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Knowledge

The Green Construction Board

Low Carbon Concrete Routemap

Setting the agenda for a path to net zero

Low Carbon Concrete Group
The Green Construction Board

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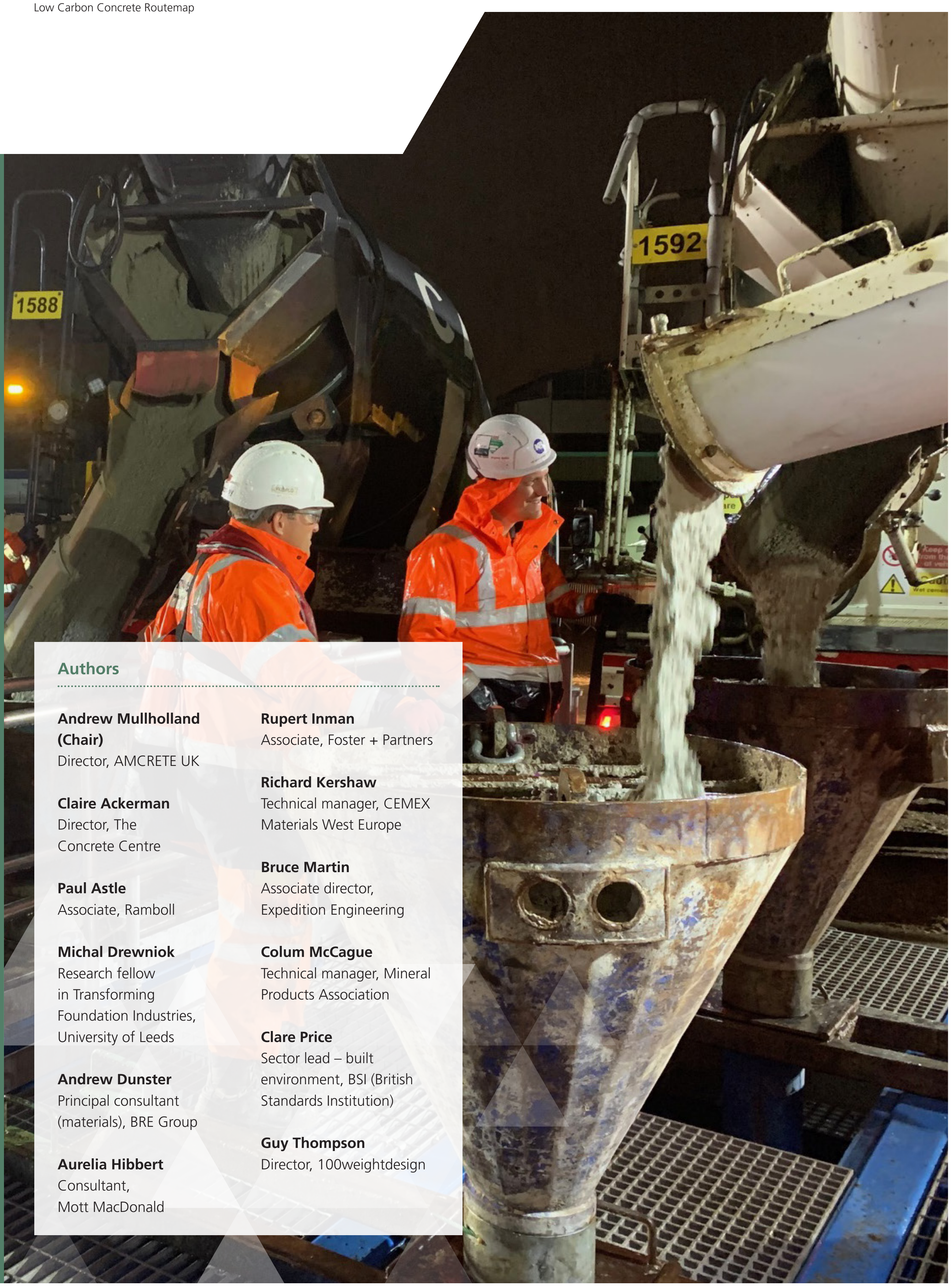

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Foreword

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As the world digests the outcome of last November's UN Climate Change Conference (COP26), it is clear that the construction industry must do everything it can to minimise carbon emissions.

Part of this is to ensure that the built environment is constructed in such a way that in-use emissions are minimal, but it is also necessary to minimise the impact of the construction materials themselves. This Low Carbon Concrete Routemap is an urgent part of the overall strategy to reduce carbon emissions.

Concrete is the most ubiquitous of construction materials. In the UK it accounts for approximately 1.2% of greenhouse gas (GHG) emissions, although globally the cement production GHG emissions associated with concrete utilisation could be as high as 4.0%-5.0%.

As we aim to build back better in the post-Covid world, we need to work even harder to reduce or eliminate carbon from the assets we seek to construct across all sectors.

This Routemap can be considered not just as a comprehensive guide to reducing the carbon emissions associated with the construction industry, but also as a unique document in itself – never before have we been able to assemble such a wide range of independent experts working together to tackle this, each of whom has volunteered their time willingly. They represent a full cross-section of the value chain involved in specifying, designing, constructing and supplying materials for buildings and infrastructure.

The Routemap sets out recommendations and actions to drive out carbon from concrete. It has been published jointly by the Green Construction Board and the Institution of Civil Engineers to ensure ongoing ownership, commitment and drive.

I recommend this Routemap to you, the reader, and invite you and your organisations to embrace it and become involved in making it a reality.

Let's truly build back better.

Low Carbon Concrete Routemap

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Introduction

Andrew Mullholland
Chair, Low Carbon Concrete Group

The challenge before us is as clear as it has ever been, and with that challenge comes the realisation that we must meet it head-on with all of the tools available to us, without surrendering that responsibility to the generations that follow us.

As we publish the Routemap, it is important to understand that this document does not simply represent an assembly of good ideas – rather, the strategies set out in each strand are signposts for a cooperative interaction between science-based technology, available materials, skills, knowledge and approaches to design and delivery that creates an enhanced combined effect.

The Routemap sets out its proposals across seven strands, followed by a section identifying the 'next steps' with a timeline for improvements. The legislative focus is on 2050; however, our aim is to have in place a new norm by 2035 by adopting a staged approach beginning immediately.

There is no one silver bullet to address carbon reduction in the construction industry and it remains the case that some technologies are not yet mature enough to contribute to meaningful reductions until beyond 2035. Therefore, the focus of the Routemap is on demonstrating what we can use today in terms of materials, how we can develop better construction methods and how we can utilise clever design approaches, as well as what actions are required and by when to simplify the specification of cement and concrete.

The work of the Green Construction Board's Low Carbon Concrete Group (LCCG) is not complete – in fact, it is probably only just beginning as the Routemap will remain a live document that is subject to annual updates as we measure the progress we make in decarbonisation, as well as look to adopt new or better means of carbon reduction. Such is the size and complexity of the task before us that it would be impossible to include all topics surrounding decarbonisation in this document. As such, this Routemap complements other publications, such as PAS 2080 and the Mineral Products Association (MPA)'s UK Concrete and Cement Industry Roadmap to Beyond Net Zero.

The LCCG's efforts and the contributions of its members exemplify the collaborative approach required. All that you read on these pages has been presented, challenged and justified as appropriate and realistic means of significantly reducing our combined carbon impact.

It has often been the case that perceived barriers such as standards have been cited as reasons why a certain approach cannot be adopted – but as the Routemap explains, most of these barriers can be considered merely as hurdles to get over. It is no longer acceptable to remain rigid in our business-as-usual models – we are the custodians of our future and that of future generations, so now is the time to eliminate fragmentation, push convention and commit.

One final word from me as the chair of the LCCG – I am extremely proud of the work that has gone into this document over the past 18 months and what I know and understand now is a far cry from what I knew at the beginning. This Routemap has been shaped by the members of the LCCG who came together because they wanted to make a difference. Their views, experiences and expertise together represent a true consensus of all of those involved in construction activities – which should provide you, the reader, with the confidence that what we propose is more than possible.

Low Carbon Concrete Routemap

Executive summary

The concrete challenge

Concrete is a composite and is the most used material on the planet. It is strong, durable and the constituents are abundant almost everywhere. We rely on many forms of concrete each day, from the pavers that we walk on to the high-performance structural concrete used in our tall buildings and infrastructure. It is an incredible material that has supported the development of our societies and improved the quality of life for billions of people.

Concrete is made of three main constituents with typical mass proportions as follows:

- Aggregates (gravels and sands) 70%-85%
- Cement (the active ingredient) 10%-20%
- Water (which reacts with the cement) 3%-10%

Up to 90% of the greenhouse gas (GHG) emissions associated with the production of concrete are down to the cement

Conventional Portland cement is made by heating limestone and clay and grinding the resulting material, known as clinker, into a fine powder. The process of heating and decomposing the limestone releases about 0.86kg CO_2e for every 1kg of cement produced. This is partly down to them chemical process as well as the fuel used in heating the limestone[1].

UK CEMENT CONSUMPTION

11.7Mt UK cement consumption per year[2] → **9Mt** CO_2e per year[3] → **1.2%** UK GHG emissions (2018)[4]

4%-5% global GHG emissions (2018)

Concrete
90Mt (37,500,000m³) per year[5]

10Mt CO_2e per year

Equivalent to emissions from **8 million** cars (assumes 125g CO_2e/km and 10,000km/year)

\+ **Other cement-based products**
Screed, render, mortar, architectural items, ground improvement techniques, furniture, etc

Concrete accounts for about 25% of embodied carbon of construction in the UK[6]

The challenge we face is how to continue to benefit from using concrete when the active ingredient is such a significant source of greenhouse gas emissions

1 MPA (2019) Factsheet 18, Embodied CO_2e of UK cement, additions and cementitious material
2 European Ready Mixed Concrete Organisation – ready-mixed concrete industry statistics 2018, Table 2a
3 Based on final UK greenhouse gas emissions national statistics. UK Government document, BEIS, 2021 and industry statistics
4 Based on UK's carbon footprint 1997-2018. UK Government, Defra, 2021 and consumption emissions using refs 2 and 3
5 MPA (2020) UK Concrete and Cement Industry Roadmap to Beyond Net Zero
6 UK Green Building Council's Net Zero Whole Life Carbon Roadmap for the Built Environment (2018 data)

A zero-carbon future

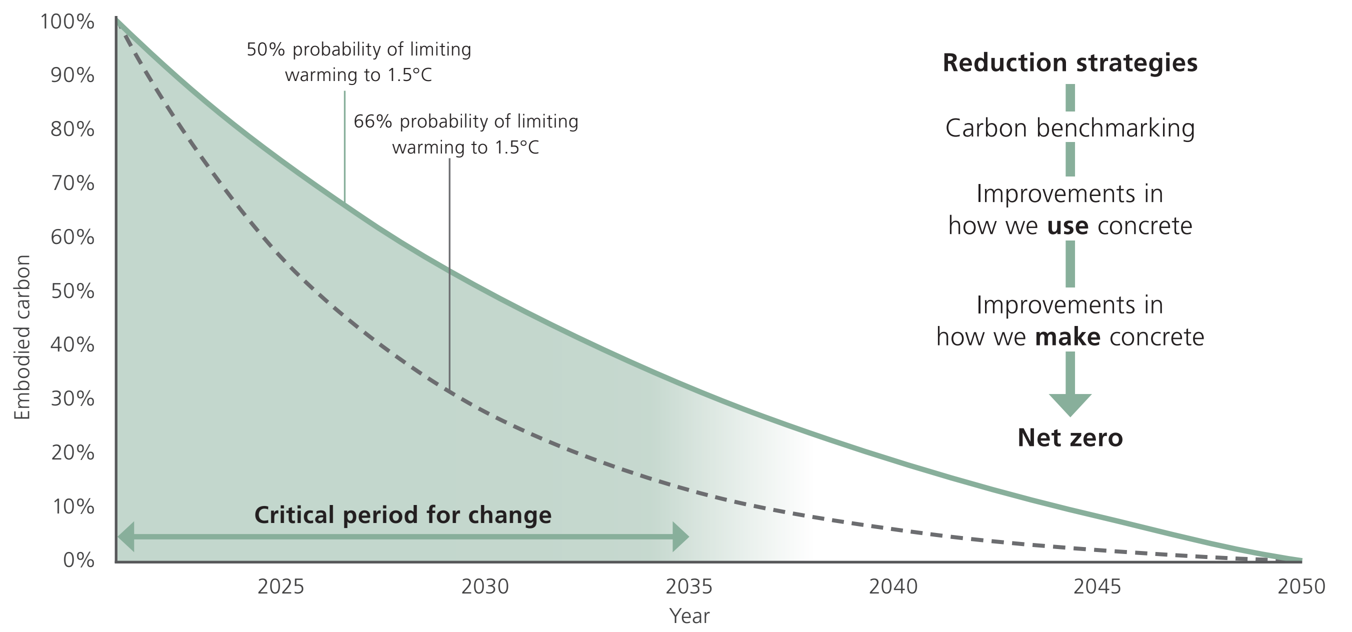


Fig 1: Idealised reduction rate for embodied carbon in concrete

The Low Carbon Concrete Routemap is focused on structural concrete used in the UK, although much of the guidance is applicable to other sectors in the construction industry and other regions. The document has seven strands of knowledge that must be developed concurrently to reduce the embodied carbon of concrete. The eighth strand provides a summary and framework of opportunities for further engagement. Every strand will require continued research and development to meet the target of net zero by 2050, with the next 10-15 years being critical to scale up new technology and approaches. The first strand covers the continuous process of accurately benchmarking concrete. Strands 2, 3 and 4 are related to the use of concrete. Strands 5, 6 and 7 are related to the production of concrete. Below is an introduction to each strand and the Low Carbon Concrete Group Routemap:

1 DEFINING AND BENCHMARKING THE CARBON IN CONCRETE

A zero-carbon future for concrete can only be mapped out from an accurate starting position. The LCCG has been working with industry to establish appropriate boundaries to classify concrete by embodied carbon. Further work is required to build on this data and establish a simple rating system for carbon in concrete.

ACTION:
Cross-industry efforts to standardise measuring, reporting and benchmarking of the greenhouse gases associated with different types of concrete.

EXAMPLE OF AN EMBODIED CARBON RATING CERTIFICATE

A++	<63
A+	63-121
A	121-172
B	172-210
C	210-242
D	242-280
E	280-331
F	331-389
G	>389

B 195kg CO_2e/m^3

All figures kg CO_2e/m^3
Bounding figures are only applicable to specified strength class

Data:

Concrete mix	Option A
Cube strength, f_{cu}	35 MPa
Cement type	IIIA
SCM	GGBS
Cement content	300kg/m³
w/c ratio	0.65
SCM content	40%
Aggregate size	20mm
Admixtures	Superplasticiser
Slump class	S4

STRENGTH *C28/35*

Executive summary

Using concrete

Strands 2, 3 and 4: Best practice in using concrete

There is huge variation in how concrete is used and specified. It is possible to significantly reduce the carbon intensity of concrete through better design, specification and construction practices – this requires a focus on carbon and the necessary guidance and support.

ACTION:

A coordinated approach between the client, industry and government to optimise the benefits of concrete for carbon. Embedding the requirement to address CO_2e within the whole supply chain.

2 KNOWLEDGE TRANSFER

Knowledge transfer is crucial to addressing barriers and accelerating the use of lower-carbon concrete. There needs to be clear guidance on how to specify, design and use lower-carbon concretes within the existing and emerging standards, challenging them if necessary, as well as a better understanding of performance and how and when to engage with stakeholders. There needs to be an agreed approach to the embodied carbon values used for concrete constituents. Coordination between institutions and trade bodies is important to ensure guidance is effective.

3 DESIGN AND SPECIFICATION

The use of concrete must be optimised within the design process regardless of its carbon intensity. Guidance that demonstrates how material savings can be made through efficient design is required. The specification of concrete and concrete products must include appropriate carbon intensity, and specifiers need to understand how they can work to reduce it while meeting other performance requirements.

4 SUPPLY AND CONSTRUCTION

Consideration must be given to how a concrete will be produced and whether in-situ or precast concrete offers greater potential carbon savings. The performance requirements, installation method and project-specific logistical constraints should all be considered during early collaboration between the concrete producer and the project team. There must also be a clear plan for verification of the material to avoid waste or an excessive testing regime.

ENVIRONMENTAL PRODUCT DECLARATION
as per ISO 14025 and EN 15804

Owner of the Declaration	British Precast Concrete Federation
Programme holder	Institut Bauen und Umwelt e.V. (IBU)
Publisher	Institut Bauen und Umwelt e.V. (IBU)
Declaration number	EPD-BPC-20170148-CCD1-EN
Issue date	11/12/2017
Valid to	10/12/2022

UK manufactured Precast Concrete Ground Beam
Produced by members of the British Precast Architectural and Structural (BPAS)
a product group of the British Precast Concrete Federation

Institut Bauen und Umwelt e.V.

www.ibu-epd.com / https://epd-online.com

mpa British Precast Architectural & Structural

Left: Precast concrete ground beam environmental product declaration (EPD)

Above: Concrete placement using a concrete pump

See Glossary, page 74, for definitions of the terms used on these pages.

Making concrete

Strands 5, 6 and 7: Best practice in making concrete

There is also huge variation in how concrete is produced and the constituents used. While the engineering performance of concrete is standardised, its carbon intensity is not and there are many opportunities using existing technologies as well as new approaches.

ACTION:

Concrete industry to promote the use of best practices and new technologies in concrete mix design, batching and production to realise consistent and lower-carbon concrete. Government support will accelerate this process.

5 OPTIMISE EXISTING TECHNOLOGY

Within current standards and practice, it is possible to produce concretes that have lower embodied carbon. To achieve this, stakeholders need to work together to ensure that all options for cement types are considered. In addition, the project team must work to ensure that the cement content is optimised for a given cement type. Collectively this optimised approach will realise significant carbon savings over typical practice. It must also consider the limited availability of the most common currently available SCMs and seek to use them as efficiently as possible to reduce carbon emissions.

6 ADOPTING NEW TECHNOLOGY

Concretes that use other cements or constituents outside of current standards will be part of the overall solution to reducing the carbon intensity of the industry. Some of these concretes are an extension of existing technology, while others adopt wholly different chemistry. Wherever possible and appropriate, these new technologies should be supported by the industry to allow the accelerated development of standards and an increase in commercial readiness and application.

7 CARBON SEQUESTRATION, CAPTURE AND USE

Carbon sequestration within concrete can offer some benefit in performance. Guidance on how to use novel carbon curing technology and a better understanding of how to maximise long-term carbonation are required. Carbon capture technology to reduce the intensity of cement production requires large-scale industry and government support and should be recognised as an end-of-pipe solution that should be developed with, not instead of, other carbon-saving approaches. Sequestering captured CO_2 into new SCMs and aggregates should be supported and accelerated.

