and there was a strong desire within the office that if it looked monolithic, then it should be monolithic. We considered conventional in-situ walls with insulation in the middle, but then decided we were after something more textured, more gritty, a bit more of the place. We looked all over the world for something that could provide that, before deciding on rammed concrete."

The chosen wall system was a Canadian product called Sirewall – "Sire" standing for "structural insulated rammed earth". Although there is some debate about where rammed earth finishes and rammed concrete begins, its sand, aggregate and cement mix would seem, despite its name, to make Sirewall more at the rammed concrete end of the spectrum. However you describe it, the walls at Narbo Via are impressive not

WE DECIDED WE WERE AFTER SOMETHING MORE TEXTURED, MORE GRITTY, A BIT MORE OF THE PLACE

ABOVE
The whole building is raised on a landscaped podium to prevent flooding

PLAN

1 Public entrance
2 Entrance atrium
3 Shop
4 Auditorium
5 Permanent exhibition
6 Temporary exhibition
7 Lapidarian gallery
8 Workshops
9 Patios
10 Vineyard
11 Amphitheatre

only aesthetically but also in terms of how hard they work for the building: their many functions include structure, weather shield, internal finish, acoustic control, thermal "flywheel" and humidity regulation.

In Roman times Narbonne was a major port, and Narbo Via is constructed primarily to house a collection of more than 1,000 Roman funerary stones recovered from the city's medieval walls in the 19th century. These are displayed on a long wall of metal shelving that cuts the 8,765m^2 museum's rectilinear plan into two squares. One is dedicated to double-height public galleries; the other, featuring a mezzanine floor, provides space for education, research, restoration and administration.

The site is prone to flooding, so the whole building is raised on a low, landscaped podium – lending some elevations an appropriately classical or temple-like appearance. Voids below the ground floor in-situ concrete slab have been used to house the majority of primary services.

But it is the walls which catch the eye and define the building. "It's worth noting that these are structural walls," says Foster + Partners' head of structural engineering, Roger Ridsdill Smith. "They have to resist the vertical loads of a precast-concrete roof structure, as well as lateral loads including wind, and there is also seismic loading to consider. So we needed substantial and dependable structural properties from the walls – not least for them to be acceptable in the context of stringent French codes."

To achieve all of the above, the 6m-high walls are 800mm thick, comprising a 200mm outer skin, 200mm of solid foam insulation, and a 400mm inner skin.

"The inner and outer skins of rammed concrete are joined by horizontal rebar which connects vertical rebar in each skin," explains Ridsdill Smith. "But we didn't want tie holes, so the forms are just pushed up to the wall and held in place without them. There's less need for ties because, being created in layers, the drier mix does not exert hydrostatic pressure in the way that wet concrete would" (see box, page 23).

The attractive striations result partly from the rammed concrete construction process in which a 200mm-deep layer, usually some 6m long, is "poured" into forms (although the mix, Stewart says, is "dry in the hands"). It is then compressed by hand-held mechanical tampers. After this it is firm enough for forms to be removed if desired, though the concrete continues to cure, with a strength gain curve to 28 days somewhat steeper than many concretes.

ABOVE
The museum houses more than 1,000 Roman funerary stones on a long wall of metal shelving

As for the unusual colouring, the aggregates are from a local quarry, but Stewart says that the shades and patterning mainly result from alternating mixes with various amounts of oxide colourants. "We created two palettes – one more blood red and this one, which is more pink and orange. After trials, we decided the first was too strong but the second was similar to the local terracotta roof tiles, helping the building to be of its place."

As with most larger Sirewall projects, the Narbo Via site used a volumetric mixer customised to work with

RIGHT
A relief map of the Roman Empire is cast into the rammed concrete

the drier mix. Once the mixer had been calibrated, the colour could easily be changed from one lift to the next, allowing each layer to be visually contrasted. "The arrangement of differing shades is carefully chosen," explains Stewart. "We had full-size paper prints hanging in the office, testing out the shades and helping us decide exactly what the order should be. It's meant to look natural, but it's not the slightest bit random."

A number of environmental benefits result from the wall design. The 400mm inner layer, exposed to the air inside, absorbs and releases heat to even out diurnal temperature variations and saves energy by reducing the need for heating or cooling. There is so much exposed thermal mass – the roof is also exposed concrete – that the benefits extend beyond daily cycles to seasonal ones, says Stewart. "It is a happy marriage between looking beautiful and having a significant thermal flywheel effect. The inside stays remarkably cool, even on the very hot days this part of France enjoys in summer."

Material usage is reduced as there

Use the force

The rammed concrete system used at Narbo Via was developed by Vancouver-based Sirewall, a company founded in 1992 by self-styled "legendary dirt Jedi" Meror Krayenhoff. So how does it work?

"Soils and aggregates are different all over the world," says Krayenhoff. "Our technology is able to analyse what's available and come up with an optimal mix design. A big difference between Sirewall and most plain rammed earth systems is the strength. They don't tend to get much beyond 7.5MPa, whereas we achieve a minimum of 20MPa and Narbo Via was 30MPa. You can blast Sirewall with a pressure washer and it will just stay there."

He explains that a typical Sirewall mix will have 9% ordinary cement and just 8% water, or something like half that of a standard concrete mix. Sirewall also is no separate external cladding or interior lining required. "All the materials are basic and local to the site, reducing the environmental costs associated with manufacturing and transport."

Aesthetically, Stewart is pleased with the way the walls' gritty appearance contrasts with both the floor and ceiling of Narbo Via. The internal floor is a polished concrete floating screed cast on rigid insulation over structural hollow core slabs, "with a bit of quartz magic dust thrown over it to make it sparkle". The exposed roof structure is also smooth, being precision-made from precast concrete.

In a less distinctive building, this roof structure might qualify as the main design event, cantilevering out from the walls on all sides. The walls are spanned primarily by seven massive precast concrete beams, H-shaped in section and 1.4m high. "We wanted an exposed and service-free ceiling," says Ridsdill Smith, "so having H-sections allowed us to use the 200mm cavity for service distribution, and also for insulation where this was needed at the building perimeter."

Like most of the precast concrete in the building, the beams were manufactured by Girona-based Planas, each one made in several sections. Planas project manager Lluc Valldosera explains: "Some of the shorter primary beam sections were fabricated with an H-shaped mould, but the larger ones were fabricated in two units and assembled on site. The largest

contains a hydrophobic admixture which, together with the compacted density of the wall, prevents air and water ingress. This means there is no need for expensive corrosion-resistant stainless steel rebar, as required by some rammed earth systems.

