Designed by BIG, the CityWave office complex in Milan is being built with 90,000m^3 of concrete made with calcined clay based cement supplied by Holcim. This has reduced the carbon footprint by 54% compared with CEM I

Photo: Archweb / Martino Sanna

Decarbonising cement is a key lever for reducing concrete's carbon intensity. Andrea Charlson looks at the options available right now, and what's on the near – and distant – horizon

HOW LOW CAN WE GO?

Portland cement is the magic glue that binds concrete together, and allows it to set, harden and strengthen. In terms of performance, it's a wonder material – which means that finding anything that is as good is very difficult. It is however responsible for around 97% of the carbon intensity of concrete, while making up only 10-15% by weight. That's why much research has focused on exploring ways to decarbonise it, from supplementary materials and alternative chemistry, to process efficiency improvements and capturing carbon.

While nothing yet available is a like-for-like replacement for Portland cement, there is very strong field of products that can work together to do almost the same job. With any change in composition, there will be implications for strength, placement and durability that designers must bear in mind, as well as the potential for different aesthetic effects too. Looking further into the future, there are also experimental products in development in labs around the world that promise radical carbon savings through a range of different solutions, while carbon capture and storage is beginning to be implemented at scale. So how low could the carbon intensity of concrete feasibly go?

SCMs

It's possible to reduce the carbon intensity of standard structural concrete today by 40-50% very easily, by using supplementary cementitious materials (SCMs) in combination with Portland cement.

The longest established are ground granulated blast furnace slag (GGBS) and fly ash. Current British standards also permit the use of limestone fines and calcined clays. All have different properties, carbon intensities, and maximum and optimal cement replacement levels (see table, overleaf). Since 2023, it's also been possible to specify SCMs in combination, giving specifiers more flexibility and more potential routes to carbon reduction targets. Finding the lowest-carbon concrete for a specific application involves balancing carbon, supply chain availability, the behaviour of the fresh concrete, and long-term strength and durability.

Under current standards, the maximum level of cement replacement is 95%, using GGBS, or 65% using GGBS in combination with fly ash, calcined clay or limestone, although this will only be appropriate for very specific applications, such as groundworks.

Why can't SCMs replace all of the Portland cement? It comes down to chemistry. Portland cement's uniqueness lies in the way it reacts with water, kicking off a sequence of chemical reactions that bind the cement and aggregates together into hard, durable concrete.

SCMs work in a similar way, but they need something to kickstart the reaction, which is the role that Portland cement usually plays. Most of the replacements are chemically very similar to Portland cement, mainly silicates and aluminates. The missing ingredient is calcium. Fly ash and calcined clays don't react when mixed with water, but as soon as calcium hydroxide is present, produced by the hydration of cement, they will set hard.

Evolution of SCMs

Traditional SCMs use by-products and waste from declining industries, so finding alternatives is a major research focus. Transition materials like GGBS are still very valuable for carbon reduction while new supply chains are developed, but it's important to use them efficiently.

Fly ash from burning coal is also a transition material – but recovered fly ash is a potentially very abundant source. Because of its lack of reactivity, fly ash will sit inert for years. The UK Quality Ash Association estimates that at least 100 million tonnes are stockpiled at the UK's former coal-fired power stations, and is working with Dundee University to understand its characteristics and performance in concrete.

There is also growing interest in using calcined clay as an SCM in concrete, and research has identified many potential sources within the UK that could be suitable for calcination, including from quarry and manufacturing waste. It has already been used in in-situ concrete at a commercial scale in both infrastructure and buildings. Industrial-scale trials are underway to make lower-carbon paving and larger precast concrete elements.

"IT'S POSSIBLE TO REDUCE THE CARBON INTENSITY OF STANDARD STRUCTURAL CONCRETE TODAY BY 40-50%"

Another promising waste stream under consideration is recycled concrete fines (RCF), a by-product from crushing concrete aggregate from demolition waste. A recent research project produced and validated a range of cement blends and concretes using RCF sourced from demolition processing sites in the London area. So far, strength and durability tests demonstrate interchangeability between limestone and RCF. The results will be submitted to the British standards committee for review and potential inclusion in BS 8500.

Performance enhancers

Producers are also starting to supplement SCM-cement combinations with additives that change the composition of concrete in other ways. For example, adding graphene may increase strength, which could ▶

Visualisation: Fereday Pollard

Right: Visualisation of a prefabricated bridge designed by Fereday Pollard for the Lower Thames Crossing, on which National Highways is targeting a 70% reduction on baseline emissions. The BSI Flex 350 code of practice has been incorporated into the concrete specification to assess lower-carbon alternatives to Portland cement, including trials of alkali activated binders for the diaphragm walls

HOW DO SCMs COMPARE TO PORTLAND CEMENT?