Above: Precast panels at the Global Change Institute made using Wagners EFC

Right: Waste clay at a quarry with potential for use as calcined clay

Low Carbon Concrete Routemap: selected actions to 2030

The creation of a Concrete Decarbonisation Taskforce would catalyse activities and allow their coordination to realise the most rapid transition to a low-carbon concrete industry in the UK

Group	Strand	2022			2030
	1 CONTINUOUS BENCHMARKING	Public reporting of CO_2e for all concrete works against the LCCG benchmarking as standard practice	Clients define product requirements using the LCCG benchmark rating criteria and commit to buying concretes that meet that criteria	Periodic updating of LCCG benchmark and guidance	CO_2e calculations based on kg CO_2e/kg of materials as used, not general database values
USING CONCRETE	2 KNOWLEDGE TRANSFER	Formation of Concrete Decarbonisation Task Force and repository to showcase low-carbon technologies and initiatives	Working group to assess risk and consequence levels and where the use of different concretes should be accepted or expected	Encourage pilots of low-carbon concrete materials and technologies with a focus on rapid scale-up. Mandate piloting on publicly funded projects	Develop performance-related standards
USING CONCRETE	3 DESIGN AND SPECIFICATION	Increase utilisation factors and optimise elements through geometry, including forming voids and profiled sections	Include requirement for embodied carbon measurement within specification and set a target if possible, using the LCCG benchmark	Creation of a one-stop low-carbon concrete portal where the industry can find up-to-date guidance	Continuous improvements in efficiency, designing with re-used elements and for re-use
USING CONCRETE	4 SUPPLY AND CONSTRUCTION	Add a requirement for procurement to take account of CO_2e throughout the supply chain, with measuring mandatory	Develop guidance on carbon reductions: minimise waste through BIM, avoid sacrificial concrete in temporary work, adopt working methods that are less reliant on early strength	Modify batching plants to enable production of lower-carbon concretes. For example, add silos for alternative SCMs, add dispensers for AACM activators	Reclaim cementitious material and aggregates from demolition arisings for reprocessing and use in new concrete
MAKING CONCRETE	5 OPTIMISING EXISTING TECHNOLOGY	Increase and optimise use of GGBS, fly ash and limestone as an SCM with adoption of additional multi-component cements into standards	Propose alternative lower-carbon concretes/mixes to clients, including as pilots. Enabled by, for example, changes to minimum cement content for durability	Fly ash reclaimed from stockpiles as an SCM and plant locations and mixes optimised for use	AI/sensing enabled real-time adjustment to optimise mix design used at scale
MAKING CONCRETE	6 ADOPTING NEW TECHNOLOGY	Identify clays in the UK with mineralogy suitable for calcining to use as cementitious materials (SCM or AACM)	Convert PAS 8820:2016 to a British standard	Accelerated test methods to determine long-term properties of new concrete products	AACMs based on calcined clay (including metakaolin)
MAKING CONCRETE	7 CARBON SEQUESTRATION	Coordinated database of pilots required and identification of optimal locations for factories that will make use of captured CO_2	Increase in projects using concretes that incorporate CO_2 and also cure using it	Establish pilots of CO_2 capture at cement works	Synthetic SCMs/AACMs and aggregates that sequester CO_2 during manufacture

2050
Mass roll-out and transition to
NET ZERO

Strands 1-7 set out decarbonisation knowledge and where further development is required to realise carbon savings. Strand 8 sets out how this knowledge will contribute to a net zero future for concrete and is an invitation for collaboration from all stakeholders. The opportunities and ideas seek to address the climate and biodiversity emergency and focus on the next 10 years. There is no one technology, idea or opportunity that can address the concrete challenge and the LCCG proposes multiple areas for development, all of which can in principle be delivered at scale in the UK.

See Glossary, page 74, for definitions of the terms used in this infographic.

kg CO_2e/kg, kg CO_2e/t, kg CO_2e/m^2 or kg CO_2e/m^3?

Environmental product declarations (EPDs) and industry databases usually report the carbon intensity or carbon coefficient in kg CO_2e/kg. Aggregate and cement suppliers often refer to kg CO_2e/t. Building developers find it useful to consider kg CO_2e/m^2. Concrete is generally specified and costed by volume. The embodied carbon is also often quoted by volume, in kg CO_2e/m^3, so that total embodied carbon can easily be calculated using readily available information on quantities.

For example, when used in a 300mm thick slab, the carbon intensity of the concrete described in Fig 1.1 might be described by different parties as: 0.119 kg CO_2e/kg, 119 kg CO_2e/t, 86 kg CO_2e/m^2 or 286 kg CO_2e/m^3.

LCCG recommendation:

- During carbon calculations, kg CO_2e/kg should be adopted.
- For general reporting and comparison with concrete carbon benchmarks, kg CO_2e/m^3 should be used.

The concrete strength class must be taken into account when comparing the carbon intensity of different concretes.

Low Carbon Concrete Routemap

Low Carbon Concrete Routemap

1 Setting the benchmark

1.1 Measuring carbon in concrete

This document focuses on the embodied carbon associated with concrete production in a batching plant or precasting factory: a 'cradle-to-batching plant gate' or 'cradle to precasting mould' approach. That is, covering LCA (lifecycle assessment) stages A1 to A3 in accordance with recognised assessment framework and standards BS EN 15643[1] (superseded by EN 17472 as of March 2022), BS EN 15804[2] and BS EN 16757[3].

The GHG emissions caused by transport to site (A4[1]), site works (A5[1], including wastage and curing in precasting factories), use (B[1]), end of life (C[1]) and the benefits and loads beyond the system boundaries (D[1]) should also be considered when making decisions based on embodied carbon. However, as these are project-specific, they are not included in this benchmarking comparison.

The benchmarking covered in this strand is specific to concrete. Reinforcement, finishes, etc are not included but should be considered when making decisions based on embodied carbon.

To calculate the carbon intensity of concrete, it is important to consider the constituents and their respective contributions. GHG emissions associated with transporting materials to the batching plant or precasting factory and batching/mixing should be included.

Fig 1.1 provides an indication of the typical distribution of embodied carbon for a structural concrete of design strength C25/30 for LCA stages A1 to A3. This has been calculated with a theoretical mix and using carbon intensity figures (carbon coefficients) from the Inventory of Carbon and Energy database[4] and has a total embodied carbon of 286 kg CO_2e/m^3 for LCA stages A1 to A3[5].

The variety of available data sources is an important consideration as it is important that when measuring embodied carbon, and to deliver credible reductions, a robust and fair approach is used. The LCCG recommendation for the use of data sources to calculate embodied carbon is set out in section 1.2. Embodied carbon values for concrete should be accompanied by a clear summary on the sources of data used in the calculation and whether the value is self-determined or independently verified.

Regardless of data sources, it is clear from Fig 1.1 that cement is the main driver of embodied carbon in concrete

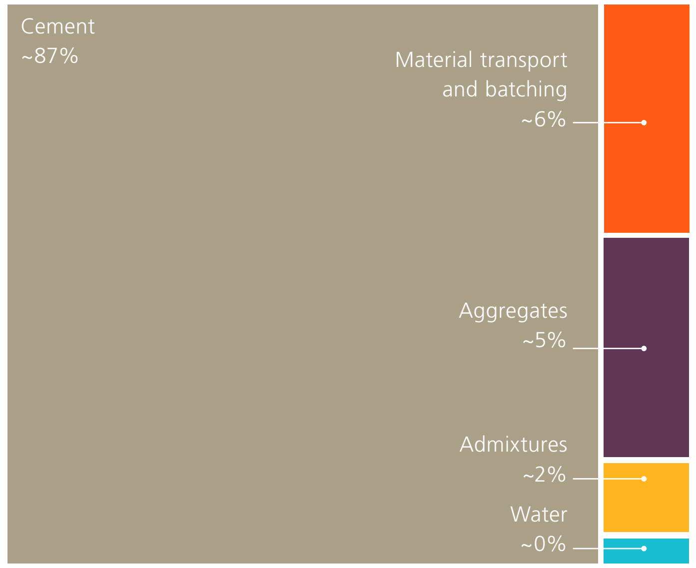


Fig 1.1: Distribution of embodied carbon in a typical structural concrete (RC25/30), LCA stages A1 to A3

today. Therefore, cement is the focus of most of the work to decarbonise concrete. Other constituents and activities must also be decarbonised over the coming decades, but at present cement offers the greatest potential to realise substantial carbon reductions. Improved data on the carbon intensity of the other constituents and activities will be required to guide practitioners.

1.2 Embodied carbon measuring hierarchy

The calculation of embodied carbon should use the most accurate available information. As projects move from design to procurement and construction, the most accurate available information will change. Embodied carbon assessments should be updated accordingly.

Quantity of concrete:

1. Record of material delivered to site (including material that is wasted)
2. Design information

Mix constituent quantities:

1. Batching records for material delivered to site
2. Supplier's mix design
3. Design information

Carbon intensity of constituents or concrete:

1. EPDs for the constituent materials
2. Supplier's EPD for the concrete, assessed against as-batched constituent quantities once available
3. Average industry values for the carbon coefficients of constituent materials from industry databases
4. Generic industry EPDs for concrete of the specified strength class
5. Generic average values for cast concrete from industry databases

1.3 Benchmarking

Methods of assessing the carbon intensity of concrete

There will be rapid reductions in CO_2e of concrete over the next 10 to 20 years. As the concrete industry continues to decarbonise, today's low-carbon concrete will become tomorrow's carbon laggard.

Typically, the starting point in trying to assess the carbon intensity of concretes is to measure reductions in carbon relative to a reference value for each strength class. The reference values are based on mixes that use Portland cement without any SCMs (secondary cementitious materials). High-, medium- and low-carbon concrete are defined according to a percentage reduction in carbon intensity relative to the reference value. This method does not communicate how the carbon intensity of a mix compares with wider industry performance, and what may be possible.

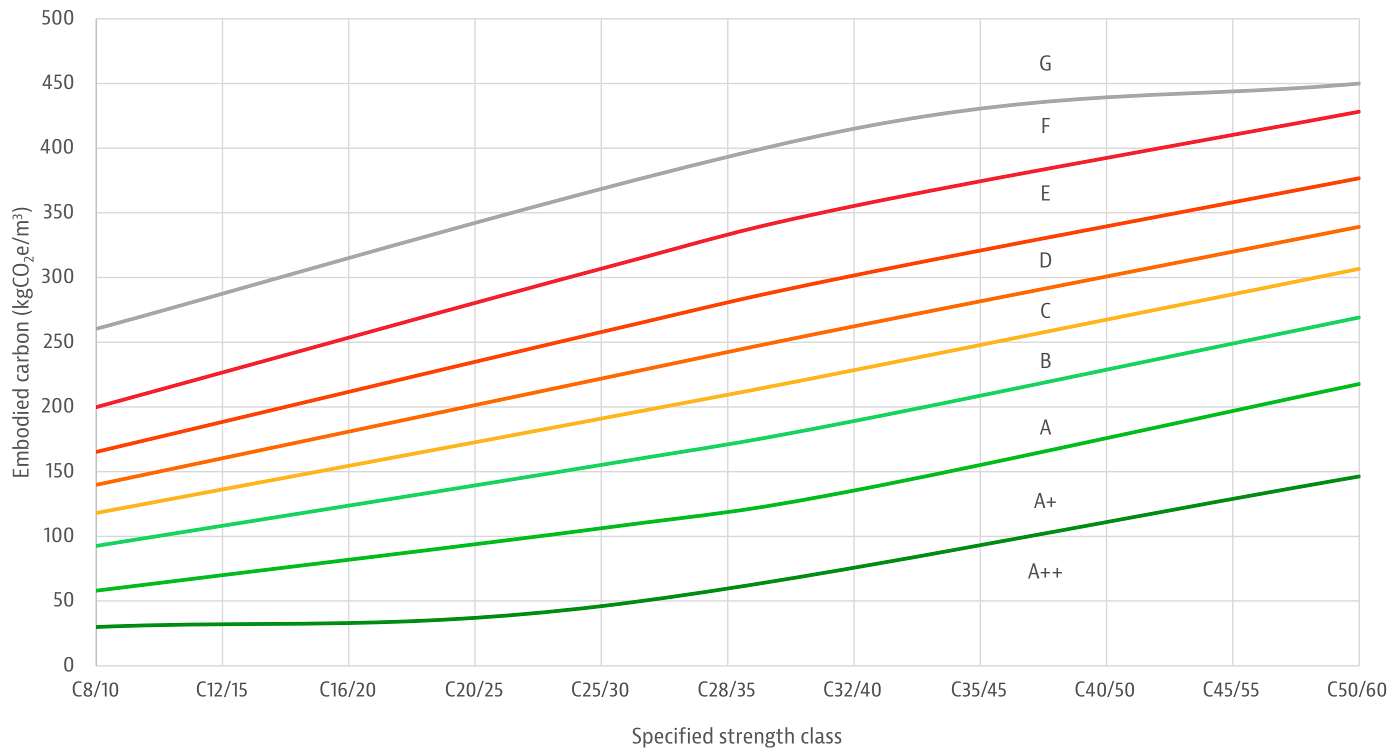
In this Routemap, the carbon intensity of concrete is defined in the context of the range of concretes in use across the market. For practical comparison across industry, it is sensible to compare concrete based on the kg CO_2e/m^3 by strength class.

To enable comparison between projects, the rating is based on the specified strength class only. This provides opportunities to improve the rating by, for example, adjusting the type and percentage of SCM, requirements for early strength gain, consistence, environment (e.g. by use of protective barrier layers), minimum cement content (kg/m^3), water/cement ratio, use of admixtures, type and grading of aggregates, age at which the specified strength must be achieved, and sources of constituents.

The rating takes no account of how efficiently concrete is used (the 'functional equivalence' of the concrete). For example, a well-designed precast unit may make more efficient use of material than a typical cast in-situ element. This should be allowed for when assessing the embodied carbon of complete elements.

Note that the performance requirements may make it impractical to achieve some ratings for a particular application.

Fig 1.2: GCB/LCCG benchmark ratings for embodied carbon, normal-weight concrete, LCA stages A1-A3 (ready-mix: cradle to batching plant gate; precast: cradle to mould)



Notes :

- The benchmark ratings are based on embodied carbon of normal weight concrete mixes used recently in the UK
- Performance requirements may make it impractical to achieve some ratings for a particular application
- Achieving a rating of A, A+ or A++ through use of a high proportion of GGBS with an associated requirement to significantly increase the total binder content (kg/m^3) may not be an effective method of reducing global GHG emissions
- Opportunities for reducing the carbon rating may typically be achieved by adjusting: type and % of SCM, requirements for early strength gain, consistence, environment (e.g. by use of protective barrier layers), minimum cement content (kg/m^3), w/c ratio, use of admixtures, type and grading of aggregates, age at which the specified strength must be achieved, sources of constituents

Key recommendations:

■ The CO_2e of concrete mixes should be assessed by reference to contemporary industry values of kg CO_2e/m^3 for each strength class.
■ In this way, 'low-carbon concrete' is defined in the context of the range of concretes in use across the market.
■ The LCCG suggests the following bands for each strength class:

Rating	kg CO_2e/m^3 fractile range within the strength class
A++	kg CO_2e/m^3 below those of benchmarked concretes
A+	0%-5%
A	5%-20%
B	20%-40%
C	40%-60%
D	60%-80%
E	80%-95%
F	95%-100%
G	kg CO_2e/m^3 above those of benchmarked concretes

Carbon intensity increases with fractile. Generally, for a given strength class, concretes in higher fractiles make less use of SCMs to replace Portland cement (CEM I) and/or include a higher total cement content (kg/m^3).

Table 1.1: Distribution of kg CO_2e/m^3 to different fractiles for a given strength class

Summary of the benchmarking analysis and limitations

To establish the appropriate carbon intensity to be used in assessing current concrete, recent UK mixes have been analysed. AMCRETE, Byrne Bros, Price and Myers, Ramboll and WSP provided information on the carbon intensity of recent mixes. In total, data has been provided for 624 different normal-weight concrete mixes for strength classes ranging from C8/10 to C80/95. As only seven of the mixes related to strength classes greater than C50/60, these have been excluded from the analysis.

The majority of the data provided relates to ready-mix concrete. Some mixes for precast concrete were included. It is not known if precast concrete was under- or over-represented in the data.

The kg CO_2e/m^3 values have been calculated by the companies that supplied the data. The calculations have not been independently verified. In most cases, the kg CO_2e/kg assigned to each ingredient has been identified from industry databases. In some cases, EPDs for individual ingredients have been referenced.

Information on the volume of concrete used was provided for 340 of the mixes.

Benchmarking analyses were completed without taking account of the volume used and, for the mixes for which volume information was provided, using volume weighting. For both analyses, the mean for all mixes was 232 kg CO_2e/m^3.

Between the two analyses, the mean for individual strength classes varied by up to 12%. The two analyses generated similar carbon ratings for strength classes C25/30 and above. For these strength classes, there was more 'noise' in the volume-weighted analysis, perhaps owing to the reduced number of mixes for which data was provided. Little data on volumes used was provided for strength classes below C25/30.

Therefore, the LCCG benchmark has been generated using the analysis that does not take account of the volumes used. A better representation of industry practice will be achieved if future analyses include weighting to take account of the volumes used.

The British Ready-mixed Concrete Association (BRMCA) provided data on the mean value for concrete of each strength class as reported by four of the large UK concrete producers. The BRMCA mean values were about 11% higher than the mean values calculated using the data submitted by AMCRETE, Byrne Bros, Price and Myers, Ramboll and WSP. Apart from the upper- and lower-bound ratings (between A+ and A++, and between F and G), the benchmark values have been raised so that the mid-range values are broadly consistent with the BRMCA mean values.

The benchmark has been reviewed by representatives of two of the large UK concrete producers, with the conclusion that the ratings are reasonable. Data that was not used in generation of the benchmark has been plotted against the benchmark. The resulting distribution of mixes appears compatible with the benchmark ratings.

The LCCG view is that Fig 1.2 provides an acceptable first iteration of a benchmark for rating the carbon intensity of fresh concrete. Users should bear in mind the limitations of the benchmarking analysis and consider the boundaries between ratings as approximate.

A copy of the data and analysis used to generate the benchmark can be obtained from the LCCG.

Updating the benchmark

The benchmark should be updated, if possible annually, and preferably with data from a larger number of companies. Over time, as concrete is decarbonised, the bands are expected to cluster lower on the chart. The Mineral Products Association (MPA) and the BRMCA hope to obtain the relevant authorisations so that data submitted by their members can be provided directly to the LCCG for maintaining the benchmark.

While the simplicity of a single benchmark should be retained, users may also find it useful to compare mix performance by element type and environment. With a more comprehensive data set, it will be possible to distinguish the carbon intensity of concretes in different environments and uses (core walls, slabs, foundations, blinding, precast, post-tensioned, etc).

Creation of, and publicising of, an app or website for submission of data will help to obtain data to keep the benchmark current and add granularity.

LCCG benchmark: industry actions

Clients should:

■ Make use of the benchmark when setting the brief for project teams, subject to including a requirement to make effective use of GGBS (ground granulated blast-furnace slag) to reduce overall global emissions
■ Require public reporting of the as-constructed benchmark ratings
■ Require submission of concrete strength and carbon data to keep the benchmark current

Professional institutions, universities, and industry bodies should:

■ Establish good practice on public reporting of concrete benchmark ratings
■ Develop guidance on optimal use of GGBS in the UK to maximise global reduction of carbon emissions
■ Create systems for digital submission of data to keep the benchmark current
■ Establish methods for project digital carbon records to be linked to as-batched mix information and the EPDs for the mix constituents

Designers should:

■ Report concrete benchmark ratings during design development and on issue of construction information
■ Make use of the benchmark in concrete specification, subject to a requirement to make effective use of GGBS to reduce overall global emissions
■ Ensure submission of as-built concrete strength and carbon data to keep the benchmark current

Contractors and suppliers should:

■ Reference concrete benchmark ratings during development and selection of mix designs
■ Report benchmark ratings of constructed items
■ Submit as-built concrete strength and carbon data to keep the benchmark current

Improving the carbon ratings by using GGBS – the limits of current practice

Use of GGBS as an SCM to replace Portland cement is the current 'go-to' method for reducing the carbon intensity of UK concrete.

GGBS is a finite resource with UK availability forecast to reduce, potentially rapidly if other nations increase their use of GGBS as an SCM. Use of GGBS as the go-to method for decarbonising concrete in the UK may be possible only in the short to medium term. Current annual global production of GGBS is about 10% of annual global cement use.