"There's a big difference in aggregate too," says Krayenhoff. "Concrete tends to have, say, a 20mm aggregate and a 600 micron sand, but we use the full range in between, depending partly on the granularity of the finish required. Although we can't have organics in the mix – we don't just stick a shovel into the nearest bit of countryside – we can have up to 10% silt and 15% clay, again very different to standard concrete."

He says that the wider range of particle sizes has a crucial influence on the way the mix constituents bond under pressure from tamping. "What we are doing is getting it all to fit together tightly – effectively creating engineered sandstone, but a little quicker than geological processes." Compressing many different sizes of particle together means there is less space between the particles than between sand and aggregate in standard concrete: "It's one reason we are able to use less cement – because there's less of it that's effectively just being used as filler."

In addition to reduced cement and water content, Kreyanhoff claims other environmental benefits for his product: "We can use local products, reducing transport. We can use manufactured rather than scarcer natural sand, and we have also used recyclate or waste products in our mixes. And what you end up with has all the thermal mass benefits of individual beam was 21m long and weighed 22 tonnes, so the full beam with the two pieces assembled weighed 44 tonnes. There were seven of these, plus another seven 18m long, and another 35 smaller units of 12m."

All the units were made from steel moulds, and the mix contained 1% white oxide to achieve the paler shade required. The secondary beams run at right angles to the tall H-beams and span up to 15m between them. These are made from 165 inverted U-shaped sections, typically 15m long, 1.75m wide and 1m high.

Spanning between the "U" section beams are 470 reinforced concrete planks, the majority 7.5m long, 1.35m wide and 60mm thick. "We worked with Planas to design a slight taper into both the primary and secondary beam units to ensure easy striking and a smooth finish," says Ridsdill Smith. "The roof is finished with a structural concrete screed poured on

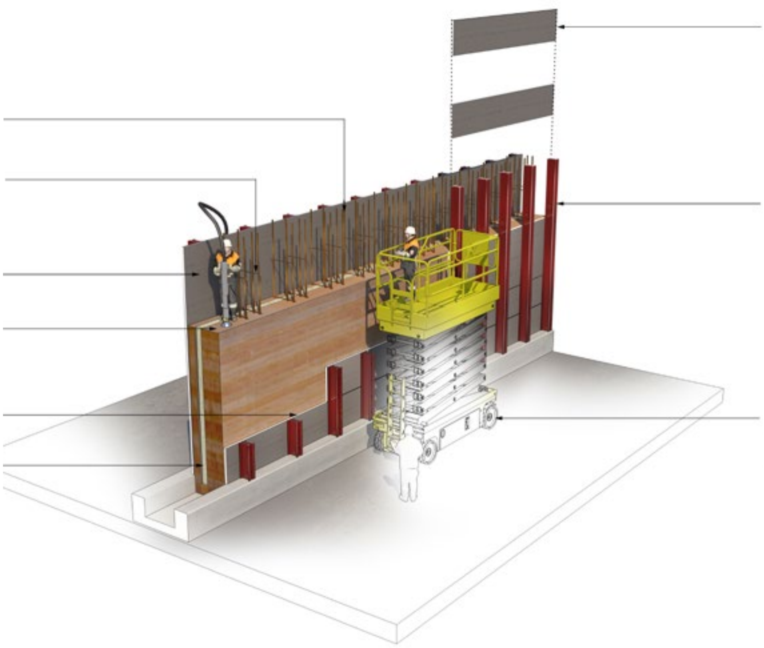
exposed concrete, but as well as a thermal flywheel, you get a humidity flywheel. Sirewall absorbs excess humidity, and releases moisture when the air is dry."

Sirewall's customers also appreciate its acoustic properties: "We did a house for Randy Bachman of the rock group Bachman Turner Overdrive. He had one room with very smooth walls for echoey reverb, and another with a more granular finish for a sound-softening effect."

The system does have limits: it is difficult to tamp if the space above the "pour" is not clear. Nor can rammed concrete flow into quite the small detail that concrete, particularly self-compacting concrete, might be able to. Some detail is possible though, as evidenced at Narbo Via by the creation of a relief map of the Roman Empire on the rammed concrete wall.

Kreyanhoff also concedes that rammed concrete is labour-intensive: "Some years back we compared bespoke house-build costs in North America and found a Sirewall equivalent might cost 15% more – which obviously we think is well worth it."

LEFT
The precast-concrete roof structure cantilevers out in all directions



top of the precast planks. The lateral loads, due primarily to seismic forces, descend from the roof, through the primary beams and into the walls via reinforced cast in-situ connections."

The genius of the Narbo Via design is in no small part down to how this massive, highly visible roof structure works with the similarly substantial and distinctive rammed concrete walls. The low, long proportions of the building conspire to make these vast elements look elegant, as well as reassuringly solid and built to last. The Romans would surely approve. ■

PROJECT TEAM

Architect Foster + Partners
Collaborating architects Jean Capia, Jean-Louis Fulcrand
Structural engineer Foster + Partners, SECIM
Contractor SOGEA
Precast concrete Prefabricats Planas
Rammed earth system Sirewall