	Portland cement / CEM I	GGBS	Fly ash	Limestone fines	Calcined clay	Recycled concrete fines
What is it and how is it made?	Limestone is heated in a kiln to 1,450°C to form clinker, a chemical process that releases CO_2. The clinker is then ground with c.5% gypsum	Produced by grinding granulated blast furnace slag, a by-product of blast furnaces that produce iron for steel production	A by-product of burning coal in coal-fired power plants. Facilities to process fly ash recovered from stockpiles are in development	Limestone, a natural material available across the UK, is quarried and ground into a powder	Clay, which can either be extracted or recovered waste from quarries or manufacturing processes, is heated to around 850°C	Fine residue that makes up 10-35% of concrete construction waste, or waste concrete that has been crushed and ground
Indicative embodied carbon ($kgCO_2e$/tonne)	840	155	22	44	48-274	0-0.21
Maximum replacement level (under EN 197)	n/a	95%	55%	20%	55%	35%
Optimal/typical replacement level for best performance	n/a	45%	30%	15%	30%	15%
How does it affect the properties of concrete, compared to CEM I?	n/a	Improved durability, lower heat of hydration, slower strength gain, reduced abrasion resistance, lighter colour	Reduced water demand, improved consistency; slower strength gain; darker colour	Supports the formation of hydration products, improving early strength gain of other SCMs	High chloride resistance, slightly higher carbonation in low-strength mixes; potentially pinker in colour	Equivalent to limestone in terms of strength development, setting times and water demand
Can it be specified under BS 8500?	Yes	Yes	Yes	Yes	Yes	Anticipated in next revision

mean less cement is required to reach the same strength classification. A pilot project to make railway sleepers for the Global Centre for Rail Excellence demonstrated that adding a graphene-based admixture enabled a cement reduction of around 10%.

Other additives include biochar, produced by heating biomass so that it decomposes into a stable, carbon-rich product. When added to concrete, this can improve workability and water retention and reduce shrinkage. It also means the carbon is permanently locked in the structure, potentially lowering carbon intensity from the other side of the balance sheet, through sequestration.

“IN NORTH WALES, HEIDELBERG MATERIALS IS CONSTRUCTING A CCS PLANT THAT WILL CAPTURE NEARLY ALL OF THE EMISSIONS FROM THE CEMENT KILN”

Producers are also experimenting with injecting CO_2 directly into fresh concrete, where it speeds the hydration process. Heidelberg Materials, which has trialled this technology at its Greenwich plant in south-east London, says this reduces the cement needed in ready-mixed concrete by an average of 5%.

Alternative binders

Different chemical pathways to make concrete that use little or no Portland cement are evolving. These alternative binders are proprietary products and not yet included in BS 8500, but some may be specified via the BSI Flex 350 standard. This allows novel mixes, as long as performance testing has demonstrated that they can meet the required criteria and that the constituents are covered by an existing standard.

One example is alkali-activated cementitious materials (AACMs), also known as geopolymers. These are made by activating an SCM such as GGBS or fly ash with an alkaline solution, though future generations will probably be based on calcined clays. Manufacturers claim the embodied carbon of geopolymers can be up to 85% lower than Portland cement.

Other alternative binders that can be assessed using Flex 350 include calcium sulfoaluminate or belitic cements. These are made from similar raw materials to cement, but via a chemical sequence that takes place at lower temperatures, with fewer process emissions. Manufacturers report carbon reductions of about 20-40%. It should be noted that all of these solutions are currently less commonly available in the UK.

Moving into the realms of frontier chemistry, there is a diverse group of products that rethink the process of making concrete completely. These include cements based on magnesium, rather than calcium, and even bacteria.

It is still too early to know which of these innovations will be able to scale up, and whether any of them will be technically equivalent to Portland cement.

Zero-carbon cement

As for Portland cement itself, the prospect of zero-carbon clinker is a step closer – last June, Heidelberg Materials' Brevik cement plant in Norway became the world's first to be fitted with industrial-scale carbon capture and storage (CCS). Now operational, it will capture 50% of the plant's annual emissions and store them permanently under the North Sea.

Heidelberg Materials is going further at Padeswood in North Wales, constructing a CCS plant that will capture nearly all of the emissions from the cement kiln, as well as the emissions from its own combined heat and power plant, to make near-zero cement. It is expected to become operational in 2029.

This represents a major investment by both the private and the public sector, and an essential one for hard-to-abate sectors like concrete. But exciting as zero-carbon cement will be, it doesn't mean specifiers are off the hook. Initially, quantities will be limited as the technology scales up.

In the net-zero future, the best strategy for specifying concrete will be the same as it is today: take advantage of every possible route to lower its carbon intensity. It's just that the options for how to achieve this are likely to be wider. ●

Andrea Charlson is senior sustainability specialist and circular economy lead at The Concrete Centre

WHICH SCM? COMPARING CARBON AND STRENGTH

To determine the lowest-possible carbon concrete for a particular application, we have to compare both embodied carbon and performance. One of the most significant characteristics is the strength of the resulting concrete.

The Re-C3 project looked into the potential of reclaimed calcined clays, and found that mixes with 30% calcined clay were equivalent in strength to mixes with 36% GGBS. The optimal replacement level for calcined clay on its own is 30%, compared to up to roughly 45% for GGBS. But adding limestone enables a higher proportion of cement replacement: a three-component mix with 30% calcined clay and 15% limestone fines was only slightly lower in strength than a mix with 45% GGBS (see table).

As the carbon intensity of Portland cement decreases – through fuel switching, energy efficiency and carbon capture – the relative carbon intensity of SCMs will become more significant. But right now, it doesn't matter which one is used because all of their embodied carbon values are much lower than Portland cement. The best approach is to specify a carbon target and a performance category, and allow the supplier to find the best way to meet it based on their technology and supply chain.

Binder composition	Compressive strength at 28 days (MPa)	Embodied carbon ($kgCO_2e/m^3$)
30% calcined clay	54.5- 75.5	205-215
36% GGBS	57	202
30% calcined clay + 15% limestone	46.5-56.5	164-187
45% GGBS	58.5	181

Source: Re-C3 project

Right: The 100m-tall absorber at Heidelberg Materials, CCS plant in Brevik, Norway. Amine-based technology will separate CO_2 from flue gas, capturing about 400,000 tonnes of CO_2 per year

Photo: Heidelberg Materials