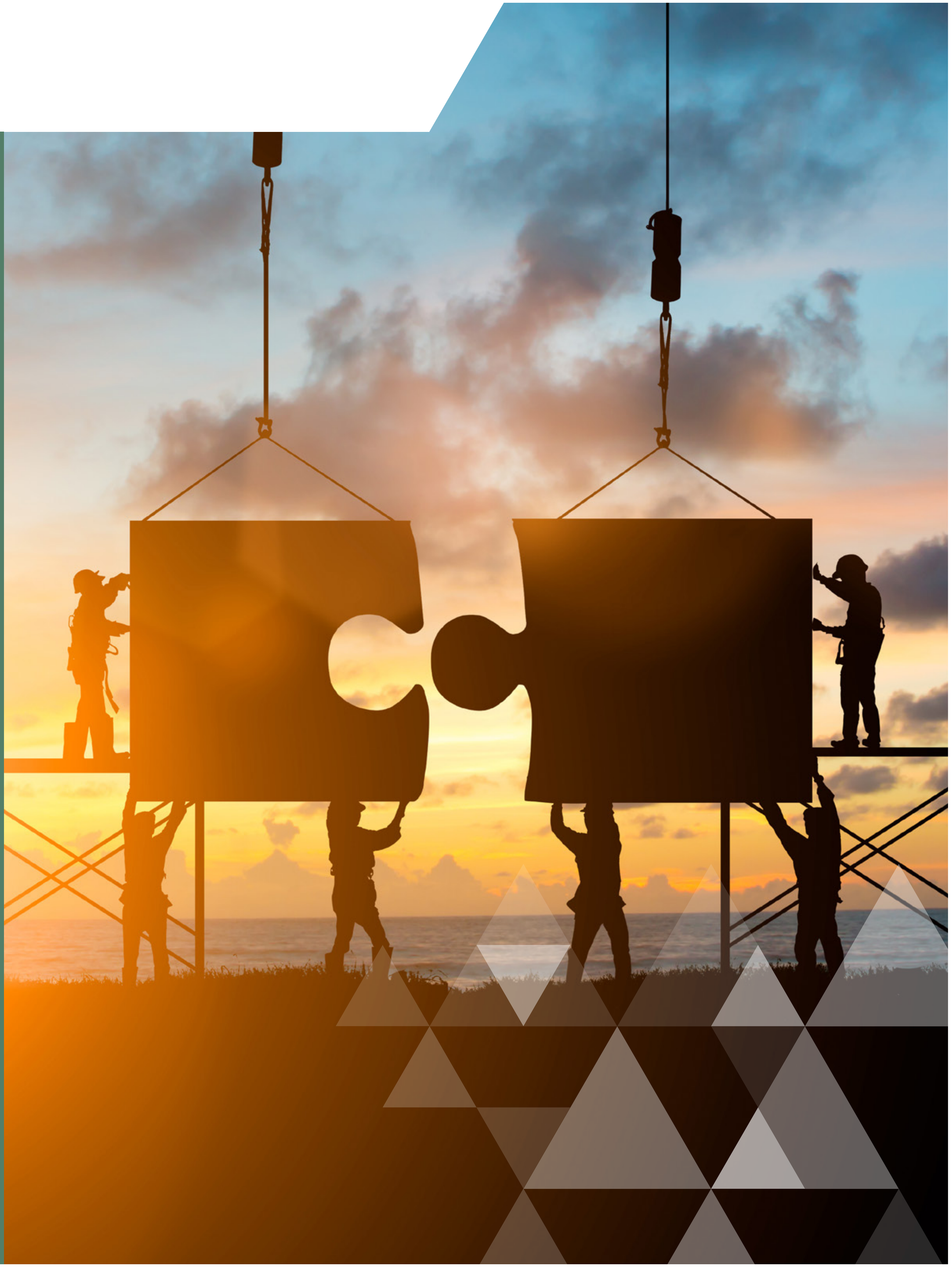
Use of GGBS to replace Portland cement often requires an increase in the total cement content (kg/m^3). The percentage increase in total cement content is usually greater for higher strength classes with GGBS replacement rates above 50%.

GGBS used to increase the total cement content in these mixes is not available for use in other mixes that would require a smaller percentage increase in total cement content. Those other mixes may therefore use more Portland cement. Therefore, if the use of GGBS leads to a substantial increase in total cement content it may result in a low carbon rating for that mix but an overall increase in the global use of Portland cement, with an associated increase in GHG emissions. Use of GGBS to decarbonise concrete is only appropriate if to do so reduces global GHG emissions.

Guidance is required on the most carbon-effective use of GGBS as an SCM or AACM (alkali-activated cementitious material) in the UK. In the absence of such guidance, it may be appropriate to base decisions on the UK availability of GGBS: if GGBS is not readily available, increasing the total cement content by more than about 10% to enable a higher percentage of GGBS may result in increased global use of Portland cement, with an associated increase in global GHG emissions. Similar considerations may apply to the use of other SCMs with limited availability.

Setting the benchmark

1 BS EN 15643 Sustainability of construction works – Framework for assessment of buildings and civil engineering works
2 BS EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products
3 BS EN 16757 Sustainability of construction works – Environmental product declarations – Product category rules for concrete and concrete elements
4 Circular Ecology, Inventory of Carbon and Energy 3.0
5 This value corresponds with the Inventory of Carbon and Energy value to be used for RC 25/30 in the UK when information on the type and quantity of cement replacement is not available. The figure is close to the Inventory of Carbon and Energy value for RC 25/30 with 15% PFA replacement of Portland cement.



Using concrete

2 Knowledge transfer

Our Routemap to adopting lower-carbon concrete starts with something that all supply-chain members can do now, and that is share knowledge and access guidance on the most appropriate low-carbon concrete for their needs. If the UK is to achieve net-zero emissions by 2050, current behaviours need to change. There is a need for project teams to challenge perceptions with reliable data and facts and to access knowledge from across the supply chain to overcome barriers for adopting lower-carbon concretes.

The LCCG carried out a workshop and survey to understand the perceived barriers to the adoption of low-carbon concretes; the results of this survey are referred to throughout this section.

The survey identified that education or knowledge transfer was seen as a key strategy to improve awareness of what could be used and how. Of the 178 responses to the survey, 27 people viewed education as the main barrier to overcome (15%). The LCCG supports the use of this Routemap as a tool for education and awareness programmes throughout the supply chain.

The survey highlighted the importance of codes and standards in adopting new technologies. Some 11% of respondents cited the lack of inclusion in existing standards and the impact that had on warranty providers as a barrier to adopting a low-carbon concrete. Meanwhile, 31% of respondents agreed with feedback from manufacturers regarding the difficulty of introducing low-carbon technologies, including the lack of European assessment documents (EADs) or European technical assessments (ETAs).

A commonly reported barrier is a risk-averse approach to structural design, but this is not solely the responsibility of the structural engineer. With early collaboration and knowledge sharing within the project team and supply chain, many perceived barriers to lower-carbon concretes can be shown as just that – perceived – and be addressed with structural design and concrete mix design strategies.

Perception is defined as how we interpret something, and our interpretations are influenced by what we know or do not know. In this section, the aim is to challenge some of those perceptions and share guidance, with the aim of accelerating the use of lower-carbon concretes, remembering that we cannot simply look at the carbon intensity of a cement alone – alternative design approaches can yield an appropriate approach yet utilise a cement with less material.

2.1 How – Standards

Concrete is specified and concrete structures are designed based on industry standards and guidance. Examples of UK standards and guidance for concrete include:

- BS 8500:2019 Concrete – Complementary British Standard to BS EN 206
- BS EN 1992:2004 Eurocode 2, Design of concrete structures
- BS EN 197-1:2011 Cement – Composition, specifications and conformity criteria for common cements
- BS EN 197-5:2021 Cement – Portland-composite cement CEM II/C-M and composite cement CEM VI
- BS EN 206:2013+A1:2016 Concrete – Specification, performance, production and conformity
- PAS 8820:2016 Construction materials – Alkali-activated cementitious material (AACM) and concrete specification

The process of updating UK standards and guidance requires sufficient data to be available for any new products and consensus to any update to be sought from the committee responsible for their development. Formal standards are reviewed by the BSI committees every five years when they consider whether to confirm, withdraw or revise the documents and take the appropriate action. Delays to revisions or even the publication of new standards will be inevitable if the information required is not collated in a chronological and technical manner for assessment (see Fig 2.3, page 26) or if there are not sufficient resources available to consider any application.

There are likely to be more low-carbon concretes that can be specified now than designers are probably aware of, such as those that have cement types covered in EN 197-5. BS 8500-2 clause 4.4.3 provides a mechanism to use cements that are not currently recognised in BS 8500. Other cements with sufficient technical supporting data in relation to performance could also be considered, based on a project's lead time.

BS EN 197 parts 1 and 5 define a total of 32 cement types, all of which have a wide range of CO_2 footprints, that can be specified in construction projects or concrete products. Some 27 of these are from BS EN 197-1 and five are from BS EN 197-5. Only 17 of the 27 BS EN 197-1 cements are recognised in BS 8500. The absence of the remaining 10 BS EN 197-1 cements and five BS EN 197-5 cements is not down to them not being suitable but that more data is required to determine their suitability for generic concrete applications.

Cements can be categorised into two groups:

- 'General purpose' – i.e. those with suitability established in the UK concrete standard BS 8500
- 'Other cements' – i.e. those with suitability not yet established in BS 8500

General purpose cements include low-carbon options that contain GGBS (ground granulated blast-furnace slag) or FA (fly ash) rather than clinker as the main ingredient. For example, CEM III/B contains up to 80% GGBS and has 73% lower embodied carbon than Portland cement CEM I, which has up to 95% clinker. Other cements can depend heavily on SCMs to achieve low embodied carbon, but, unlike general purpose cements, their use requires testing to demonstrate that the concrete meets the performance requirements of the application. The exposure environment will dictate whether it is necessary to follow an equivalent durability procedure (e.g. PAS 8820:2016 for AACMs).

Some examples of other cements include:

- CEM III/C cements contain 81%-95% GGBS and 5%-19% Portland cement clinker, but applications are limited by its slower setting. If 95% GGBS is specified, CEM III/C cements can reduce the embodied carbon of cement by 86% versus CEM I.
- CEM VI cements contain three ingredients: 31%-59% GGBS, 35%-49% Portland cement clinker and 6%-20% limestone powder. These new multi-component cements can save up to 60% in embodied carbon versus CEM I. The Mineral Products Association (MPA) recently completed a project, part-funded under the Department for Business, Energy and Industrial Strategy's Industrial Energy Efficiency Accelerator programme, which has successfully demonstrated the suitability of CEM VI cements as general purpose cements. CEM VI cements should be included in the next revision of BS 8500.
- CEM II/C, a new multi-component cement type, can contain 50%-64% Portland cement clinker and a combination of 16%-44% calcined clay and 6%-20% limestone powder as ingredients. Calcined clay requires high temperatures for calcination, which limits the potential reduction in thermal emissions, but it does not have any process emissions compared with Portland cement. It could also replace dwindling (or globally limited) supplies of GGBS. The carbon intensity of calcined clay is about 350kg CO_2e, which is significantly higher than that of GGBS or FA. But supplies are effectively limitless, so there is greater potential for global reductions regarding carbon footprints.
- AACMs contain circa 90% common SCMs (that react readily in the presence of alkalis and water e.g. GGBS, fly ash, calcined clay, etc, but not limestone powder), and circa 10% alkali-based materials (usually either Portland cement clinker, alkali reagent chemicals or a combination thereof). PAS 8820:2016 gives guidance on the specification of AACMs and concretes for construction applications. Owing to high proportions of SCMs, very low values of embodied carbon are possible. However, it is wise to establish the emissions associated with the production of the activators.

BS 8500-2 (clause 4.4.3) and the Eurocodes (EC0, BS EN 1990 clause 5.2 and D3.1d) provide clear mechanisms to use and specify other cements. The Building Research Establishment (BRE) has outlined possible routes to demonstrating performance of AACM concrete products[1]. A similar approach is shown in Fig 2.3 for other cements (including AACMs).

Whatever the cement to be specified it is recommended to use a performance-based specification, which could be modelled on ASTM C1157-02 Standard Performance Specification for Hydraulic Cement. The ASTM C1157-02 guidance resists stipulating minimum cement content, water-to-cement ratio or the proportion of SCMs, which would give the concrete producer more flexibility to offer a lower-carbon concrete. This change of specification behaviour is supported by organisations including RILEM[2] and BRE[1]. In essence, a significant volume of concrete used for temporary works could be subject to a performance specification rather than recipe-based specifications.

Any new technology needs to demonstrate a performance that is equal to or better than conventional cement choices for a given application and environment. This is significant, as to demonstrate equal or better performance, time and commercial viability from research to delivery are required (see Fig 2.5, page 28).

2.2 Why – Reduce carbon

To deliver the lowest possible carbon concrete, it is important that all members of the project team, including the client (and those who provide warranties), are aligned and prepared to challenge default behaviour that is likely based on prevailing prescriptive standards rather than performance standards, cost and programme being a priority, and not the reduction of carbon. The LCCG survey showed that 70% of respondents had explored the use of low-carbon concretes. It also showed concerns about the availability of low-carbon technologies (22%) and the ability of concrete producers to provide a low-carbon alternative (35%).

The primary driver for using a lower-carbon cement is to reduce the embodied carbon of a concrete mix design. However, other aspects of the concrete's performance may also be influenced by the cement used. Availability of the materials used in low-carbon cements will also influence specification e.g. the supply of FA and GGBS will reduce as coal-fired power plants close and steel manufacturing moves away from blast furnaces. In the short term there is global availability, even a surplus; in the medium term it may become commercially viable to recover stockpiled FA. Still, we must keep an eye on progress being made regarding the research and development of alternative SCMs to ensure that no disruption to future construction activities is encountered.

There are UK-sourced alternatives, such as calcined clay, silica fume and limestone powder, all of which have the potential to become the dominant SCMs in the mid to long term. But to be available at scale, the infrastructure needs to be in place to recover, manufacture, deliver and batch them. Strand 6 discusses the complexities of providing new and emerging technologies in addition to the existing range of cements. For example, a barrier to making more concretes available is space or cost for the producer to erect new silos across the local network of batching plants. This issue could be addressed, in part, by client investment such as guaranteed minimum supply contracts from major projects or the Government that would meet the initial capital expenditure required.

Fig 2.1 shows the estimated global availability and use of Portland cement and SCMs. In comparison with Portland cement, it is clear that the supply of GGBS (slag) and FA are limited, but there is abundant supply of calcined clay and limestone powder (filler). There is growing evidence in the form of research and durability data for cements containing these SCMs.

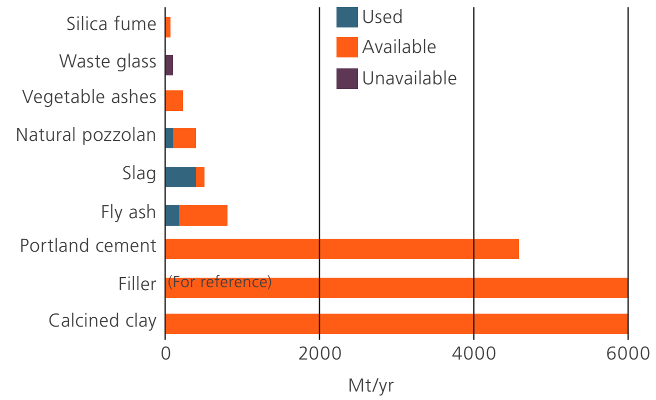


Fig 2.1: Estimated global availability and use of Portland cement and SCMs. From Scrivener K et al (2018) Calcined clay limestone cements (LC3), Cement and Concrete Research 114, 49-56.

2.3 What – Data and evidence

In this section, we look at what sources of reliable data are available to understand and compare both the performance and carbon credentials of concrete mix designs. Some 23% of survey respondents declared a lack of awareness and knowledge as the most important barrier to overcome.

Calculations for embodied carbon often rely on information from various sources, such as the MPA Factsheet 18 or EPD programmes such as BRE, IBU and Environdec. Half of respondents did not feel meaningful embodied carbon data was easily available, creating a reliance on generic data for constituent materials. This could lead to under- or over-reporting of a project's embodied carbon.

Despite these observations, the absence of absolutely accurate carbon coefficients is not really a barrier to adopting common-sense approaches to reducing the carbon footprint. It doesn't matter if the cement you are using has a carbon coefficient of 850kg CO_2e or 860kg CO_2e – if the reduction of a given cement content is 10% through efficient aggregate gradation, then the concrete's carbon footprint is likely to drop by approximately 9%.

The LCCG recommends a collaborative approach early in a project to harness the shared experiences and lessons learnt from lower-carbon technologies. Discussions are already under way on the initiation of a case-study repository for industry members to access. Initial use of new and emerging technologies in low-risk applications can be used as a case study for the construction industry to learn from and inform use in further applications.

The LCCG also promotes the development of product-specific and verifiable EPDs that detail the accurate embodied carbon for each mix design, and provision of carbon data at a project level (see Strand 1). It is accepted that it may be some time before all of the concrete constituents and concretes are covered by verifiable EPDs at project level. In the meantime, it may be necessary to use generic EPDs or other data sources mentioned above.

The tendency is to compare one mix design with another, but identifying the most appropriate lowest-carbon mix can be more complicated than that. To assess the carbon credentials of any mix design, a factor that needs to be considered is the availability and suitability of the mix design to the application.

Taking AACMs as an example, some AACM technology may require in excess of 420kg of GGBS to blend with an alkali activator to achieve a concrete with a strength class of C32/40, whereas a Portland cement-based mix design may require only 200kg of GGBS. Optimisation of mix designs utilising other cement types is necessary so as not to waste valuable SCMs such as GGBS. A balance therefore needs to be achieved between lowering the embodied carbon of a concrete mix and material efficiency/ availability. This can be achieved if we understand the different technologies and compositions that are available and suitable.

When considering a low-carbon technology, design considerations will include: safety of the design in terms of the material and the application; speed of construction; commercial viability; aesthetics of the concrete and the finished element; and sustainability. Sometimes a trade-off is possible depending on the primary drivers or what element is being constructed. For example, a pile does not necessarily have an aesthetic value but will need to perform safely, not just for the construction period but throughout the service life of the structure. Whatever the considerations are, ultimately the chosen concrete and lower-carbon technology has to be suitable and fit with the design.

For new and emerging technologies, the correct assessment of the technology readiness level (TRL) will enable the appropriate selection of an application or concrete element (see Figs 2.2-2.5). In this regard, assessment of the TRL could

Low Carbon Concrete Routemap

be challenged depending on what evidence is available at the time, so for new and emerging technologies it is advised that structural engineers are consulted early to program a robust testing regime to demonstrate suitability.

If the concrete is required for temporary works, the process of acceptance of other cements or new technology could be straightforward. For example, blinding, thrust blocks, capping beams, temporary roads, site compounds, mass fill and other low-risk applications, including some permanent works, are good candidates for low-carbon cements such as AACMs and geopolymers. Ideally, performance data will be gathered and shared with project teams to build confidence in the new technology.

2.4 When – Now

The working groups of the Low Carbon Concrete Group have all reported that to accelerate the use of lower-carbon concretes, early engagement from the entire supply chain is essential to enable knowledge and data to be shared. As market demand for low-carbon concrete increases, the speed of cement and concrete technology development will be rapid and direct engagement with concrete producers is recommended.

Clients have a significant role to play in the adoption of new concretes. Survey respondents identified clients and Government as the most significant stakeholders. Contractors also have a key role and those leading on sustainable construction have project data and experience to share. The exemplar in this case could be the final report written by Expedition Engineering for the Zero Carbon World Tiger Team project, for Network Rail, HS2 and i3P[3].

Key recommendations:

■ The LCCG recommends that clients are best placed to provide the necessary leadership but that collaboration between policy-makers, clients and suppliers is required to meet the challenge.

2.5 Who – Early collaboration

Collaboration is the key to successfully introducing new and emerging technologies, through to standards approval and finally implementation or adoption, regardless of whether the technology is based on Portland cement or alternative binder technologies. However, collaboration does not begin or end at the point of discussion between the engineer and the contractor, or between the concrete producer or proprietary technology developer. It is based on knowledge sharing and transfer between all parties, from the client to the contractor and subcontractor. In essence, collaboration is a continuous and omnidirectional requirement.

The complete supply and procurement chain should be able to gain awareness of the various technologies and solutions that are available to them, as well as learning new skills for designing, batching, handling and placing concrete. However, this can only be facilitated by those who are able to advise and train as well as disseminate practical knowledge. This report contains a number of case studies and the LCCG encourages clients and project teams to publish case studies featuring low-carbon concretes.

Information	Materials					
	Portland cement	Blast furnace slag	Fly ash	Kaolin	Sodium hydroxide	Sodium silicate
Global						
Production (Mt/yr)	4600	330	900	37	72	12
Used in concrete (Mt/yr)	4600	297	300	-	-	-
Europe						
Production (Mt/yr)	-	25	>25[(a)]	4	10.2	2
Used in concrete (Mt/yr)	-	20	25	-	-	-
Used in other applications	-	5	-	-	0.3	2
UK						
Production (Mt/yr)	10	2	1	1.36	-	-
Used in cement (Mt/yr)	10	1.8-2	2	-	-	-
Stockpiles (needs recovering/ further treatment)	-	0	<100	[(b)]	-	-

Notes :

(a) Based on 15 EU member states: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden and (at the time) the UK.

(b) UK kaolin reserves are not published because of the commercial nature, but more than 50 years' capacity is reported to be available using current technology.

Table 2.1: Material supply and demand figures (Scrivener K et al, 2018, Eco-efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-based Materials Industry, Paris: United Nations Environment, 1-64)

There is also a role for established training providers, such as professional institutions, universities and industry bodies such as the Concrete Centre and the Institute of Concrete Technology, as well as product manufacturers. It is a priority that universities and practical training for construction and design professionals include topics such as low-carbon concrete and how to consider new and emerging technologies and encourage innovation.