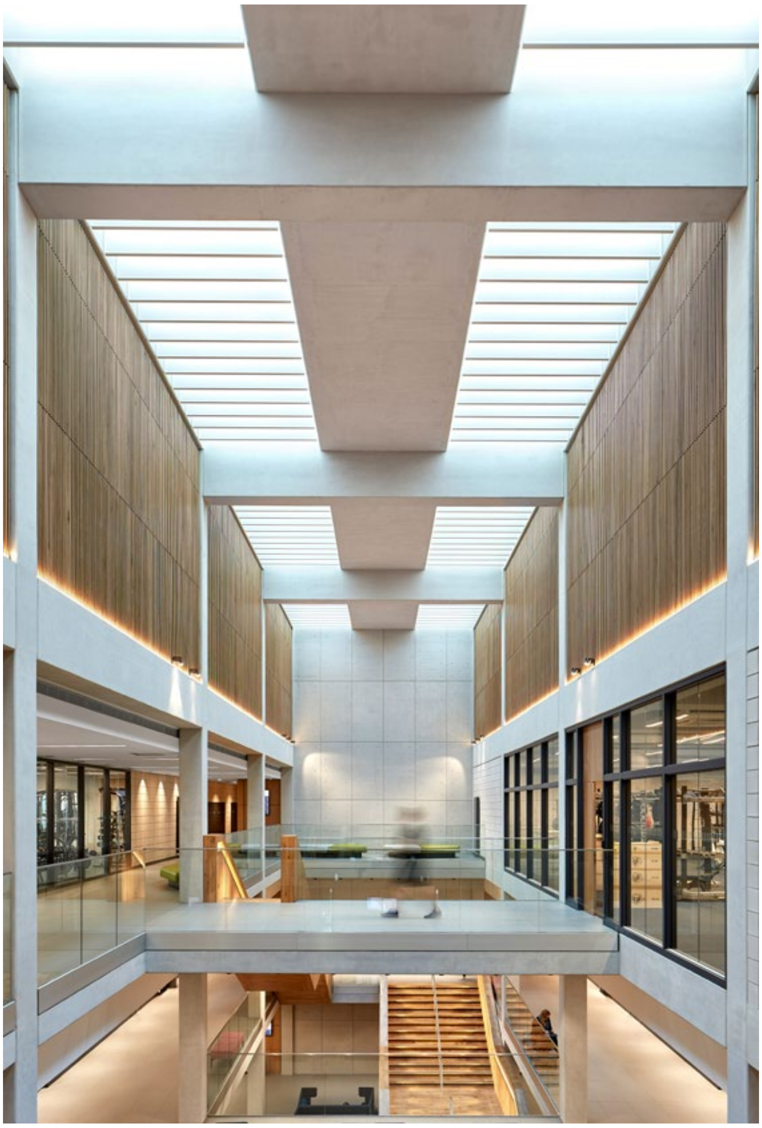
Insulating Narbo Via

Insulation is positioned in 600mm-tall boards and the mix poured in 200mm-deep layers either side. Operatives can then stand astride the insulation to tamp. When the rammed concrete reaches close to the top of the insulation board, horizontal rebar connecting the reinforcement in the outer and inner skins can be ground into the top edge of the insulation, before further insulation board is added and the process repeated. The technique results in a small amount of cold bridging through the rebar, though this is rendered negligible by the thickness of both the insulation and the concrete skins.

A FINE MOSS

University College Birmingham asks a lot from its flagship buildings, not least that they can adapt to a curriculum that changes as fast as the 21st-century work environment. For Moss House, a new teaching and sports facility over three storeys, Glenn Howells Architects achieved total freedom with a structure of repeating in-situ concrete elements.

"I wanted to set up a grid that I could just play with in terms of the positioning of the functional spaces," explains director Simon Pearson. Everything aligns with the grid – even the 100-seat lecture theatres, notoriously inflexible due to their extra height and complex servicing needs, slot into a single storey. "There's no need for downstand beams or additional thickening of the slab, so we had complete flexibility as to where penetrations and services could go. And it let us create stacked spaces with sensitive acoustic separation requirements without having to do any extra work."



Photos: Rob Parrish

PROJECT TEAM

Architect Glenn Howells Architects
Structural engineer Couch Consulting Engineers
Contractor Kier
Precast concrete FP McCann
Concrete frame Thames Formwork

READ THE FULL STORY
concretecentre.com/cq

Photos: Martine Hamilton Knight

ROOTS MANOEUVRE

The Dryden Enterprise Centre at Nottingham Trent University is a building shaped by trees. Not just because its glazed upper storey can feel like a treehouse, surrounded in the canopy of the neighbouring London Planes. But also because its distinctive form, with curving corners, alcoves and overhangs, is a direct response to the roots spreading below.

"The structure had to do something quite clever to dance around the root protection zones," says John Evans of Matlock-based architect Evans Vettori, most notably in a 6m cantilever over the entrance. This required huge upstand beams to be integrated into the flat slab, spanning nearly 6m into the building and 4.5m out to the external terrace. "When it was there in its raw form, before the masonry facade had been installed, it looked seriously imposing – just concrete flying in mid-air," says Evans.

READ THE FULL STORY
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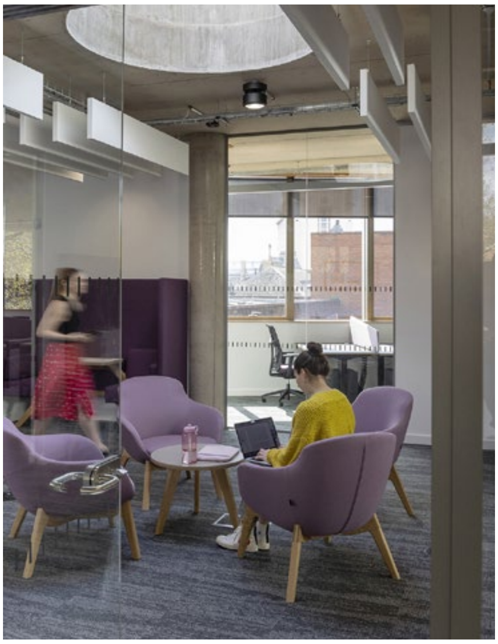

PROJECT TEAM

Architect Evans Vettori Architects
Structural engineer Mott MacDonald
Main contractor Henry Brothers
Precast concrete Evans Concrete

Photos: © Lily Maggs

NOWHERE TO HIDE

At the House on the End in south-east London, architect Hugo McCloud has taken an approach that he describes as "very much raw is more". The detailing had to be scrupulous: "You don't have the luxury of paint or plaster to cover your mistakes. There are no architraves, no skirtings, nowhere to hide junctions. We had to rethink how we were going to construct it."

McCloud chose to use a proprietary fibre-reinforced concrete, which derives its flexural strength from strands of polypropylene and steel. This reduces the embodied carbon of the structure by cutting both the amount of steel and the amount of concrete cover to protect it – the slabs only needed to be 180mm thick and the walls 150mm. The carbon impact is further minimised through the use of 40% GGBS in the mix, and the absence of any other internal finishes.