The Concrete Institute of Australia has recognised this as an integral part of its strategy to reduce carbon and it provides the example of producing recommended practice for AACM concrete, which they refer to as geopolymer concrete[4]. In the UK, a similar approach is endorsed by the Zero Carbon World Tiger Team, whereby the emphasis is on bringing skilled professionals together to assess gaps in learning and propose solutions – in this case, training solutions. This initiative, which has become known as a 'best practice programme', should ensure current practices, material selection, innovation and compliance with standards are kept up to date and disseminated in an accurate, timely manner.

Fig 2.2: Understanding commercial and technology readiness. The use of a commercial and technology readiness scale is important in assessing the scalability of new and emerging technologies.

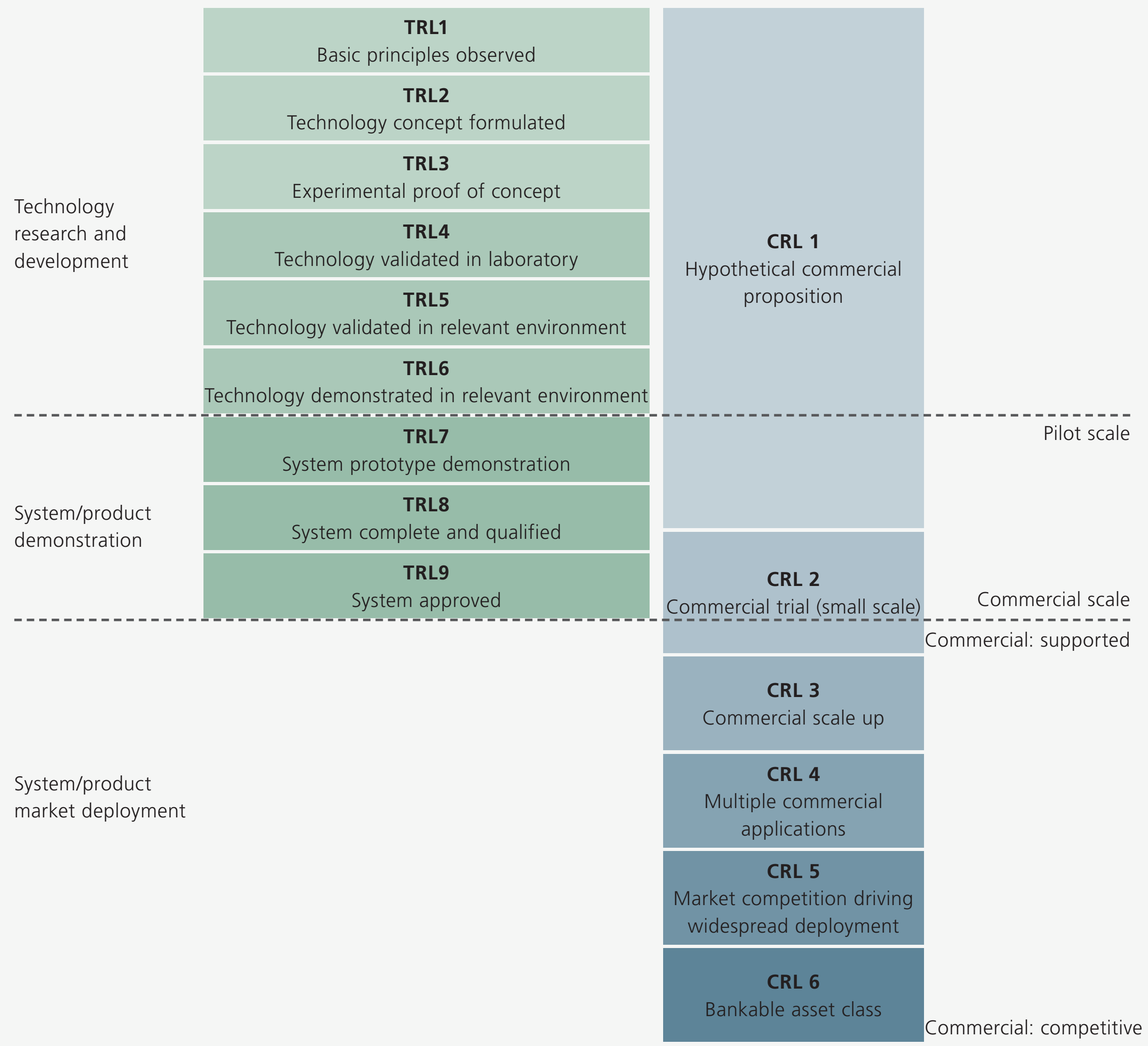


Fig 2.3: Technology readiness for low-carbon concrete
This diagram expands on the key stages of technology readiness when bringing a new lower-carbon concrete technology to market.

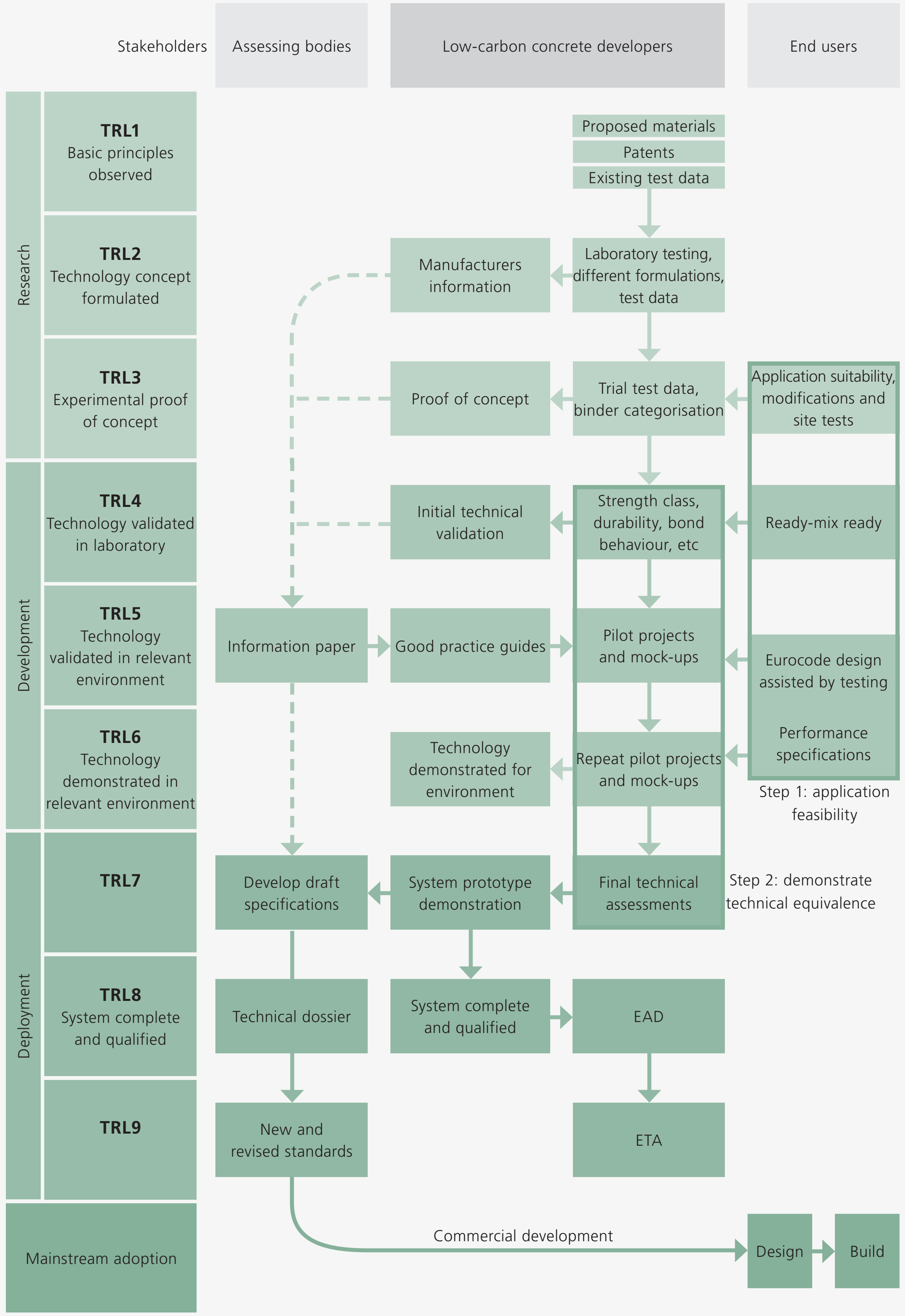


Fig 2.4: Step 1 – Application feasibility assessment

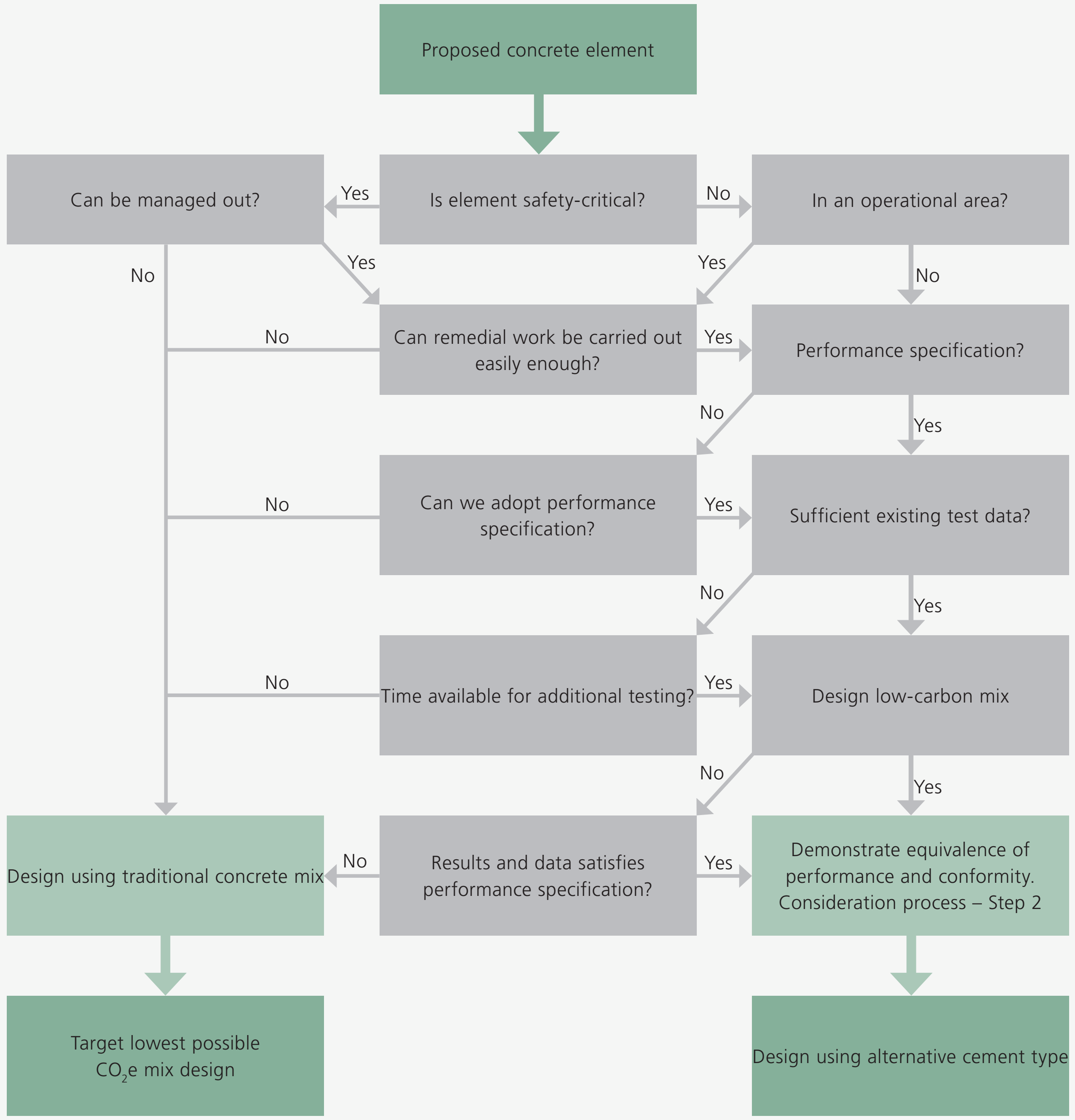
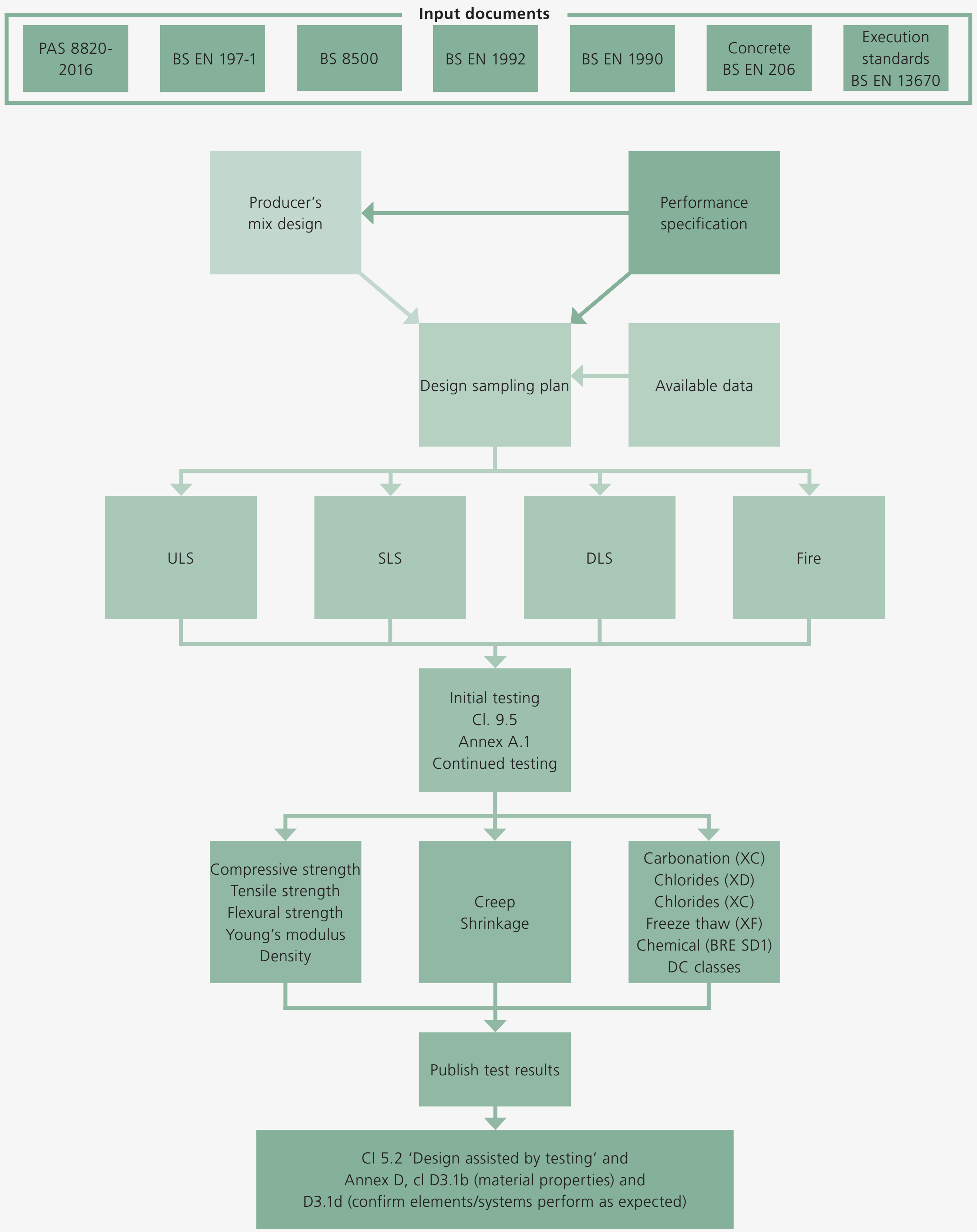


Fig 2.5: Step 2 – Demonstrating technical equivalence



Case study: Geopolymer concrete – following the guidelines set out by the Low Carbon Concrete Group

Concrete developer: Geopolymer UK
Patent owner: Geopolymer Solutions, Texas, US
Consultant: AMCRETE UK

Over the past few years, more and more interest has been shown in cement types other than Portland cement, leading to extensive trial programmes and pilot projects to prove suitability for a given application. However, only a small number of these other cement types are proving to be viable technically or commercially, with many seeming to stall in progress towards full commercialisation.

This may partly be down to a perceived lack of support and inclusion in the existing standard framework, or – just as likely – the significant investment required to develop and prove a new cement.

In North America, new cements can be introduced that comply with the performance specification ASTM C1157, which covers hydraulic cements for both general and special applications. In addition, ASTM C1157 does not list any restrictions on the composition of the cement or its constituents. ASTM C150 and ASTM C595 are the two prescriptive standards for Portland cement and blended cements respectively.

Following the performance criteria in ASTM C1157, Geopolymer Solutions has developed a cement that is reported to be at least equal to or better than traditional Portland cement blends in aggressive environments, as well as promoting significant strength development while dramatically reducing the embodied carbon of the concrete.


Geopolymer concrete for foundations and fire protection applications

Examples of the geopolymer concrete in use in North America are:

- **BWX Technologies**, Lynchburg, Virginia: nitric acid containment concrete structure
- **Canadian Natural Resources**, Alberta: fireproofing solution
- **Veolia Energy**, Philadelphia, Pennsylvania: sulfuric acid containment tanks
- **Motiva Enterprises**, Texas: sulfur pits for petroleum refining, evaluated by consultancy Jacobs

Geopolymer UK has now embarked on a significant testing and trial programme that is closely aligned to the steps set out in Figs 2.2 and 2.3 (see pages 25 and 26), to demonstrate performance against UK standards EC0, BS EN 1990 clause 5.2 and D3.1d and BS 8500-2 clause 4.4.3 – Equivalent concrete performance concept.

The LCCG shall be following the progress being made and will update the Routemap in future revisions accordingly.

Knowledge transfer

1 Dunster A and Gall D (2016) Alkali-activated binders for precast and ready-mixed concrete products: a route map to standardisation, certification and guidance (IP4/16), BRE
2 RILEM Technical Committee 224-AAM
3 i3P Zero Carbon World Tiger Team Project – Part 1 Discovery: www.i3p.org.uk/en/custom/news/view/9358
4 Pathways and barriers for acceptance and usage of geopolymer concrete in mainstream construction (2015) World of Coal Ash Conference, Nashville, US

Towards net zero

This strand focuses on the design and specification of concrete once it has been established that it is not possible to 'do nothing' or to re-use an existing structure or element, and that an alternative material would not provide a lower-carbon solution.

It is understood that the UK concrete industry, and the wider UK construction industry, will decarbonise over the coming decades. The focus of this strand is on moving the concrete industry towards net zero, and minimising carbon emissions as the industry transitions to net zero.

Where practical, facilities and elements should be designed to ease re-use when they will no longer be required to serve the original design intent. However, a requirement for new or altered facilities will remain, with an associated requirement for new concrete. This strand addresses the need to move to net zero carbon for the new concrete.

Using concrete

3 Design and specification

If it has been established that it is not possible to 'do nothing' or to re-use an existing structure or element, and that an alternative material would not provide a lower-carbon solution, then concrete may be an appropriate choice. Note that the lowest carbon design may use concrete working compositely with other materials.

The design should be optimised to use materials efficiently to achieve the lowest practical whole-life CO_2e. This is likely to require minimisation of the quantity of concrete used and use of concrete with the lowest carbon intensity that is suitable for the performance requirements in the intended application.

To make efficient use of materials, the design team should adopt best practice in selection of the structural form and general arrangement to reduce structural demand. Clear spans should be the minimum necessary. Structural zones should be sufficient to allow efficient use of materials. Elements should be optimised for embodied carbon, considering the balance between reinforcement and concrete quantities and the carbon intensity of the different materials. Voids, coffers and non-structural fill should be used to reduce the total volume of concrete.

'Utilisation' refers to how 'hard' a structure, or part of a structure, works to resist the design loads. 'Optimisation' refers to how efficiently material is used throughout the structure. A structure may have a reported utilisation of 100% but be poorly optimised – such a structure makes inefficient use of materials. Clients should consider asking for, and designers should routinely provide, reports on structural utilisation and optimisation.

Requirements for placing concrete and striking formwork or demoulding often give rise to a cement content that delivers in-service concrete strengths that exceed the specified strength as used in the design calculations.

Before detailed design, the designer should engage and collaborate with local concrete suppliers, concrete contractors and concrete technologists to establish an optimum concrete and the minimum associated in-service strength of the concrete and the maximum age at which this strength must be attained.