PROJECT TEAM
Architect 1200 Works
Structural engineer Elliot Wood
Main contractor Altus Construction
Concrete supplier Cemex

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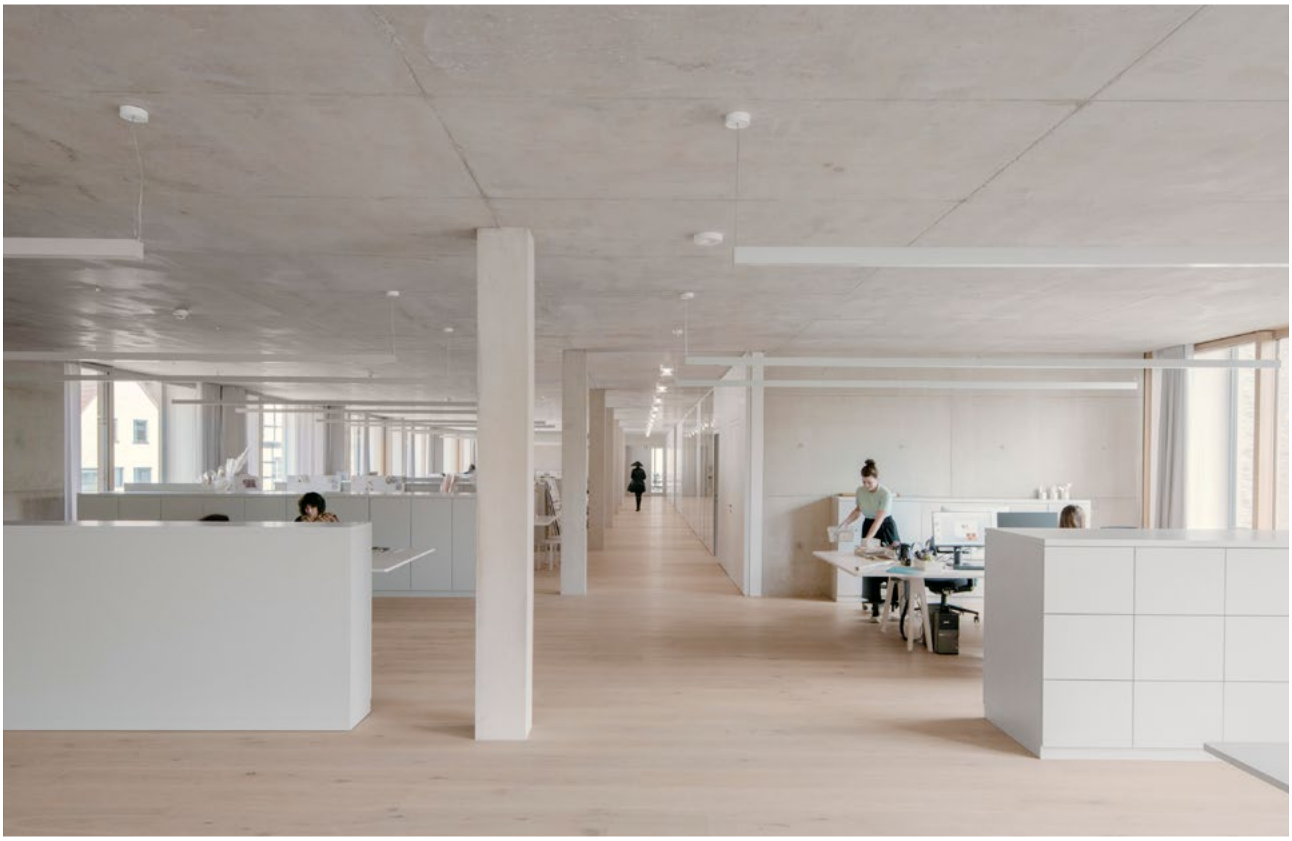


Photos: Simon Menges

READING THE RUINS

PROJECT TEAM

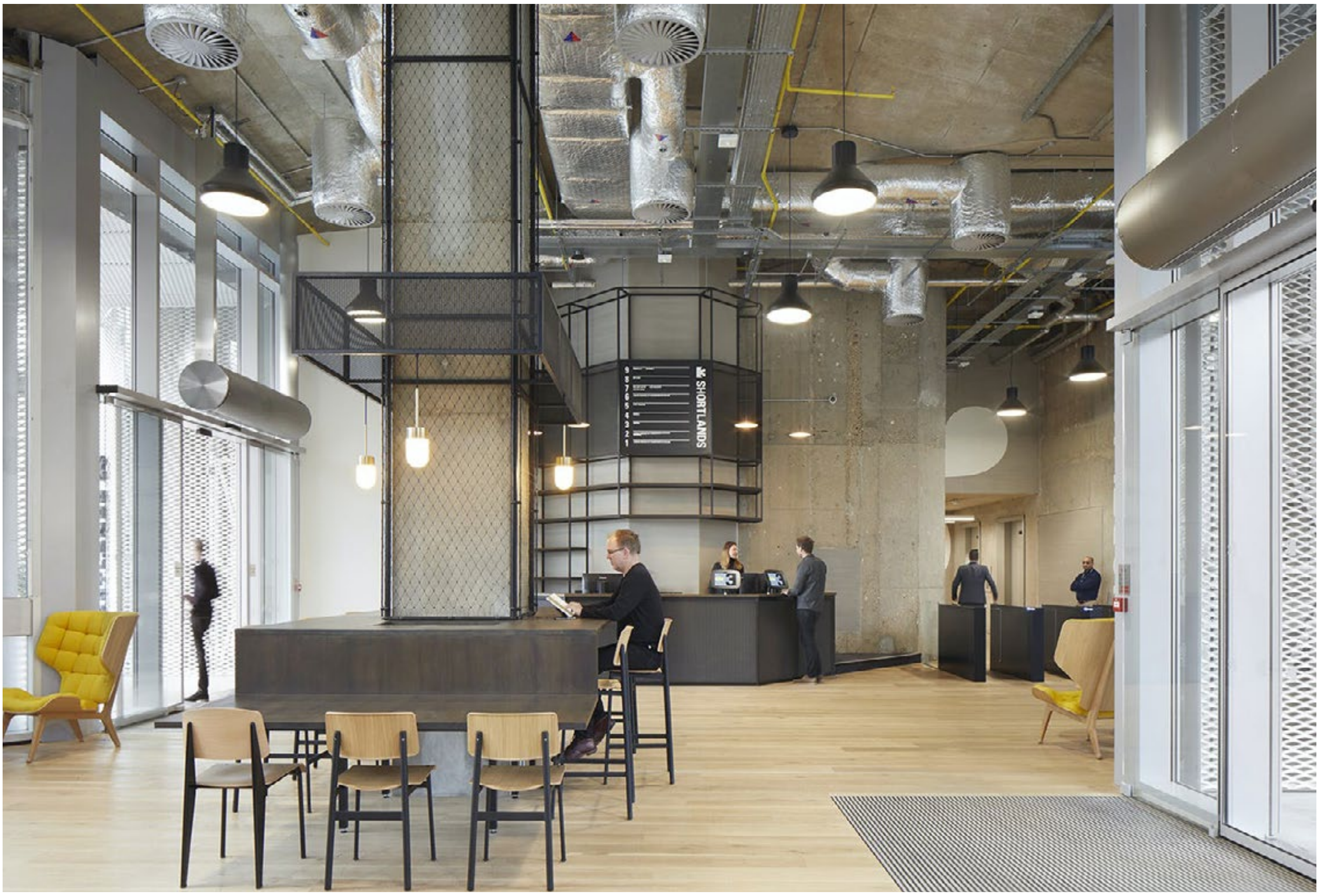
Architect David Chipperfield Architects Berlin

Executive architect Schilling Architekten

Structural engineer Gantert + Wiemeler Ingenieurplanung

READ THE FULL STORY
concretecentre.com/cq

At Jacoby Studios, David Chipperfield Architects has brought a vanished past back to life. When Jacoby, an art material supplier, bought the disused St Vincenz hospital in Paderborn, northern Germany, it wanted to clear the site and build a modern headquarters from scratch. But a process of excavation revealed the limestone-rubble walls of the site's original building, a 17th-century monastery. As with the Neues Museum in Berlin, Chipperfield has used light-toned concrete as a bridge between past and present, flanking the former chapel and sacristy with minimalist offices. The exposed soffits are also integral to the low-energy heating and cooling system. Water from a neighbouring tributary of the river Pader, which holds a near-constant temperature, is used to generate energy by means of a heat pump. For cooling in summer, the concrete ceilings are activated. In winter, heat is supplied via an underfloor heating system.



Circular economy: strategies for concrete buildings

Designers can help shift our throwaway culture to a circular one by extracting the maximum value from building structures, writes Elaine Toogood

There is a growing recognition among governments, businesses and the public that we urgently need to transform our take-make-dispose economy into a circular one, in which resources are kept in use for as long as possible while maximum value is extracted.

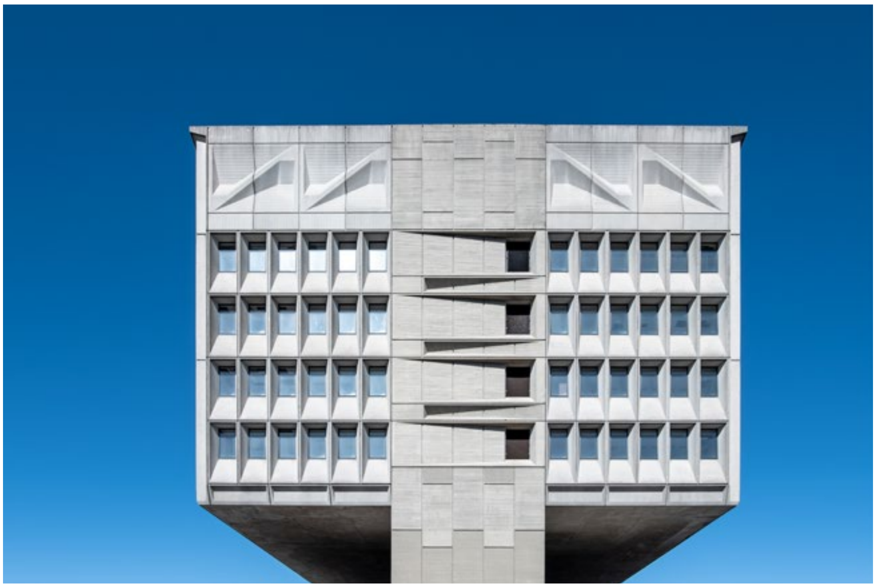
In this way, we can reduce the environmental impact of human activities and the waste that they generate, make our societies more resilient to future shocks and supply issues, and ensure that we continue to meet the needs of future generations while living in balance with the natural systems that we rely upon.

Achieving this will involve significant, sustained change in every part of society – and we need to start now. This article will consider the strategies that designers can adopt to maximise concrete structures' potential in a circular economy, and ensure that they are fit for purpose for a world in which resource use is radically lower and no material is wasted.

Photo: Timothy Soar / AHMM

LEFT
The Record Store in Hayes, west London. AHMM has transformed this 1927 art deco record factory into a modern office building

PREVIOUS PAGE
Fletcher Priest's regeneration of an outdated 1970s office building at 3 Shortlands, west London, included exposing much of the concrete structure



Photos: Pat Krupa / flickr; James Morris

LEFT
Featherstone Young's Ty Pawb in Wrexham reinvents an ageing car park as an arts centre and market

ABOVE
The Pirelli Tire Building in New Haven, Connecticut by Marcel Breuer. This brutalist 1970s office building has recently been reimagined as a net-zero energy hotel by Becker + Becker

Reuse

Reusing a building structure is the most effective way to keep its materials in use for as long as possible and to extract the maximum value from them and the benefits of retaining and reusing concrete frames are increasingly recognised by designers, developers and planners. This may involve expanding and improving an existing building so that it can continue to perform the same function as user needs evolve, as at The Bower in London's Shoreditch where AHMM repurposed two tired 1960s office buildings (CQ 268). Or it might mean using the shell of a redundant building to fulfil a completely different purpose – such as ORMS' conversion of Camden council's old offices into a home for boutique hotel chain The Standard (CQ 270).

This strategy reduces the demand for new materials, and the embodied carbon associated with new development. Retaining the existing concrete in buildings also provides the opportunity to tap into its thermal mass and so reduce operational energy use. For example, at Elizabeth II Court in Winchester by Bennetts Associates (CQ 255), coffered ceilings were exposed and became central to the new heating and cooling strategy.