In addition, higher-strength grades are often specified with the assumption that they will be more durable. Although the perception may be that a higher-strength concrete improves quality and durability, this is not necessarily the case for most modern concretes. The updating of standards to reflect current concrete technology may reduce excess cement being included for durability alone.

The design codes include opportunities to reduce material quantities; these opportunities are often neglected. For example, partial factors ('safety factors') can be reduced if appropriate construction accuracy is achieved[1]. Designers should take account of the project arrangements and make appropriate use of the opportunities.

In some cases, an alternative analysis method may model the behaviour more accurately and enable material quantities to be reduced. Designers should think beyond their standard in-house software and use the method most appropriate to the design case.

The design should be developed to facilitate eventual disassembly and re-use of elements or separation of materials for re-use or recycling.

The specification should include the project requirements for the carbon intensity of the concrete. The specification should provide as much flexibility as possible to the concrete producer to satisfy the project requirements, taking account of the available materials.

The client must provide overall direction to enable all of the above. Design and procurement need to be aligned with a constant focus on reducing carbon.

3.1 A hierarchy for design to minimise whole-life CO_2e

Table 3.1 (see overleaf) summarises the approximate proportion of whole-life CO_2e that is at present typically assigned to each of the LCA stages for concrete. In future, the proportions will vary as different sectors of industry decarbonise at different rates.

Table 3.1: Typical distribution of structural concrete CO_2e to different LCA stages[2]

LCA stage		Typical proportion of whole-life CO_2e
A	Before use	
A1 to A3	Cradle to factory gate	75%
A4 and A5	Transport and construction	15%
B	In use	Minimal*
C	End of life	10%
D	Subsequent benefits and loads	Varies

**CO_2e due to maintenance can be significant in some environments, particularly those with exposure to sea salts or de-icing salts. Carbonation of concrete causes limited take-up of concrete during the service life.*

Once it has been established that it is not possible to 'do nothing' or to re-use an existing structure or element, and that an alternative material would not provide a lower-carbon solution, the following hierarchy of design action is recommended:

1. Reduce the CO_2e attributable to LCA stage A, 'Before use'
2. Design and detail for a long life and to reduce requirements for in-service maintenance
3. Design to facilitate re-use insitu
4. Design and detail to ease disassembly and re-use or reclamation of complete elements or materials at the end of life

The hierarchy is intended to minimise carbon emissions as the UK concrete and construction industries transition to net zero.

Design and detailing for a long life protects embodied carbon and is achieved by following industry guidance on details and mix design appropriate to the service environment. In many cases, if industry guidance is followed, the CO_2e arising from requirements for structural maintenance during the design service life is minimal. Exceptions do occur and CO_2e due to maintenance can be significant, particularly in environments that include exposure to sea salts or de-icing salts. In these conditions, particular care should be taken to reduce requirements for in-service maintenance, perhaps through the use of protective barrier layers and proactive planned inspection and maintenance.

In-use benefits attributed to the use of thermal mass to reduce heating or cooling needs are subject to assumptions about the rate of decarbonisation of the energy supply.

Over time, concrete carbonates, absorbing CO_2 from the environment. For most concrete the extent of carbonation during service is limited. However, correctly planned and managed carbonation after demolition may be significant (see Strand 7)[3].

Much of the concrete cast now will remain in place after the construction industry has achieved net zero. For concrete with a shorter planned service life, such as many temporary works elements, attention should be paid to reducing the CO_2e that will arise during LCA stages C and D. This is likely to include facilitating re-use, either in-situ or following disassembly and relocation of elements, or separation of materials for re-use or recycling.

This strand addresses the need to move to net zero carbon for new concrete and minimise carbon emissions as the industry transitions to net zero. Therefore, the remainder of this section focuses on step 1.

3.2 Adopt best practice in structural arrangements to reduce structural demand

The structural arrangement describes the overall form of the complete structure and the layout of structural elements within that overall form.

Structural forms that reduce bending in elements and rely principally on axial loads (tension, compression) generally use less material and therefore result in lower GHG emissions. Arches, domes and catenary structures are examples of structural forms that minimise bending and typically deliver efficient structures. Usually, it is not possible to adopt a form in which the structural elements act in axial load only. However, it is often possible to adjust the form to reduce bending moments.

Layouts that reduce the span of slabs and beams usually require less materials and result in structures with lower CO_2e.

Post tensioning is often an effective means of reducing concrete quantities. However, analysis by Byrne Bros shows that care is required to ensure that requirements for early strength gain to limit creep relaxation do not result in an overall increase in CO_2e.

Sometimes the lowest carbon design uses concrete working compositely with other materials. Examples include concrete slabs cast compositely on metal or timber permanent formwork. Making best use of the attributes of individual materials is key to optimising embodied carbon.

In building structures, a typical breakdown of structural concrete volumes is: 50% slabs; 20% foundations; 20% lateral stability system; 10% columns and other walls. Reducing the spacing of columns supporting a flat slab from 9m to 7.5m, a 17% reduction in span, typically reduces the embodied carbon for LCA stages A1-A3 by at least 20%.

Structures with a simple, repetitive layout of elements tend to have lower embodied carbon. This may be because rationalisation of element sizes and bar layouts leads to inefficiencies in structures with a more complicated layout.

Further reading

- Building for a Sustainable Future: Construction Without Depletion, Mike Dixon, Institution of Structural Engineers
- Design for Zero, Institution of Structural Engineers

3.3 Optimise elements for embodied carbon

Use of voids, coffers and non-structural fill

In many structures, large volumes of the concrete contribute little to the structural performance. Sometimes it is possible to omit some of the concrete or to replace some of it with low-carbon non-structural fill such as gravel or low-strength infill concrete. In some cases, this can reduce the concrete volume by more than 50%[4]. Care is required in the selection of void formers: sacrificial polystyrene void formers may contain more carbon than the displaced concrete.

Often, only a small proportion of the concrete on the tension side of the neutral axis is required to carry shear load, hold the reinforcement in position, and provide corrosion and fire protection to the reinforcement. Careful placement of voids in these locations can reduce overall concrete volume by 30%-50% (c.f. waffle slab, coffer slab, T and TT precast units)[4].

In thick sections such as raft slabs, the central part acts principally as a spacer to hold the tension and compression 'flanges' apart. Voids or non-structural fill can be used in the central section to reduce the volume of concrete. Similarly, voids in profiled retaining wave walls may be filled with non-cementitious material when weight is needed for stability.

The technology exists to cast voids and coffers into concrete sections. However, the cost premium from use of more complex formwork currently exceeds the financial saving achieved by reducing the concrete volume. Economics of construction were different in the 1950s-70s, when voids and coffers were widely used. Reintroducing voids and coffers in contemporary designs can make a substantial contribution to reducing CO_2e.

Structural utilisation and optimisation

'Utilisation' refers to how 'hard' a structure, or part of a structure, works to resist the design loads. 'Optimisation' refers to how efficiently material is used throughout the structure. Utilisation can be governed by the 'serviceability limit state' (SLS) or the 'ultimate limit state' (ULS).

Serviceability criteria define the in-service performance requirements, such as limits on deflection. A structure, or part of a structure, with an SLS utilisation of 100% is at the limit of one or more of the serviceability criteria.

If a structure, or a part of a structure, has a ULS utilisation of 100%, the risk of collapse under one or more of the specified loading combinations matches the risk that society has determined to be appropriate. Note that failure is extremely unlikely to occur until the loads substantially exceed the specified loading combinations.

The reported utilisation is the highest of all of the various SLS and ULS conditions. Efficient structures have utilisation of less than, but close to, 100%.

Papers by Dunant[5] and others report that the utilisation of the vast majority of structures and structural elements falls well below 100% and is often below 60%.

Designers should routinely report utilisation of structural elements. Clients should consider including reporting of utilisation rates as a design deliverable. Experience indicates that, although optimisation and utilisation may be hard to assess, simply asking for a utilisation and optimisation report improves material efficiency.

One part of a structure or element may be fully utilised while the rest remains underused. Therefore, a structure may have a reported utilisation of 100% but be poorly optimised. In an optimised structure, all of the structural materials work to the maximum extent possible to satisfy the SLS and ULS criteria. A fully optimised structure uses the minimum possible CO_2e to satisfy all of the SLS and ULS criteria.

Optimisation can be difficult to assess. Designers, including designers of concrete mixes, should report what steps have been taken to optimise the design and what further steps could be taken but have been discounted for economic or other reasons. Clients should consider requiring reporting of optimisation as a design deliverable.

Reductions in CO_2e that can be achieved by increasing utilisation are typically about 30%. It is anticipated that similar reductions in CO_2e may be possible by increasing optimisation.

Aim for optimal strength of concrete to limit carbon

For elements governed by axial load or shear, increasing the strength of concrete can reduce the volume of concrete required so that the increased carbon intensity of the concrete is more than offset. For elements governed by bending the reduction in concrete, volume achieved by increasing the concrete strength may be insufficient to offset the increase in carbon intensity of the concrete.

Design using the strength of concrete as constructed

Often, the quantity of cement (kg/m^3) in concrete is governed by construction criteria to achieve required fresh concrete properties, such as consistence (workability) or sieve segregation resistance. High cement contents are also used to reduce formwork striking time or demoulding, or to limit post-tension stress loss owing to early creep. This can result in concrete with actual strengths that significantly exceed the strength specified.

Sometimes reductions can be achieved in the overall quantity of concrete or reinforcement if the design is based on the strength of concrete that will be required to achieve construction criteria.

Limit early thermal cracking
Increasing the use of SCMs in concrete typically reduces the extent of early thermal cracking. This can reduce the CO_2e of any crack control reinforcement.

Avoiding risk of corrosion of reinforcement
Minimum cement content and cover are often determined to limit corrosion of steel reinforcement during the design life. In some cases, particularly those that include exposure to sea salts or de-icing salts, adoption of measures that reduce, or eliminate, the risk of corrosion of reinforcement may allow reductions in the cement content and cover. Both reduce the LCA A1-A3 greenhouse gas emissions. Use of measures such as protective barrier layers or non-corrodable reinforcement, such as glass fiber reinforced polymer rebar (GFRP) or basalt fiber reinforced polymer rebar (BFRP), to prevent corrosion of reinforcement are also likely to reduce the maintenance required during the service life.

Select an appropriate design life
Design to deliver an inappropriate 'design life' can substantially increase carbon. Care is required to balance the benefit of a long life and potential for future re-use against the release of additional GHG as a result of construction before the industry has decarbonised.

Structures are likely to be serviceable well beyond their design life, subject to an assessment and any associated remedial works. As such, unless there is a specific need for a longer design life, additional measures taken in new designs, which can add carbon, may be unnecessary.

Make full use of code provisions to reduce material quantities
Designers should make full use of provisions in the code to reduce the volume of structural materials while maintaining an appropriate level of performance. This includes taking into account enhanced workmanship and inspection to reduce cover to reinforcement[6] and partial factors[7]. Combining actions using Eurocode Basis of Design 0 equations 6.10a and 6.10b in place of 6.10 is reported to deliver reductions in material use of about 4%[8]. Where self-weight governs the design, annex C of Eurocode 0 can be used to reduce the partial factor for self-weight of precast concrete elements[9].

Analysis methods to reduce carbon
Substantial reductions in design actions may be achieved by using more accurate analysis methods. For ULS design, this may, for example, include measuring peak bending moments at the face of supports instead of at the analysis model nodes, use of a finite element model instead of an arrangement of beam and column strips, accounting for moment redistribution, strut and tie modelling, or use of a membrane, yield line[10] or reliability analysis[11] to calculate the design section resistance.

Reliability analyses take account of statistical variation of material and geometrical properties. Evidence indicates that a reliability analysis can deliver substantial savings. 'Big data' will enable collection of as-built data to provide increased confidence in statistical properties, leading to larger benefit from reliability analyses.

SLS criteria often govern design. In these cases, use of calculation to assess SLS performance in place of more generic methods can enable significant reductions in material quantities.

Balancing concrete and reinforcement quantities
The optimum design for minimum CO_2e varies with the carbon intensity of the concrete and reinforcement. In some cases, a thinner, more heavily reinforced section has lower CO_2e than a deeper section with less reinforcement. Typically, as the proportion of SCM is increased, the carbon intensity of the concrete reduces but the optimum section depth increases so that, although the concrete volume is greater, less reinforcement is required, resulting in a reduction of overall embodied carbon of the constructed item. Designers need to consider the sensitivity of their structure to these factors, noting also that cement type can influence cover requirements.

Use appropriate SLS and ULS performance criteria
Optimisation is not just about refining utilisation and mix design. Selection of the SLS and ULS performance criteria affects the material quantities required. There is more often scope to define project-specific criteria for SLS performance. This may include factors such as applied loads as well as limits for deflection, crack width and vibration at SLS. As many designs are governed by SLS requirements, this can present real opportunities for reducing material quantities.

3.4 Balance risk and consequence

The performance of new low-carbon concretes is often less well understood than that of established products. It may be appropriate to use products with less evidence of performance in locations where the consequences of failure are lower. For example, it may be appropriate to use a new concrete for haul roads and outbuildings before the concrete can be used for the structure of multi-storey buildings.

3.5 Be flexible and collaborate with contractors and suppliers

The specification of a low-carbon concrete is a collaborative effort. It is important that all of the stakeholders who have a part to play in influencing the carbon intensity of the concrete – the engineer, contractor, supplier, client and wider design team – work together to develop compliant and appropriate solutions.

To seek lower-carbon concrete, it can be tempting to include rigorous limitations on cement type and other criteria to maximise the use of cement replacements. However, this can be counterproductive, particularly if the construction demands force the supplier to use a greater quantity of a specific cement type to meet the necessary performance.

Collaboration with the constructor and the supplier of the concrete as early as possible is fundamental to establish the appropriate requirements of the concrete during its placement, when it has established early strength and in its final permanent state. Specifiers and engineers should also draw on knowledge within the industry by using the resources from concrete technologists, the Concrete Centre, and professional institutions where possible.

Once project-specific performance requirements are established, the supplier can identify suitable mixes for further discussion and identification of the most appropriate low-carbon option. It should be recognised that different batching plants will have different solutions to the optimum concrete, and it is important that specifiers become familiar with options available on their project. For example, the chosen or available aggregates will influence the cement content, water demand and the quantity of various specific admixtures for a given concrete.

As such, in contrast to a more restrictive specification, it can be beneficial to allow a greater range of flexibility in proposed mixes and discuss the most appropriate concrete and cement type for the various elements on the project. Any structural concrete will still need to meet the requirements for durability, strength, and any other criteria.

It should be recognised that there will be a greater range of lower-carbon cements available in forthcoming updates to the standards. Through collaboration and flexibility, the full range of low-carbon cements can be explored. The need to expand the range of potential cements will have an impact on both the supply and specification sides of the industry and will need to be considered carefully by all stakeholders; this may result in new market drivers within the sector.

Aspects of flexibility in concrete specification
A flexible specification should be open to different cement/combination types, which should be determined in the context of the types available from local suppliers. Where possible, provide opportunities to use lower-carbon mixes with a limited track record in less critical areas of a project.

Admixtures can play a significant part in reducing cement content and thus carbon. Allow and encourage the use of admixtures with demonstrated performance – this may include accelerators to enable rapid strength gain in mixes with a high proportion of SCMs.

Where possible, programme site works to accommodate the rate of strength gain of an available low-carbon concrete. The traditional requirement that the specified strength is attained at 28 days may lead to increased cement content. It may be appropriate to accept that the specified strength is achieved at 56 days, 72 days or later.

Sound site supervision
Enhanced site supervision and inspection has particular benefit when working with an unfamiliar concrete, or a mix that has reduced margin on the specified criteria. In these cases, the concrete supplier should be invited to contribute in the development of the site supervision plan.

Use of identity testing
With a more flexible approach to specification, testing may be viewed as a necessary safety net to ensure compliance. Conformity control[12] and identity testing[13] are essential methods of demonstrating that a concrete conforms not just to the design from the concrete producer but also to the performance required by the contractor and engineer.

The producer who is under a third-party accreditation is obliged to sample the concrete under continuous production at a minimum rate of 1nr cube/400m^3. However, it is common for specifiers to dictate additional identity testing, often at frequencies far greater than that already undertaken by the producer, to ensure conformity. The concept for identity testing is introduced where there is doubt over concrete quality, lack of independent data, or for structurally critical elements. Where there is no doubt, or when independent data exists, then the engineer should resist the temptation to replace reliable conformity data with relatively unreliable site identity data.

Unduly onerous identity testing regimes may cause concrete producers and contractors to include more cement in the mix design. This is counterproductive if seeking to utilise a lower-carbon concrete. This practice is exacerbated by the failure of some test samples owing to poorly sampled and cured concrete cubes, rather than a defective concrete.

To overcome the unintended consequences of an overcautious testing regime, engineers should collaborate with contractors and suppliers to agree an appropriate level of identity testing.

3.6 Set an upper embodied carbon limit, and request indicative values

The benchmarking section of this document (Strand 1) has sought to establish a frame of reference from which concrete carbon intensity can be measured. However, the data for carbon intensity of concrete is still in its infancy and there remains considerable uncertainty and variation.

Environmental product declarations that set out the global warming potential of materials, measured in CO_2e, are available for ready-mixed concrete. Generic EPDs and industry databases are a useful source for concrete CO_2e values during the development of the design. However, once mix designs and batching records are available, CO_2e values should be based on these. Mix design certificates should include the carbon intensity (kg CO_2e/m^3) of the concrete. Carbon intensities based on mix designs should be verified by supplier reporting of the carbon intensity of the concrete as batched. At the time of writing, some concrete producers are not able to provide carbon calculations based on concrete as batched. Where possible, the carbon calculations based on mix designs and batching records should use CO_2e values of the mix ingredients obtained from product-specific EPDs.

Requiring the concrete supplier to provide embodied carbon calculations for the project mixes should be standard practice.

The benchmarking strand allows us to understand the real-world carbon intensity of concrete. From this, we can identify reasonable upper bounds for carbon intensity that can be incorporated into specifications. It is intended that this be used in a similar fashion to the approach adopted by the Institution of Structural Engineers with the SCORS curve[14] for overall carbon per m^2.

It is envisaged that it will be possible to include a target embodied carbon range in specifications in order to view potential options for a given project. Target embodied carbon ranges must take account of the agreed construction requirements for consistence and early strength gain.

There is an opportunity for concrete suppliers to publish data on the carbon intensity of their mixes. This will help designers to specify upper bounds on concrete CO_2e that can be supplied.

> “The specification of a low-carbon concrete is a collaborative effort. It is important for all stakeholders who have a part to play in influencing the carbon intensity of the concrete – the engineer, contractor, supplier, client and wider design team – work together to develop compliant and appropriate solutions.”

Publication by concrete suppliers, and preferably by individual batching plants, of the carbon intensity of their mixes will help project teams to identify the suppliers that are best able to deliver the project requirements for CO_2e.

3.7 How to specify an appropriate embodied carbon for a concrete

When seeking the lowest-carbon concrete in a project, it is important to approach the design and specification in a systematic way with the overall goal of optimising the carbon part of a holistic approach.