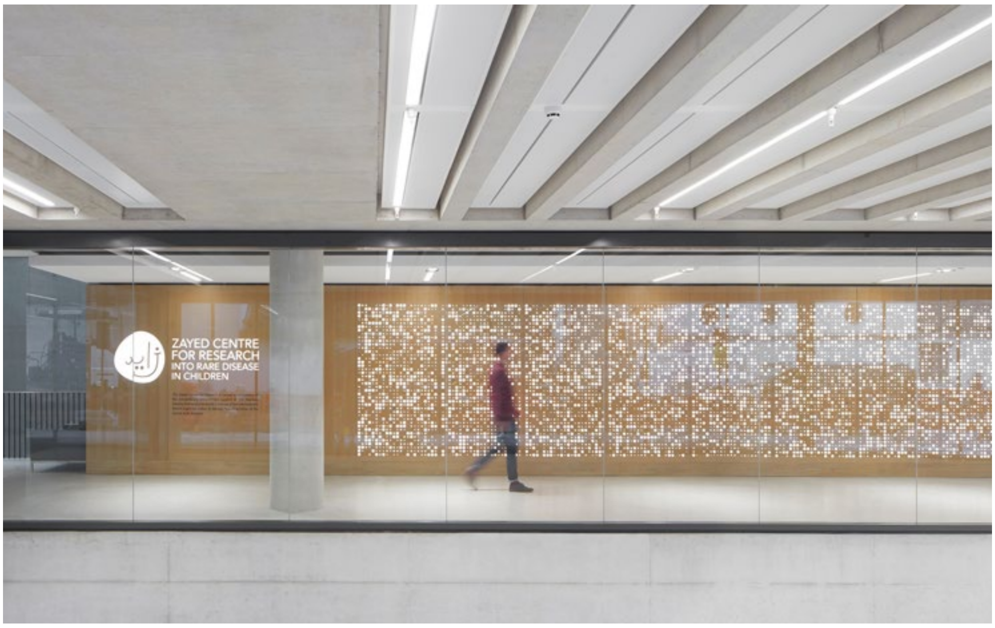


Photo: Hufton + Crow

Design for future reuse

Where a new structure or building is required, this should be designed to optimise future reuse, so embedding good circular economy practice. Here, the durability of concrete is an advantage. According to the design standards for a concrete frame located internally – in other words, in an environment classed as "low exposure" – no additional measures are required to achieve a service life of over 100 years compared to 50. (See BS 8500-1, tables A4 and A5, XC1 exposure class.)

The inherent low maintenance requirements of a concrete structure, and its resilience to fire and the impacts of weather, mean that it can remain serviceable over a long period, with the potential for multiple reuses during its lifetime. The key to optimising this therefore lies not so much in the material itself, but rather in the way that it is designed.

The "long life loose fit" approach to design is well established and can ensure future functionality through consideration of spans, optimum loads, regular grids and generous floor-to-ceiling heights. The many lessons being learned through current retrofit projects will also help inform the future-proofing of today's new buildings.

Design for disassembly and reuse can also maximise the lifespan of both individual components and the building structure itself. This is particularly applicable for parts of a building that are likely to be changed or replaced more frequently, such as fixtures and fittings, but is being increasingly considered for more integral elements such as

ABOVE
At the Zayed Centre in central London designed by Stanton Williams, the use of post-tensioned flat slabs with clear spans and very few downstands will help to enable future reconfiguration

CURRENT RETROFIT PROJECTS WILL ALSO HELP INFORM THE FUTURE-PROOFING OF NEW BUILDINGS cladding. Designing the less permanent layers in this way increases the reuse potential of the underlying structure by making it easier to upgrade it or to strip it back to facilitate an alternative use.

Structural elements themselves can also be designed for disassembly, especially for buildings that have relatively short lifespans. This is an approach that is already taken for precast concrete products, such as stairs and stadium seating, fencing, barriers and paving. For example, the upper tiers of London's 2012 Olympic stadium are fully demountable so that they can be reused elsewhere, though for now they continue to fulfil their original function as the home of West Ham United – a good example of the circular economy hierarchy in practice. In this way, concrete structures should be viewed as a useful resource for future development.

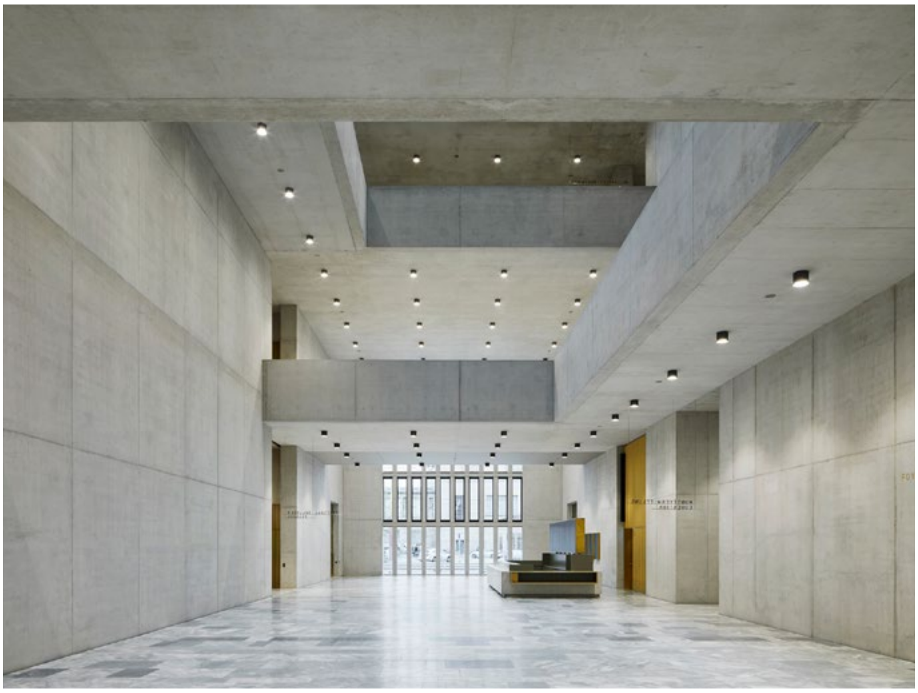


Photo: Noshe

ABOVE
David Chipperfield Architects' Kunsthaus Zurich was built from 98% recycled concrete. In Zurich, to qualify as recycled concrete for use on public buildings, it must contain either 50% recycled concrete aggregate or 25% mixed demolition waste aggregate

Recycling concrete

When concrete does eventually reach the end of its life, it can be recycled. This applies to all concrete, and the process can be repeated again and again in perpetuity to provide a low-carbon resource with a range of applications.

The majority of concrete's volume/mass is aggregates, and when recycled, it becomes aggregate again. Some of this makes its way back into new concrete, but most is used "unbound" as sub-base materials, fill and hard core. Here, one industry's waste is another's raw material. Already, over 90% of the UK's hard construction, demolition and excavation waste, of which concrete is a significant proportion, is diverted from landfill for use in construction.

The UK's geology can provide a long-term supply of low-carbon, local, responsibly sourced natural aggregates for use in concrete. As recognised in the latest version of BREEAM New Construction, this can often prove to be the most sustainable solution. Elsewhere, in countries without this security of supply, there will be a greater need to use recycled aggregates in new concrete and the technical capability to do so is developing (see case study).

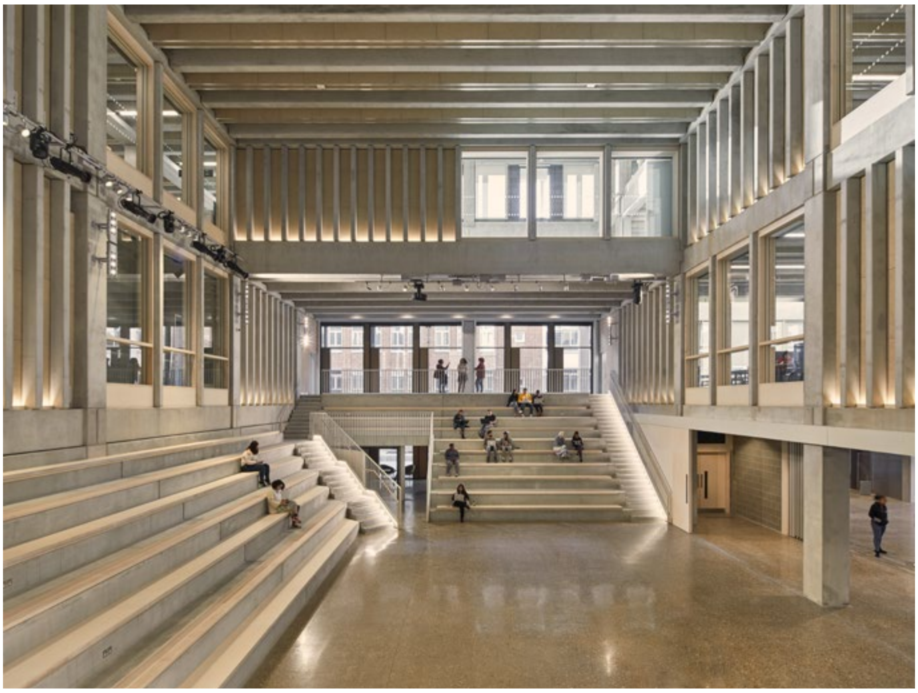


Photo: Ed Reeve

ABOVE
Kingston Townhouse in Surrey by Grafton Architects. Generous open-plan floor plates with long spans and high floor-loading capacity offer long-term flexibility as users' needs change

Concrete's role in reusing other materials

Most concrete contains some recycled material, and each of its principle constituent parts – aggregate, water, cement and reinforcement – can include recycled content. Common secondary cementitious materials such as GGBS and fly ash are, for example, by-products of other industries and the latest data shows that most steel reinforcement made in the UK uses about 96% recycled steel.

As a structural material, quality control and performance are understandably paramount. The allowable percentage of recycled aggregate content varies according to the intended use of the concrete, its location and the durability requirements, but also the type or grade of aggregate. Recycled aggregate (RA) results from the reprocessing of inorganic material previously used in construction, such as masonry rubble. Crushed concrete aggregate (CCA) is a form of RA but principally comprised of crushed concrete.

Typically, lower strength and unreinforced concrete can contain 100% CCA as coarse aggregate permitted in GEN (general concrete) designations. Many other designated concretes can contain up to 20% CCA without special declaration. Higher percentage replacements are technically possible, provided the aggregate is tested to show it meets the required quality. It is worth noting that in comparison with the typically local and low carbon natural aggregates available in the UK, recycled aggregates can sometimes raise the embodied carbon of concrete, particularly where more cement content is required to meet required strengths.

Another source of recycled content is secondary aggregates – by-products of other industrial processes. These materials, such as air-cooled blast-furnace slag and china clay waste, also known as stent, have similar properties to primary or natural aggregates and are commonly used as an alternative fine or coarse aggregate in concrete in some parts of the country.

BELOW
At Resources Row in Copenhagen, architect Lendager reused old bricks by angle-grinding entire sections of existing walls and embedding them into precast-concrete facade panels (see case study)

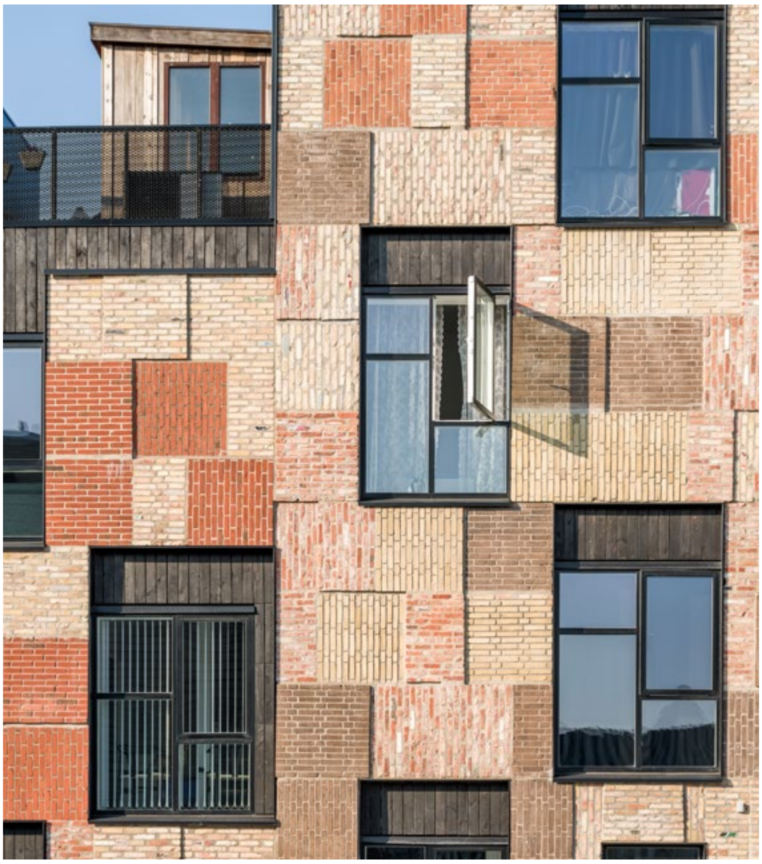


Photo: Rasmus Hjortshøj

Around the world, there are many research projects that seek to use local waste resources in concrete – from coffee grounds and plastics to shredded car tyres or oyster shells. The ability of concrete to "hold" other elements in its surface using aggregate transfer or seeding – well-established processes for embedding material into the surface of concrete – can also facilitate the reuse other waste materials into useful construction products, such as waste bricks in concrete cladding panels (see left and case study overleaf).