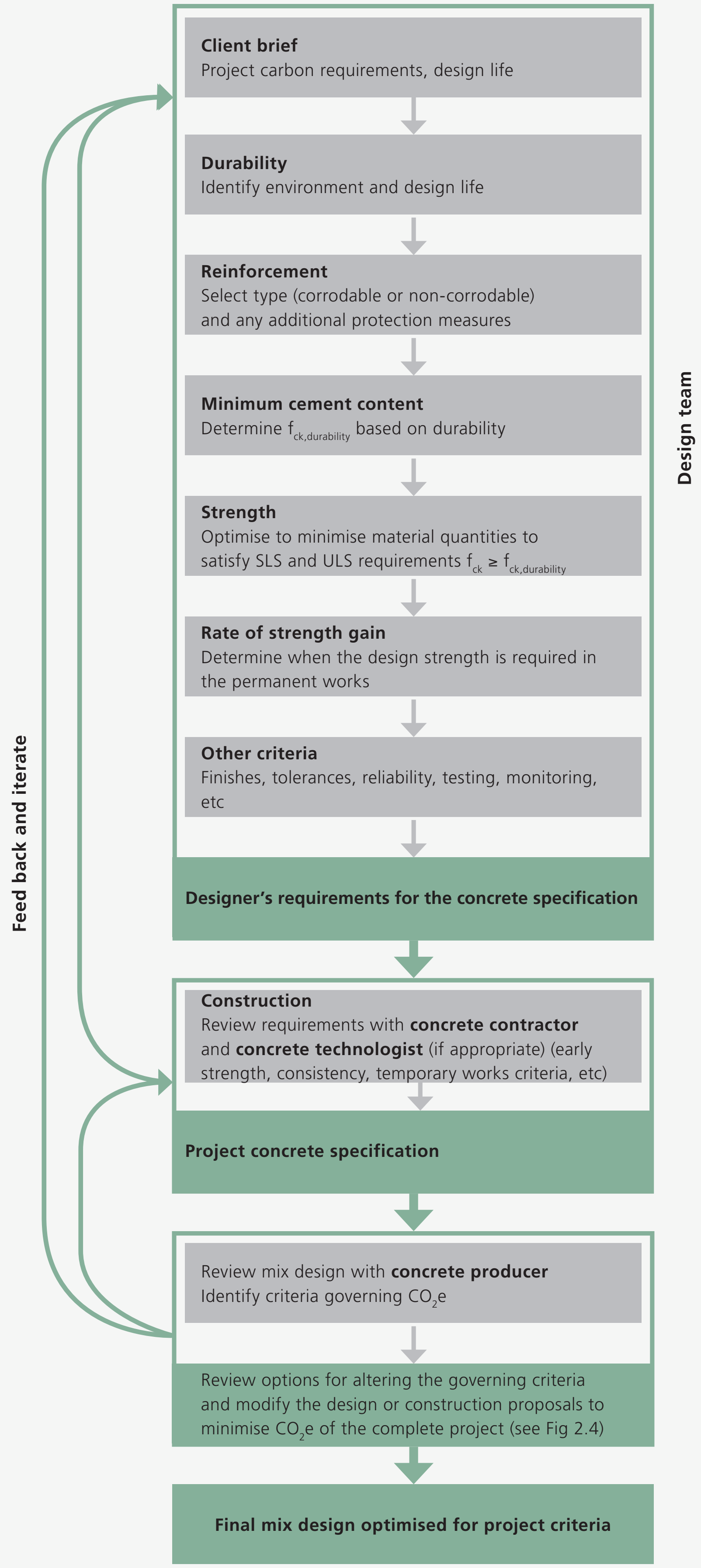
It should be recognised that, in some circumstances, the carbon intensity of the concrete in a given element may be increased to optimise carbon across the whole project. Fig 3.1 provides an indicative flow diagram that sets out a systematic approach that can be adopted in the development of a concrete specification.

Design and specification

1 BS EN 1992-1-1 Annex A
2 Astle P (2021) How can we reduce the embodied carbon of structural concrete, The Structural Engineer 99, 2; Frischknecht et al (2019) Comparison of the environmental assessment of an identical office building with national methods, IOP Conf. Series: Earth and Environmental Science 323, section 3.2, Fig 2
3 BS EN 16757, due to be published in 2022
4 Drewniok M (2021) Relationships between building structural parameters and embodied carbon Part 1: Reinforced concrete floors solutions (ENG-TR.013): www.doi.org/10.17863/CAM.75783
5 Dunant C F et al (2021) Good early-stage design decisions can halve embodied CO_2 and lower structural frames' cost, Structures 33, 343-354
6 BS EN 1992-1-1 cl. 4.4.1.3(3)
7 BS EN 1992-1-1 cl. 2.4.2.4(3) and A.2
8 BS EN 1990 cl. 6.4.3.2
9 BS EN 1990 Annex C
10 Kennedy and Goodchild (2004) Practical Yield Line Design, The Concrete Centre
11 BS EN 1190 Annex B
12 EN 206:2013+A1:2016, Annex B
13 EN 206:2013+A1:2016, cl. 8
14 Arnold W et al (2020) Setting carbon targets, The Structural Engineer, October
15 BS EN 1990 Annex D

Low Carbon Concrete Routemap

Fig 3.1: Flow diagram for the specification of optimal low-carbon concrete



Low Carbon Concrete Routemap

Case study: Network Rail optimisation of precast platform slabs

Client: Network Rail
Contractor: G-Tech Copers
Precast concrete: Anderton Concrete
Structural engineer:
Studio One Consulting
Innovation partner:
Expedition Engineering
Concrete consultant: AMCRETE UK

Many of the principles described in Strands 3, 4 and 5 of the Routemap have been applied to reduce the embodied carbon of precast concrete platform slabs.

The resulting changes are being introduced incrementally. Much of the reduction in embodied carbon has been achieved by changing the types of concrete and reinforcement. However, section optimisation and partial factors have also contributed.

Partial factors

Measurements of cast units and the coefficient of variation of the concrete strength demonstrated that the partial factors for concrete and steel reinforcement could be reduced from 1.5 to 1.35 and 1.15 to 1.05 respectively[7].

Assessment of the weights of cast units and a review of the accuracy of analysis and verification methods, which included load testing[15], demonstrated that the partial factor for self-weight could be reduced from 1.35 to 1.05[9].

The studies demonstrate the potential for partial factors to be reduced where the quality of construction is high.

Section optimisation

In the final design, the form will be modified so that the spanning units taper towards each end. The tapered form reduces the volume of concrete and improves optimisation for bending. The arrangement of reinforcement has

been developed to increase utilisation and the layout has been optimised.

Carbon intensity of components

The use of SCMs is being progressively increased to reduce the Portland cement content. The current design uses an 80% GGBS mix. It is intended that the cement content will be further reduced in the final design. The associated reduction in early strength gain has required alterations to the arrangements for demoulding.

The benchmark structural design specified a C40/50 mix. To satisfy the requirements for placement in the moulds and demoulding, the actual cement content used was consistent with a structural design based on a C50/60 mix. In this case, designing for a higher strength of concrete provided minimal benefit to reduce concrete and carbon. Therefore, the mix design and demoulding arrangements have been modified so that the cement type and cement content can be optimised for carbon for the strength class.

The precast units have minimum thicknesses varying between 65mm and 100mm. Non-corrodable reinforcement is used in sections with a minimum thickness of less than 100mm. In the final design, basalt reinforcement (BFRP) will be used where non-corrodable reinforcement is required rather than stainless steel. This change (from stainless steel to BFRP) substantially reduces the CO_2e of the reinforcement of these units.

Load testing has demonstrated that in some (but not all) of the precast units, loose bar or mesh reinforcement can be replaced by fibre reinforcement, which will contribute to reducing carbon.

Carbon reduction

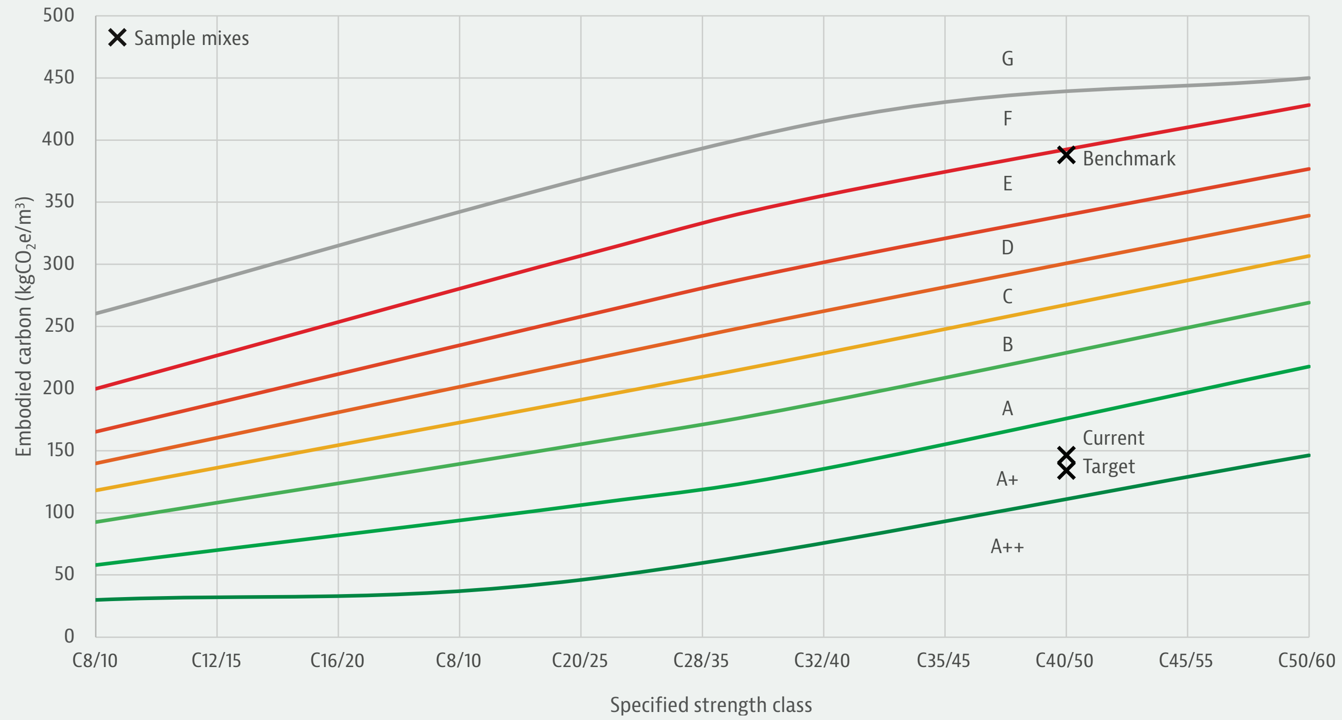
To date, the cement has been changed from a CEM I to a CIIIB (80% GGBS). The reinforcement arrangement has been optimised and the utilisation factor has been increased. The geometry of the units has not been altered. Carbon reductions achieved to date vary with unit type from 45% to 49% [63%]. It is anticipated that the final carbon reduction will vary with unit type from 54% to 63% [66%].

Significance of transport and factory emissions

For the benchmark design, transport and factory emissions accounted for 11% to 18% [4%] of LCA Stages A1-A3 CO_2e. For the intended final design, transport and factory emissions account for 24% to 40% [10%] of CO_2e. This demonstrates the increasing significance of carbon emissions from transport and processing as the carbon intensity of the concrete and reinforcement is reduced.

■ *Note: figures are for LCA Stages A1-A3, cradle to storage yard gate. Figures in square brackets relate to kg CO_2e/m^3 for comparison with the Strand 1 benchmark and therefore exclude rebar, waste, casting, curing and transport of cast units to the storage yard.*

GCB LCCG Benchmark ratings for embodied carbon , normal weight concrete, LCA stages A1 to A3
(Readymix: cradle to batching plant gate, Precast: cradle to mould)



Notes :

- The benchmark ratings are based on embodied carbon of normal weight concrete mixes used recently in the UK
- Performance requirements may make it impractical to achieve some ratings for a particular application
- Achieving a rating of A, A+ or A++ through use of a high proportion of GGBS with an associated requirement to significantly increase the total binder content (kg/m^3) may not be an effective method of reducing global GHG emissions
- Opportunities for reducing the carbon rating may typically be achieved by adjusting: type and % of SCM, requirements for early strength gain, consistence, environment (e.g. by use of protective barrier layers), minimum cement content (kg/m^3), w/c ratio, use of admixtures, type and grading of aggregates, age at which the specified strength must be achieved, sources of constituents

Version 1.2 March 2022

Using concrete

4 Supply and construction

This section discusses aspects of concrete construction that can influence the adoption of lower-carbon concretes and the interaction between them. As has been stated in previous sections, arguably the most important recommendation is early collaboration between designers, contractors and suppliers to realise the lowest-carbon approach for a given project.

Early collaboration should address the following key areas:

- Offsite construction opportunities
- Waste avoidance
- Concrete supply opportunities and constraints
- Consistence, placement and striking for in-situ elements
- Temporary works
- Testing and validation

4.1 Offsite construction opportunities

Construction 2025[1] identified offsite construction as a strategy that would facilitate a 50% reduction in waste and 25% less energy in use. At the early design stage (e.g. preparation of the brief, RIBA stage 1), use of offsite manufactured elements or structures should be considered as this can result in embodied carbon savings related to material efficiency, as well as savings related to waste reduction in the production process. For reinforced concrete elements, cradle-to-gate carbon savings from offsite manufacturing can reach 23%[2] (20% of concrete savings and 30% of steel for a double-storey residential building[3]).

In addition to the potential carbon savings, offsite works can reduce construction time and make construction independent from weather conditions. Time savings can even reach 50% (for a double-storey residential building[3]). With reference to section 3, offsite construction also offers the potential for the use of more sculpted elements that would not be practical to form in-situ.

The use of offsite precast elements must be considered as part of the collaborative process to reduce carbon. Precast concrete elements generally use larger quantities of cement with less or no cement replacements owing to the need for rapid demoulding and factory efficiency. Therefore, the benefit is currently limited to material efficiency and waste avoidance. However, if there is sufficient demand for lower-carbon precast elements, this may drive a different approach that could utilise the benefits of offsite construction with lower-carbon concrete. This will require new approaches to how precast elements are produced, considering curing and demoulding, but represents a significant opportunity to reduce the carbon intensity of concrete structures. Amendment to BS EN 13369:2018 (Common rules for precast concrete products)[4] may also offer an opportunity to embed embodied carbon criteria within precast products.

Key recommendations:

- Undertake a collaborative early assessment to identify opportunities for offsite elements that can contribute to a project-wide carbon optimisation approach.
- Encourage and support a greater uptake of lower-carbon concretes within precast construction facilities.

4.2 Waste avoidance

Reducing the quantities of wasted concrete is a significant opportunity to reduce embodied carbon in the concrete sector. In-situ concrete waste can reach 13%[5] but is usually 3%-6%[6,7], mainly owing to over-ordering and the leftover concrete[8]. Concrete waste includes fresh concrete returned to a concrete plant, residues inside the concrete truck drums or transit mixers or after production trials, and hardened concrete.

From current onsite practices, it is unavoidable to over-order ready-mixed concrete owing to uncertainty about the exact quantity required. In the UK waste from in situ concrete is estimated to be approximately 5%[9] and globally it is estimated that more than 125 million tonnes of fresh concrete is returned to ready-mixed concrete plants annually.

Concrete is also wasted because of errors onsite requiring amendment or total demolition and replacement. The Get It Right Initiative[10] identified errors in concrete works as the most costly out of all aspects of construction (see Fig 4.1 overleaf). Its recommendations should be adopted wherever possible to reduce waste.

It is also important that concrete works are suitably durable and robust to meet their design life, or longer if appropriate. Workmanship is an important area that affects the longevity of concrete elements, particularly the need to ensure adequate compaction and cover to rebar. Making durable elements that are resistant to the exposure classes can avoid unnecessary material wastage associated with repairs and premature replacement.

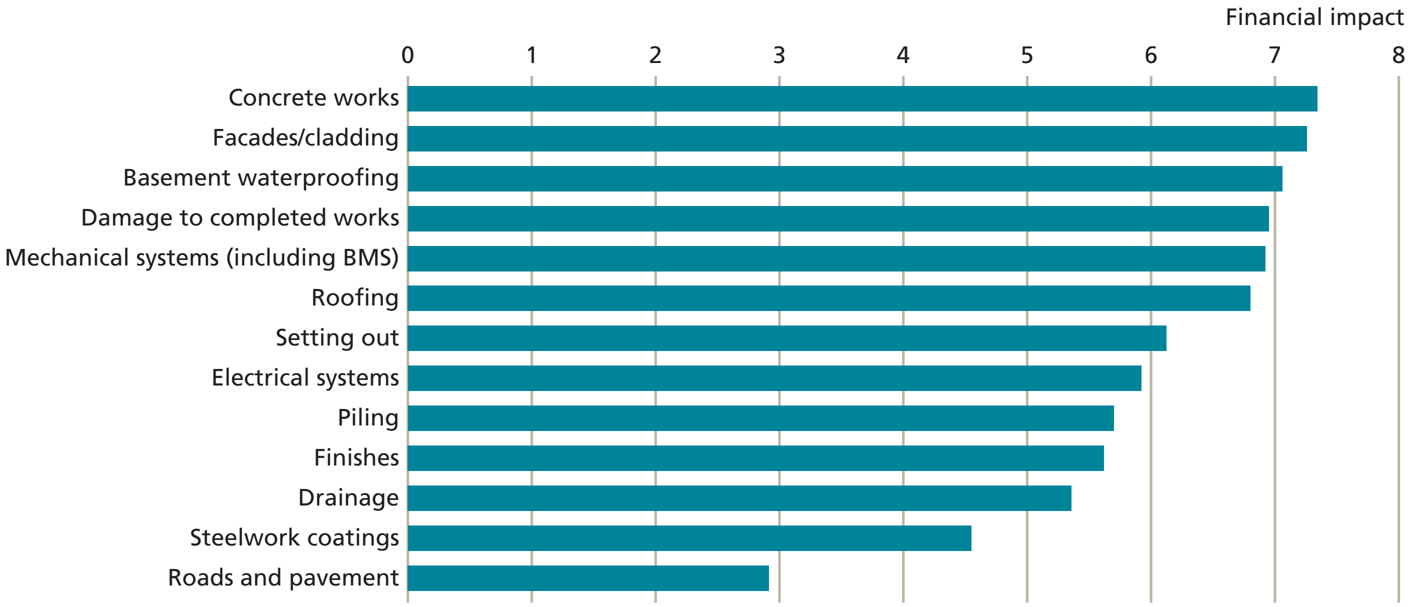


Fig 4.1: Most significant areas in terms of financial impact arising from errors in building (average values assigned)[11]

Key recommendations:

- Before construction, the project team should set out a waste avoidance plan. This should include detailed volumetric calculation and programme optimisation to avoid over-ordering.
- The concrete plant should have adopted recycling and re-use techniques and have implemented sustainable waste management systems.
- Robust pre-pour procedures should be in place to reduce the likelihood of construction error and to ensure adequate workmanship.

4.3 Concrete supply opportunities and constraints

In-situ concrete is a locally sourced material and its average travel distance is 16km. In 2019, the average delivery distance for all concrete was 48km and the average delivery distance for all raw materials for concrete was 49km[12]. As such, the extent of opportunities to use a lower-carbon concrete can be dependent on the materials available to local batching plants.

Still, if considering carbon alone, it could be effective to consider importing constituent materials from further afield depending on their influence on the carbon in the concrete, even accounting for mode of transport and associated emissions. There can also be limitations associated with the size and sophistication of the concrete plant. The use of plants with more sophisticated real-time production monitoring will allow more accurate batching and potentially a reduction in cement use.

Aggregate availability

Aggregates form the bulk of the mass of concrete and while they are typically inert, their size, shape, grading and porosity play a significant role in the water demand and hence cement demand of a given concrete. Table 4.1 shows the relationship between different aggregate combinations and the consequential impact of cement content to achieve the same strength. It can be seen that for the same concrete performance, the use of different aggregates could increase the cement demand by up to 17%.

As part of the wider drive towards sustainability and a circular economy, the use of recycled aggregates (RA), recycled concrete aggregates (RCA) and secondary aggregates (SA) are often

Mineral combination	Plain	Water reducing additive	Superplasticiser
Basalt/crushed rock fines/04 nat sand	440	390	370
Basalt/04 nat sand	390	350	330
Magnesium L.stone/crushed rock fines/02 nat sand	432	402	364
Quartz-based gravel and 04 nat sand	376	350	320
Oolitic L.stone/flint gravel/04 nat sand	388	366	334

Table 4.1: Cement content in kg/m³ (w/c = 0.5) for a mid-range concrete with 04/20 aggregates and an S3 slump class

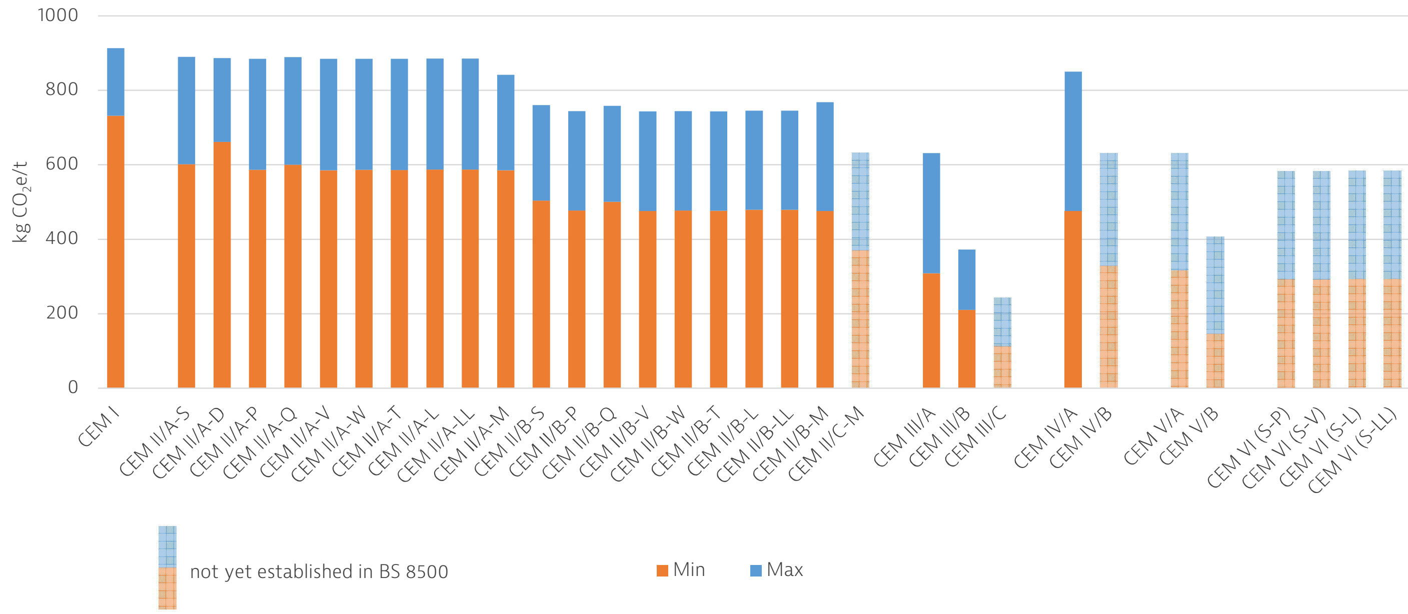


Fig 4.2: Cradle-to-gate carbon by cement types included in BS EN 197-1 and BS EN 197-5 (refer to references for breakdown of carbon intensity sources). All assumptions taken from available source literature.

highlighted by project teams as a sustainability aim on the assumption that it must lower carbon. However, while there are advantages to the use of these materials i.e. resource efficiency, waste avoidance etc, they are not necessarily beneficial with respect to carbon.

The properties of concrete with recycled aggregates are strongly influenced both by its type and proportion in the mixture. Recycled aggregate substitution can reduce the durability of concrete by increasing the water absorption and therefore increase the superplasticiser and the water dosage, in order to maintain the workability[13]. Consequently, the use of RA/RCA can increase cement demand by 20-40 kg/m³ [14]. Conversely, locally sourced, good-quality recycled aggregates could offer a carbon saving overall, including transport savings. However, a detailed sustainability and carbon assessment would need to be carried out to compare their use with natural aggregates.

Cement type availability

The European cement standard BS EN 197-1[15] defines 27 types of cements containing clinker (K), blast furnace slag (S), silica fume (D), natural and natural calcined pozzolana (P and Q respectively), siliceous and calcareous fly ash (V and W respectively), burnt shale (T) and limestone powder (L, LL). Most EN 197-1 cements can be produced in three strength classes (32.5, 42.5 and 52.5 MPa). This diversity offers great opportunities to lower the embodied carbon of binder. Used with the concrete standards EN 206 and BS 8500, a wide range of solutions can be provided.

Furthermore, there are other cements that are not currently identified in BS 8500 but which should be in future revisions. The carbon intensities of a range of EN 197-1 and EN 197-5 cements are shown in Fig 4.2. However, not all batching plants will have access to the full variety of available cements. As such, project teams should review what cements are available to their project and seek to find suitable options. For larger projects that require multiple batching plants, it will be important to ensure that concrete mixes are consistent. In these situations, it may be economical for plants to upgrade or expand their cement options to meet particularly large project demands.

More generally, there will need to be upgrades of facilities at scale to allow a wider roll-out of other cements while ensuring a smooth transition and phasing out of cements which are unnecessarily high in embodied carbon.

Key recommendations:

- Investigate aggregate type and availability to local batching plants and consider the consequences when developing the specification and optimising for carbon.
- Investigate the possibility of using recycled or secondary aggregates – but the impact on cement content must be tested before adopting their use.
- Investigate cement types available to local batching plants – this may influence the selected supplier.
- At an industry level, further engagement is required to understand what is necessary to enable an increase in capability and flexibility at batching plants to boost the range of cements offered.

4.4 Temporary works considerations

Temporary works elements are often only in use for months or even weeks to facilitate the main works. Despite this, and particularly on large urban projects, the temporary works are often very conservatively designed, which can involve the use of large quantities of concrete and reinforcement. This may be at least partly down to the fact that the code for structural concrete use, BS 8500-1, sets a minimum cement content for durability that is based on a 50-year design life. Provision for a shorter design life, or an alternative clause for temporary works with a life of less than two years would provide a simple mechanism to address this.

Opportunities should also be investigated to avoid the need for temporary works. At an early stage, the construction approach should be considered and the likely temporary works identified to determine whether there are design opportunities in the permanent works to optimise element design for carbon, considering both permanent and temporary requirements.

Temporary works design is often a critical path item with little time for detailed refinement. Establishing the key aspects early may allow an earlier appointment of the designers and a lower-carbon, more cost-effective, solution.

Key areas to consider:
■ Can the temporary works be made up of reusable elements?
■ Can the temporary works be designed for later re-use?
■ If mass is required, in thrust blocks for example, use the lowest possible strength or use concrete only where necessary and use a fill to provide the necessary mass.

Key recommendations:
■ Carry out an early workshop to identify main temporary works requirements.
■ Seek to design out requirements or allow sufficient time for more refined design.
■ Ensure that temporary works design is not dictated by inappropriate code clauses that can lock in excess carbon.

4.5 Consistence, placement and striking of in-situ elements

Consistence
The consistence or workability of fresh concrete (the ease with which concrete can be mixed, placed, consolidated and finished) is important and is affected by water content, aggregate type, shape and size, cement content and the use of admixtures. The workability of fresh concrete should be suitable for each specific application to ensure that the operations of handling, placing and compaction can be undertaken efficiently.

There can be different reasons for the need for a highly workable mix, such as the placement method, location of the element to be poured, the congestion of rebar, the architectural finish or the construction tolerances. However, in general, more workable mixes tend to increase cement demand and hence embodied carbon.

As part of the early collaboration on a project, the team should discuss the need for consistence of different elements and whether there are any opportunities in design, construction or mix design that can reduce the need for greater cement levels.

The use of self-compacting concretes (SCCs), which are proprietary high-flow mixes, can result in higher cement demand owing to the fines and water required, but this does not have to be the case. The carbon footprint of the industrial architectural SCC developed by Skanska (C30/37) using blast furnace cement and fly ash was 138kg CO_2e/m^3, compared with a typical SCC with a carbon footprint of 320kg CO_2e/m^3 (C30/37, CEM I with fly ash)[16]. Other proprietary SCC mixes are available offering similar performance.

There can also be construction and safety advantages in avoiding mechanical compaction and increasing the speed of construction works. As with all aspects of optimising carbon, a holistic approach must be taken to determine the most appropriate properties that satisfy the construction requirements while also providing the optimal lowest-carbon approach.

Strike time
The duration of setting formwork, placing concrete, curing and striking is critical to the efficiency of concrete frame construction. Formwork can only be removed when the concrete has developed sufficient strength to support itself, without excessive cracking, and to avoid mechanical damage. A minimum strength of 5 MPa is recommended in the National Structural Concrete Specification (NSCS)[17].

The speed at which a slab develops the necessary strength is a function of cement type, cement content, temperature and curing method. Using cements containing SCMs, particularly at large percentages, can slow strength gain. This is often cited as a reason to either limit replacement or maintain high cement levels. However, as can be seen in Fig 4.3, the impact on strength gain can be relatively small and may not be significant enough to affect strike times. By using accelerating admixtures, it is possible to mitigate the reduction in the rate of strength development.

It is important to review the necessary rate of strength gain for each component and optimise the programme and concrete mixes to allow a practical approach that enables the lowest carbon concretes to be considered. The development of the proposed mixes must also account for the likely seasonal impact which may require adjustments to maintain the same properties.

There is also the tendency for a conservative approach to cement content and blend owing to the uncertainty of the strength gain of a given element. It is possible to use sensing technology to monitor the temperature of the concrete during curing, which potentially allows a more accurate assessment of strength gain and can help in optimising programmes and quality assurance. There is also a significant opportunity to improve the sharing of strength data between sites and suppliers to further inform the real strength behaviour and avoid overly conservative mixes.

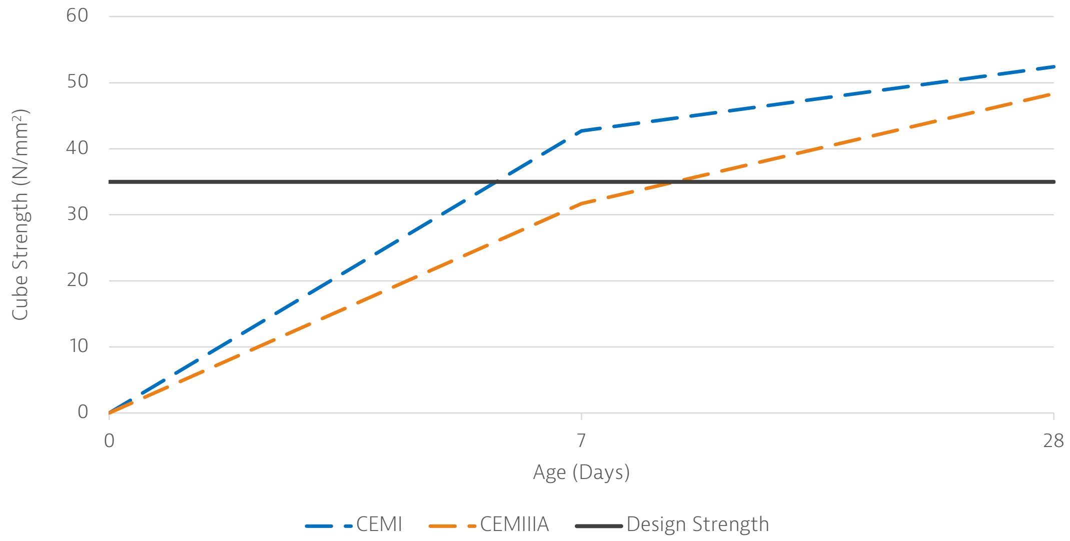


Fig 4.3: Rate or strength gain for a CEM I versus a CEM III/A mix. Data courtesy of CEMEX

Key recommendations:
■ Workability requirements tested at an early stage to avoid locking in the requirement for additional cement in a mix. Admixtures should be used to improve characteristics without increasing cement content.
■ Systematic review of early strength requirements of different elements to allow the optimum balance between embodied carbon and programme need.
■ Sharing of real site strength results with suppliers to improve understanding.

4.6 Verification and quality assurance

Once concretes have been developed with the supplier and the contractor to meet the project needs and have been optimised for embodied carbon, it is important that the supply of concrete is consistent across the project duration. The contractor should implement a quality control plan for concrete works which includes checks on the constituents of the concrete. Where appropriate, a concrete technologist should be appointed to respond to changes in the workability of the mix. This will reduce the risk of incorrect execution of concrete works and avoid the need for more conservative mixes that lock in additional carbon.

More generally, a shift in ownership of the testing and quality plan from the supplier and contractor to the client, which is standard practice in the US, may lead to a more robust testing regime.

Key recommendations:
■ Quality control plan to ensure delivered concrete is as per the optimised mix.
■ The appointment of a concrete technologist to advise changes to the mix to meet site requirements without further increasing carbon.
■ A review of ownership of quality test plans to improve efficiency and efficacy of quality systems.

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Making concrete

5 Optimising existing technology

Portland cement, with proven partial replacement materials, is likely to remain a major part of UK and global development for the foreseeable future. Without action, this demand on our natural resources and cement manufacture will increase the amount of CO_2e released into the atmosphere, thereby contributing to anthropogenic climate change.

Research and development of future technologies is essential and must continue. However, we can and should optimise the use of proven technologies that are available now, including Portland cement-based concrete.

Even though the discussion in this section is focused on Portland cement-based concrete, the principles remain relevant for other cementitious materials.

5.1 Always aim to use a cement type with the lowest possible embodied carbon

Broadly speaking, the greater the use of SCMs such as GGBS, fly ash and now increased proportions of limestone powder to replace Portland cement, the lower the embodied carbon of the cement.

The concrete supplier should be directed by the project mix design request to produce a mix of the lowest possible embodied carbon that also meets the project performance requirements. Concrete technologists and the concrete producers' technical teams are best placed to understand and influence the performance of their materials. It is imperative, and sensible, that they are afforded the opportunity to influence the mix design rather than simply develop a prescriptive design.

The concrete supplier should be provided with the maximum possible time and opportunity to select a cement to do this and, where possible, concrete specifications should provide the mix designer with flexibility in selecting the cement to use. This requires early engagement and a collaborative approach.

In the UK, BS EN 197 parts 1 and 5 and BS EN 14216 cover cements that use Portland cement clinker as the main active ingredient[1] (see Fig 4.2, page 43). The non-clinker ingredients include SCMs such as GGBS, fly ash, calcined clay and limestone powder.

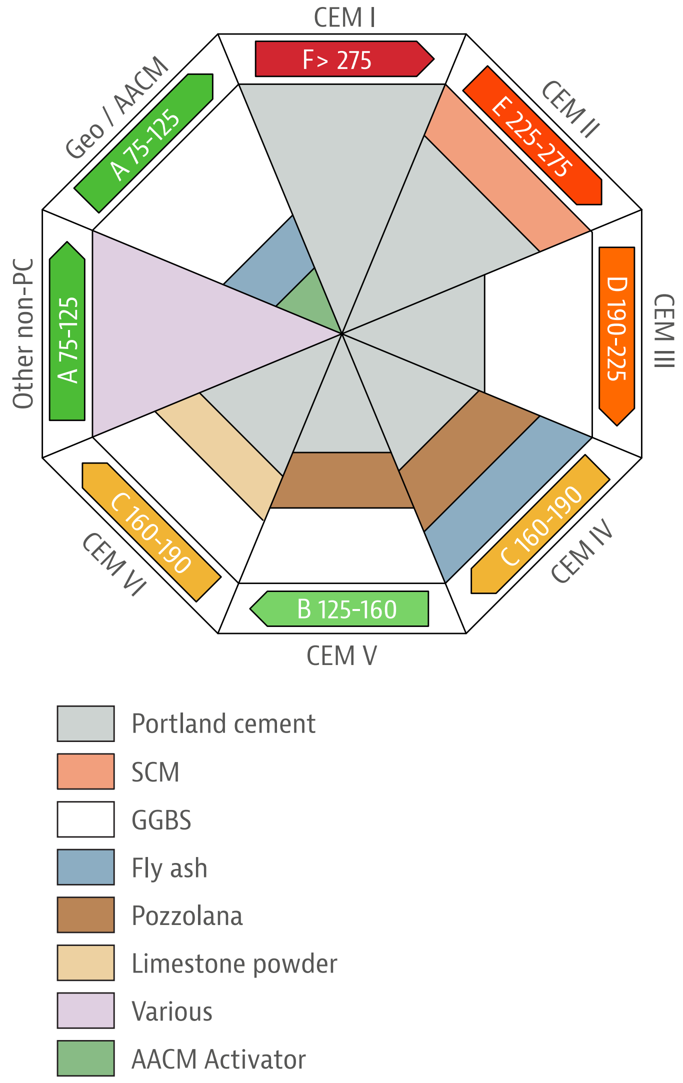

Fig 5.1: Typical carbon content of concretes made with different cements

BS EN 206[2] provides guidance on the use of all EN 197-1 cements in concrete. However, BS 8500[3] (the complementary British Standard to EN 206) provides guidance only for a subset of the EN 197-1 and BS EN 14216 cements that are identified as 'general purpose' cements. These have varying CO_2e which are linked mainly to SCM type and content.

PAS 8820 covers AACM technology and provides guidance for the use of AACMs in concrete – this includes cements that contain less than 5 per cent Portland cement of the total cementitious material. The LCCG supports plans to update PAS 8820 or to establish a British Standard for AACM and geopolymer cements and activators, through invitation to contribute within a working group headed by the MPA. Other cements covered by standards include calcium aluminate cement (BS EN 14647) and supersulfated cement (BS EN 15743). Currently, there is no UK guidance on how to use these cements in concrete. Cements that are not identified in BS 8500 require rigorous testing to demonstrate that the concrete made with the chosen cement meets the performance requirements of the application. The exposure environment will dictate the testing requirements. Equivalent durability procedures are described in PD CEN/TR 16639 (for EN 197-1 cements) and PAS 8820 (for AACM cements). Other cements should follow the principles outlined in PD CEN/TR 16563.

A case study is provided in Strand 6 (see page 57) that explains the strategy that a new-entrant cement technology to the industry will be taking over the next couple of years. The strategy aligns with this Roadmap, Strand 6 and Fig 2.3 (page 26).

Commercial availability of cementitious materials used for the manufacture and blending of all cements varies over time, sometimes rapidly, as shown in Fig 5.2. Owing to the necessary increase in cement content, when replacing Portland cement with an SCM, as explained in Strand 1, the individual prices for each component – Portland cement, GGBS, fly ash and limestone powder – will influence the final cost of any concrete design, regardless of its embodied carbon or rating (see Fig 5.1, previous page, and 'Setting the benchmark', page 15). Good communication between the concrete supplier and customer is therefore necessary to confirm which of the available cements should be used to produce concrete with the lowest possible embodied carbon.

5.2 Use cementitious materials other than GGBS and fly ash where possible

Fig 2.1 (page 23) summarises global availability of cementitious materials. Clays and limestone powder are the cementitious materials with the greatest availability. Portland cement is the most widely used cementitious material. At present, the SCMs commercially available at scale from batching plants in the UK include ground granulated blast-furnace slag and fly ash. These are already widely used and imports to the UK are currently used to meet demand. As steel manufacturing develops to improve and reduce its own carbon emissions, the regional availability of GGBS will reduce as a consequence, putting greater pressure on existing feedstocks and creating an increased reliance on imports.

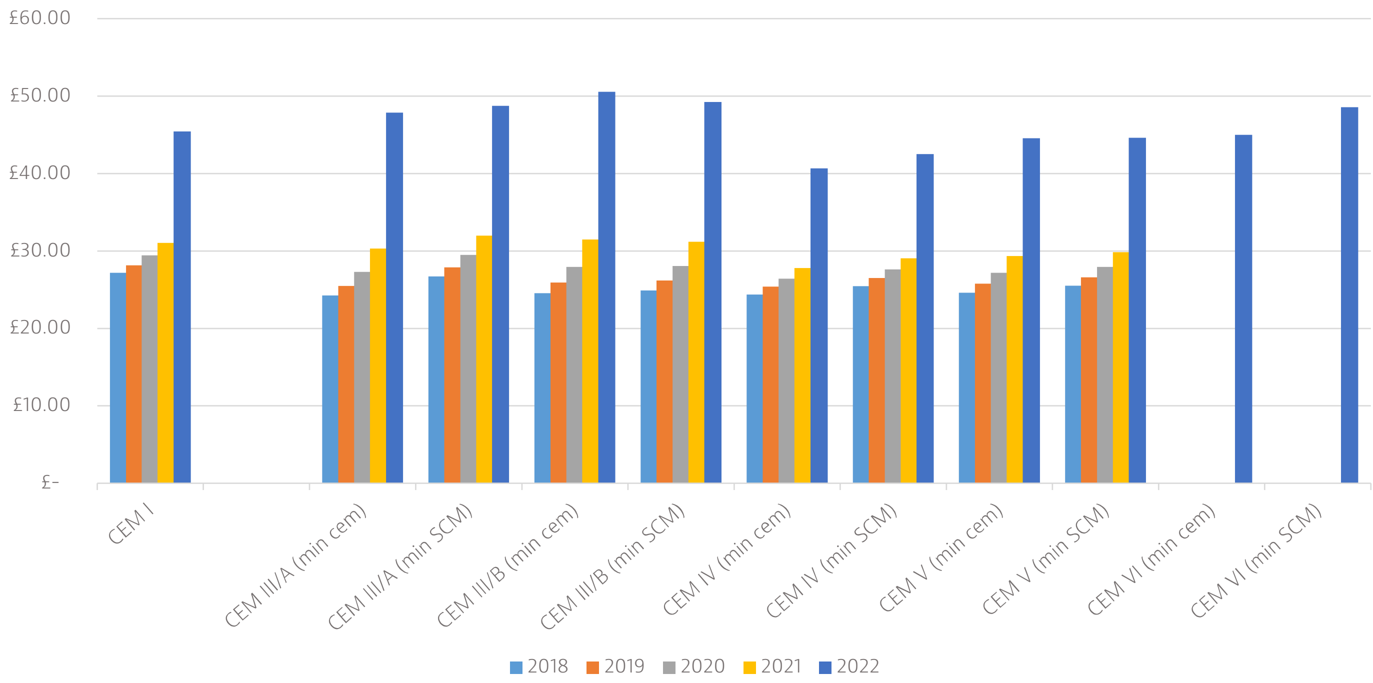

Fig 5.2: Proportion/m³ cost for cement types in typical C32/40 concretes to suit exposure class XD1, identifying the effect of minimum cement content

Low Carbon Concrete Routemap

Production of fly ash as a by-product of burning coal is forecast to continue to decline. The UK has extensive stockpiles of fly ash: however, at present, technical barriers limit the use of fly ash from these stockpiles. The UK Quality Ash Association has been working with technology providers and the University of Dundee's Concrete Technology Unit to investigate the suitability of stockpiled fly ash as an SCM.