With the growing emphasis on circular economy principles, further innovations and examples of good practice will no doubt emerge. ■

▶ Case study: Upcycle Studios, Copenhagen

For its townhouse development in Orestad, Lendager used 100% recycled local aggregate, crushing and processing the concrete on site itself

Photo: Rasmus Hjortshøj

ABOVE
The aggregate for the concrete reuses some 904 tonnes of waste from the construction of the Copenhagen Metro

Upcycle Studios is a terrace of 22 slender townhouses in the Orestad district of Copenhagen. Everything about its appearance indicates that it has been recently completed, from the fresh finish of its staggered concrete frame and blackened timber cladding to the newly planted landscaping. And yet its main construction materials all have a bit of a history: the douglas fir cladding, wooden floor boards and interior wall surfaces are all repurposed offcuts from floor manufacturer Dinesen; the glass for the double-glazing comes from abandoned buildings in North Jutland. And the aggregate for the concrete, which is used everywhere from the foundations to the floor slabs to the roof, is 100% recycled from the surrounding area.

"We wanted to do something unique and sustainable with this project," explains Anders Lendager, founder and chief executive of architect Lendager Group. "Could we take some of the largest waste fractions in the built environment sector and convert them into new resources, within the budget of a rowhouse project?"

For this project, he was able to tap into an abundant local waste stream. The Cityring extension for the Copenhagen Metro has been described as the country's largest construction project since the 1600s, incorporating 17 new stations and 15km of new tracks. Some 904 tonnes of waste concrete – mainly demolition debris and unused precast sections from the construction of the tunnels – now resides in the walls, floors and foundations of Upcycle Studios.

When Lendager sought the advice of local concrete suppliers, he found that they were reluctant to use more than 20-40% demolition waste, especially given that they couldn't be sure of what it contained. But he had set his ambitions higher than that: he wanted to see if it was possible to use only recycled aggregates. This was partly because in Denmark, unlike in the UK, virgin aggregates are a dwindling resource, while the country produces more than 1 million tonnes of concrete waste each year. He also wondered if there was a way of using this waste close to its source, avoiding the negative impacts associated with transporting it, and retaining or even enhancing its value. "We wanted to convert this waste into a material that's purposeful and beautiful. That's very important."

So he set up his own operation for crushing and processing the concrete, buying a mobile concrete plant, and putting together his own team. The crushed concrete was graded and cleaned on site and mixed with cement and 20-30% fly ash (a standard constituent of concrete in Denmark). The results were immediately encouraging: "When we learned how to control the process, we made excellent concrete with 100% recycled aggregate – actually stronger than we would usually buy."

The concrete was certified as C25/30 strength in accordance with DS / EN 206-1: 2000, and the characteristic compressive strength after 28 days ranged from 35.7-46.9MPa, more than matching virgin concrete in the same strength class. Lendager suspects that unaccelerated cement from the recycled aggregate helped to add strength to the new mix.

In all, 837m^3 of upcycled concrete was cast in the construction of Upcycle Studios, contributing to a 32% reduction in embodied carbon, according to a lifecycle analysis carried out by developer NREP .

But perhaps Upcycle Studios' true significance lies in the way that it reconstituted more than 900 tonnes of waste into an architecturally valuable asset. This in turn helps to make the recycling process more economically viable – NREP's analysis suggests that optimised production costs are slightly higher than for a benchmark standard concrete.

Lendager has subsequently used its 100% recycled aggregate on the Pelican self-storage facility, also in Copenhagen, again sourcing the raw demolition waste locally. This time, however, the source was an 80-year-

BELOW
In all, 837m^3 of upcycled concrete was cast in the construction of Upcycle Studios

Photo: Rasmus Hjortshøj

old medicine factory – a much lower grade than the high-quality concrete used for the metro. They applied the same technique, crushing, mixing and casting the concrete on site to make 3,000m^3 in total, to the required strength. "The floors needed to take extremely high loads," explains Lendager "It was a big success and showed that we could use this kind of waste too." The company is now using the same approach to cast the slip-form core of an 80m-high residential tower.

It has conducted other experiments in the circular use of concrete too. At the Resource Rows housing scheme in south Orestad, the practice has come up with a novel take on brick slips, reusing old bricks by angle-grinding entire sections of existing walls and embedding them directly into 3m^2 modules of precast concrete. This solves a problem with reclaiming modern bricks: since the 1960s, the cement mortar used in Denmark is harder than the actual bricks so is extremely difficult to remove. It also lends a unique patchwork aesthetic to the new homes (see page 34), as well as saving 500g of carbon per brick. "We had 1m^2 sections of brick that the precast factory put into the concrete to create different patterns," says Lendager. To get the finish mortar right on site, he set up his own bricklaying company: "To realise these ideas I have to be the circular connector between different partners, covering the holes in the supply chain."

Resource Rows also contains an ingenious example of direct reuse: a huge double T beam that Lendager lifted from a disused factory nearby and craned in to create a high-level footbridge between two blocks. "Kudos to the engineers for calculating the load of the beam," says Lendager. "We didn't have the budget for a bridge but because we could use this one for free, we could connect the roof gardens. Now you can walk across and meet your neighbours on the other side." ■

ABOVE
The staggered plan increases privacy between the 22 terraced townhouses

Photo: Rasmus Hjortshøj

FINAL FRAME: SHIROIYA HOTEL

Architect Sou Fujimoto has gutted a 1970s hotel in Maebashi, Japan, removing the walls and floors and exposing the rough concrete surface of the original structure to form the centrepiece of a new design hotel. This four-storey atrium, criss-crossed with concrete beams, houses the reception, restaurant and lounge, as well as an installation by artist Leandro Erlich. Called Lighting Pipes, this was inspired by the approach Fujimoto took to uncovering the concrete structure. "The pipes are a symbol of the water pipes that are always hidden inside walls and go through all buildings as veins of fluids," Erlich says.

Photo: Katsumasa Tanaka