The use of GGBS or fly ash to replace some of the Portland cement in a concrete will reduce the carbon footprint of an individual mix. However, since the national supply of GGBS and fly ash is fully utilised, their use in any one mix may not reduce overall global greenhouse gas emissions. Where possible, a project should consider cements and other types of non-clinker cement constituents for which there is potential for surplus local supply.

In the UK, there is scope to rapidly increase the use of limestone powder to the limits defined in BS EN 197-5. In 2021, the MPA, in partnership with Hanson UK, BRE and Forterra, completed a testing and demonstration programme for a range of EN 197-5 cements to inform an update to BS 8500. One of the cements containing GGBS and limestone powder (CEM VI) had a CO_2e as low as 60% against a baseline of Portland cement (CEM I). A revision to BS 8500-2 is expected in 2022, which will identify some BS EN 197-5 cements as general purpose cements in BS 8500.

In the UK, in the medium to long term, calcined clays could provide the greatest scope as an alternative to the currently widely used and familiar SCMs. Research is in progress to identify suitable UK clays. Most calcined clays are understood to perform similarly to fly ash, with some more reactive (depending on purity)[4].

5.3 Minimise the cement content (kg/m^3)

When designing a suitable concrete mix, we are currently guided by the minimum cement contents prescribed by standards such as BRE SD 1:2005 and BS 8500-1:2015+A2:2019 and other specialist literature, including BS 6349-1-4.

Although concrete technology has evolved and improved in recent years, the prescribed values in BS 8500-1 have remained fairly static and, in some cases, been viewed as onerous. The LCCG supports more research to review and potentially reduce minimum cement content or affirm the relevance of current prescriptive guidance.

The minimum cement content in concrete mixes is determined by either:

- Using the prescriptive guidance in BS 8500-1
- Performance testing (BS 8500-2 cl 4.4.3)

The cement content should be sufficient to meet the performance requirements for:

- Exposure class (interpretation of BS 8500 tables A4, A5 and A9 needs engineering judgment for temporary works, as strength development could be the main and only requirement)
- Early strength gain
- Consistence (slump or flow)
- Water to cement ratio
- Nominal cover and durability of mild steel reinforcement
- Strength required in service, typically specified as the 28- or 56-day strength

5.4 Use a mix design request form

For communication between the concrete contractor, who is ultimately the specifier, and the concrete producer, a mix design request form should be used to determine the performance and characteristics of the required concrete. An example templates is provided in the National Structural Concrete Specification[5] and should be included in procurement documentation. The LCCG recommends that these templates are revised to allow the structural engineer to set a target maximum embodied carbon per m^3 for the supply chain to meet, or to justify why such a target cannot be met. For geotechnical works, a template can be found in ICE's Specification for Piling and Embedded Retaining Walls[6].

There is variation in the strength of concrete between batches. If this variation can be minimised, then there is an opportunity to optimise cement content. The mix designer aims to achieve a target mean strength (TMS) that is higher than the specified strength to allow for the variation between batches. Improvements in quality control, as well as confidence in workmanship onsite, can reduce the coefficient of variation of the as-cast concrete and permit a reduction of the TMS and therefore the cement content. Reduction in the coefficient of variation may also permit a reduction in the material partial factor for the concrete[7].

It is recommended that the concrete supplier is asked to propose extra measures to reduce the cement content, so as to reduce embodied carbon while providing the required performance.

Optimising existing technology

1 CEM I, CEM II, CEM III, CEM IV, CEM V and CEM VI and very low-heat variants (VLH)
2 BS EN 206:2013+A1:2016 Concrete – Specification, performance, production and conformity
3 BS 8500-1:2015+A2:2019 Concrete – Complementary British Standard to BS EN 206, part 1: Method of specifying and guidance for the specifier
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6 Institution of Civil Engineers (2016) ICE Specification for Piling and Embedded Retaining Walls, third edition
7 BS EN 1992-1 Annex A

5.5 Summary: optimising mix design

Parameter	Adjustments that may be considered
Early strength gain	Is it possible to keep formwork in place for longer and use correct curing techniques? Can the factory casting sequence be adjusted so that precast elements can be removed from the mould later? Can an alternative demoulding method be used?
Consistence (workability)	Is it possible to use an alternative method of placement or compaction? Is it possible to replace crushed aggregate with rounded aggregate? Discuss with the concrete producer
Water to cement ratio	Has the use of admixtures been optimised?
Durability of mild steel reinforcement	Would unreinforced concrete provide adequate performance? Could fibre reinforcement be used instead of bars/mesh? Could non-corrosive reinforcement such as GFRP or BFRP (basalt) be used instead? Silica fume could be considered to improve durability Do we need a strict minimum cement content for service life of a structure that is considerably less than 50 years? Encourage engineering judgment based on performance data Can exposure class X0 be adopted for temporary work elements where the short service life limits potential for corrosion?
Durability of the concrete	Can the concrete be protected from the environment, for example by using an external barrier system? Would use of SCMs increase durability? Would the addition of small quantities of silica fume increase durability by filling pores and reducing permeability of the concrete? If freeze thaw governs, has the use of air entrainment been optimised?
Strength required in service, typically specified as the 28- or 56-day strength	At what age will the structure be liable to the full service loads without assistance from temporary works? Can the age at which the specified strength is required be extended to 56 or 72 days?
Aggregate grading and selection	Can the aggregate grading and selection be further optimised?

Table 5.1: Measures that may allow the mix design to be adjusted to reduce the embodied carbon of concrete

Case study: Boston Barrier scheme – low-carbon innovations and approaches

Client: Environment Agency
Engineer: Mott MacDonald
Contractor: BAM Nuttall

Minimising carbon emissions was a significant driver in the design of the Boston Barrier. This was a key aim right from the initiation of the project and an ambition for both the Environment Agency and the BAM Nuttall/Mott MacDonald joint venture.

For the structural aspects of a project, the hierarchy of actions to mitigate carbon is to:

- Design out the need for the structure
- Use lower-carbon structural materials
- Efficient design to minimise reinforcement quantities and section sizes
- Use lower-carbon constituents in the concrete mix

Rising sector gate structural design
For the rising sector gate structure, in situ reinforced concrete was the only viable solution for such a complex shape that required high strength and physical mass to support the steel gate for a 100-year design life. Therefore, from a structural perspective, the focus was on steps 3 and 4 to maximise the carbon savings on significant volumes of reinforced concrete.

■ Efficient design
The gate support structure was analysed using FEA LUSAS software to accurately model the structural behaviour and obtain a clear 'map' of the stress patterns from all possible load combinations, such that the reinforcement could be efficiently designed. Section thicknesses were minimised wherever possible; however, owing to the nature of the gate housing, much of the element sizing was not dictated by stress requirements. As section thicknesses have a direct effect on the quantity of thermal reinforcement required, this was calculated using tools developed in-house rather than the more conservative commercially available design programmes.

The temporary works sheet pile cofferdam that encompassed the reinforced concrete structure was integrated into the permanent works through composite wall design. This efficient use of available resources had benefits for increasing vertical load capacity, as well as reducing uplift, furthering economical reinforcement design.

The design also used Design for Manufacture and Assembly (DfMA) approaches where possible, such as using precast concrete sections to create the curved recess to house the gate when in its open position. This removed the need for complex and bespoke temporary formwork in the cofferdam to create the same shape from in-situ concrete.

■ Low-carbon concrete design
The concrete mix for the barrier structure incorporated 70% ground granulated blast-furnace slag (GGBS), nearly the maximum permitted proportion. Limestone powder was adopted as the coarse aggregate in the mix. This is the preferred choice for water-retaining concrete as it minimises the coefficient of thermal expansion and hence lowers the reinforcement requirements (and also the potential for cracking).

There was significant collaboration with the concrete supplier to reduce the actual cement content of the supplied mix while still ensuring it met minimum strength requirements. Mott MacDonald worked with the concrete supplier, who trialled and tested several concrete formulations, and the target of 380kg/m^3 that was agreed, while still maintaining required strength. This saved 120,000kg of cement across the 6,000m^3 of concrete.

Design out the need for a structure
By developing the design, the critical plant was moved on to the first floor, above the flood defence level, which removed the requirement for waterproofing the entire structure. Therefore, piled foundations to provide resistance against uplift were no longer required.

What's more, the site investigation information suggested that the made ground in this location was of reasonable strength for shallow foundations, which was confirmed by a settlement load test onsite. In addition to safety and programme risk reduction, this meant that approximately 70 steel tubular piles were removed from the scope of the project, which led to savings of 360 tonnes of embodied carbon and reduced the time spent on construction by four weeks and on the design programme by three weeks.

6 Adopting new technology

Cement is the binding component in concrete, as obvious as it may sound – without it, the composite material will not work as it is designed and intended. The cement component is already varied but is currently dominated by cements based on Portland cement clinker. We are now seeing the promotion of, and case studies for, other cements, which will themselves require support from standards if they are to be added to the library of available and designed concrete mixes.

Apart from already existing materials, the emphasis should be placed on the research into new cement constituents such as synthetic SCMs or additives such as graphene and biochar which may serve to reduce the embodied carbon of concrete. Further work should include minimisation and use of alternative reinforcement and composite construction. Financial support from UK Research and Innovation (e.g. the Engineering and Physical Sciences Research Council, Innovate UK) is crucial for the faster implementation of solutions. Client leadership, active collaboration with academia, innovation centres, creation of new SMEs and start-ups are also essential.

In Section 2.1 (page 21), we discussed how to demonstrate the performance of cements that are not currently recognised in BS 8500. Here we make some proposals as to how these new materials could be standardised to increase their adoption.

6.1 Material selection should be sustainable

The wider sustainability impacts of material selection and the concrete's performance must be considered in parallel to the pursuit of lowering carbon. The concrete structure produced still needs to deliver on fire safety, resilience and occupant wellbeing. Materials should come from a sustainable, responsibly

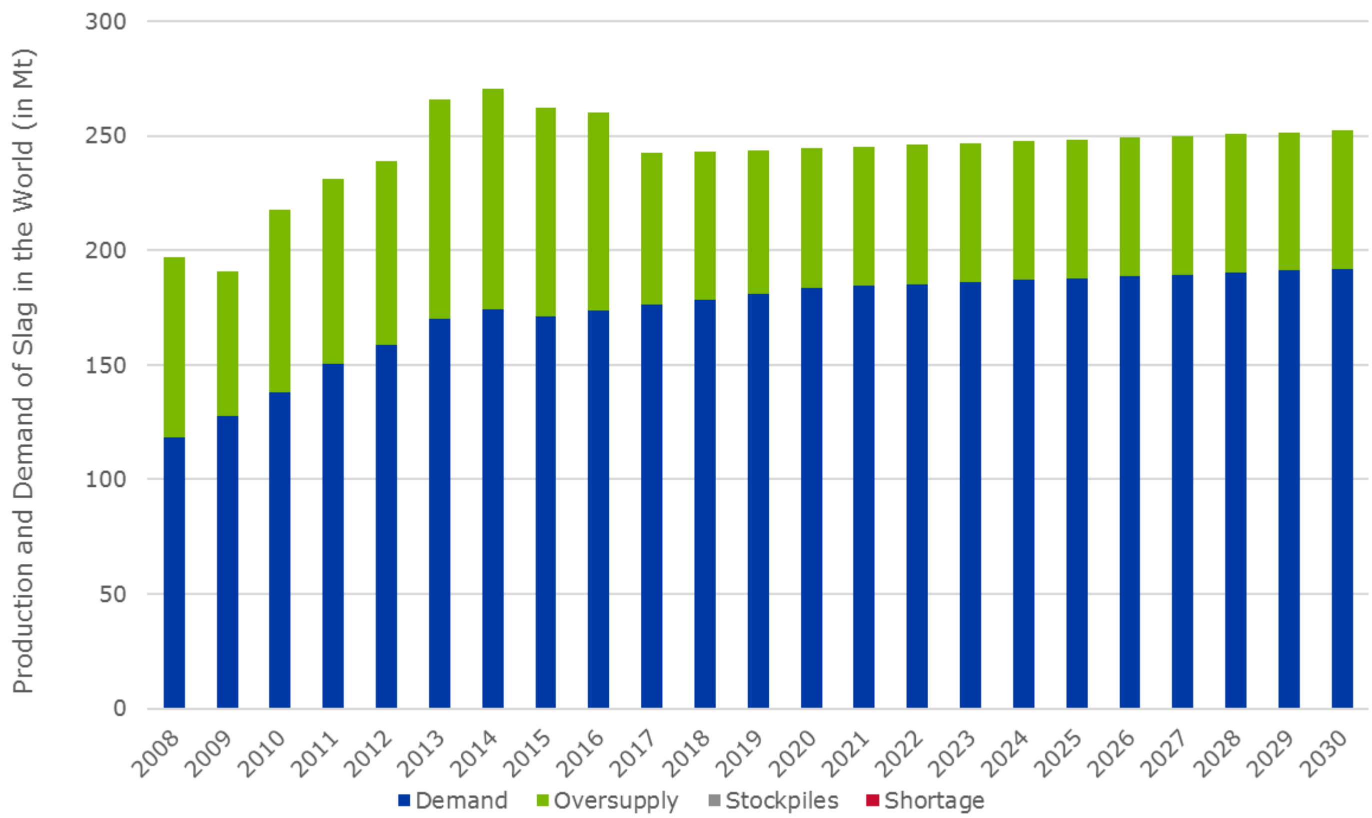


Fig 6.1: Global production and demand of GGBS (Mt)[2]

sourced supply chain with ethical treatment of people and the environment[1]. This is relevant for all construction materials.

Furthermore, when looking at mitigation actions for climate change, analysis must be considered on a system level. This is important when considering the role of finite materials.

Some new cement technologies are reliant on GGBS. When using these products, care is required to ensure that GGBS is not displaced from other uses that may have a greater effect on reducing greenhouse gas emissions globally, including consideration of transport.

There are different views on the likely medium- and long-term availability of GGBS. At the time of writing, energy prices have caused a short-term shortage. 'Many academics and people in the UK concrete industry expect medium- and long-term shortages in the UK; however, the Department for Business, Energy and Industrial Strategy's technical research paper 19[2] forecasts ongoing global surplus availability of GGBS (see Fig 6.1).

Concrete comprises more than just cements and, as such, we should consider the requirement for other constituents such as aggregates and reinforcement. These interdependencies are complex – they vary from product to product and are influenced by local availability and other project needs. A full lifecycle analysis, conducted according to relevant International Organisation for Standardisation principles[1] and not limited to carbon emissions, should be conducted for all new materials proposed for use.

6.2 Commercial viability must be demonstrated for equivalent and existing technologies

It is important to be aware that technical acceptance or certification is not, in itself, sufficient for a product to reach wide-scale adoption. While technical certification helps to reduce the perceived risks around use of a material and provides guidance on appropriate implementations, there are many other factors at play in a market as complex as the architecture, engineering and construction (AEC) sector.

A recent study, funded by the Engineering and Physical Sciences Research Council as part of the IAA Impact Starter Grants programme, published findings on the barriers to adoption of low-carbon concrete technologies[3]. Below is an extract, reproduced with permission from the authors, that identifies the following indicators of commercial readiness:

Regulation through policy
In the UK, construction regulations such as Building Regulations (England and Wales) and Building Standards (Scotland) determine what is and is not allowed in terms of building work for new and altered buildings. The highest level of development is where technologies are actively encouraged or even required by regulations as part of a performance standard.

Regulation through technical standards
Alongside policies, technical standards are widely used in the UK as a compliance requirement for the construction regulations and to ensure performance of materials, elements and structures. The most widely accepted technologies in the UK are typically included in BS EN and BS standards.

Stakeholder acceptance
The AEC industry in the UK has a complex and fragmented structure, with many different stakeholders involved in each project. As a result, a single stakeholder can often struggle to take up a technology without the acceptance of other stakeholders. Through its development, a technology may initially target acceptance in certain stakeholder groups before being accepted by all stakeholders in general industry consensus.

Technical performance
In industry, technical performance does not just relate to the analysis and testing required to achieve [technical readiness level] TRL9 (actual system proven in operational environment) but looks more broadly at the reliability of technology outcomes and the risks associated with implementation.

As technologies reach TRL9, increasing volumes of technical performance data and industry use cases will provide certainty around the ability of the technology to meet performance requirements in a range of applications and environments.

This is also essential in standardisation, for example in the conversion of a PAS document to a British Standard as is proposed for PAS 8820.

Financial proposition
Initially, the financial proposition of a technology is unknown as production costs and market value are not yet available. The highest level of financial proposition occurs when a technology has become cost-competitive with existing market alternatives, while offering additional value such as reduced carbon emissions.

Industry supply chain
The AEC industry is fragmented and has many supply-chain participants; being able to get a technology from the raw materials provider through to the end client involves the integration of many parts. The highest level of supply-chain development occurs when there are several competitive suppliers at each stage, creating a robust system.

Industry skills
With many stakeholders involved in construction projects, it is important that the skills needed in each group to correctly implement a technology are available. As development progresses, skills will be disseminated through early adopters of the technology before becoming common industry knowledge. The complexity of the sector means having one highly skilled stakeholder group is typically not sufficient to achieve market

penetration. The information presented in Strand 2, Knowledge Transfer, is highly relevant to this point.

Market opportunities
There must be a market opportunity for a technology for it to reach commercialisation. The highest level of opportunity is when the technology can be produced at scale and compete with existing alternatives due to demand-pull, rather than technology-push drivers. Vertical integration within large established market participants spanning different levels of the supply chain means that entry by new companies is relatively more challenging.

Company maturity
Where a new technology is being developed by a new company, the company maturity is at the lowest level. As the technology is developed, or adopted by larger companies, the company's performance record and market share with the technology grows to the point where the technology is being provided by industry-leading companies with strong track records.

For a new technology to achieve market penetration, all of these factors will need to be addressed. While technical performance and inclusion in technical standards are often the first items sought by product developers and users, it is important to consider the wider commercial context of the product to achieve significant emissions reductions through the use of lower-carbon concretes.

This is well illustrated by the fact that there are many more cements specified in the Eurocodes than are currently commercially available in the UK. In this case, the technical certification has not been sufficient to increase market uptake and several of the other commercial readiness indicators will need to be addressed (primarily supply chain, industry skills and regulation through policy) to bring these cements into common practice in the UK.

6.3 Certification, accreditation and codification of new cements and concretes

There are multiple routes to industry acceptance of new cements and concretes. These include:

- Inclusion in a new or existing British Standard (BS) published by BSI
- Inclusion in a Publicly Available Specification (PAS) published by BSI
- Holding a BBA (British Board of Agrément) certification
- Completion of a technical assessment leading to CE or UKCA marking by the Technical Assessment Body for the respective product area.

There is no exact timeline for the above and the processes can be complex. In some cases, the process is dependent on voluntary input from members of technical committees; obtaining input from volunteers can delay the process. Implementation of innovation solutions can be accelerated by increasing the financial support from UK Research and Innovation or by setting up expert communities of practice to support early adopters. The LCCG recommends a step-by-step process for submissions to the relevant bodies, as described below and in Fig 6.2.

Step 1: Information pack guidelines
An information pack should be developed that provides the essential technical information required to present and demonstrate the fitness for the intended use of the new cement or concrete. The guidance should recommend suitable performance testing as well as details of required evidence from independent testing facilities such as universities or commercial laboratories that are experienced in the range of tests. This guidance should be provided by the relevant technical committee and issued on request to those who seek to establish a new or revised standard.

Step 2: Technical dossier and case studies
A technical dossier should be developed by those proposing products and include a clear and concise proposal for

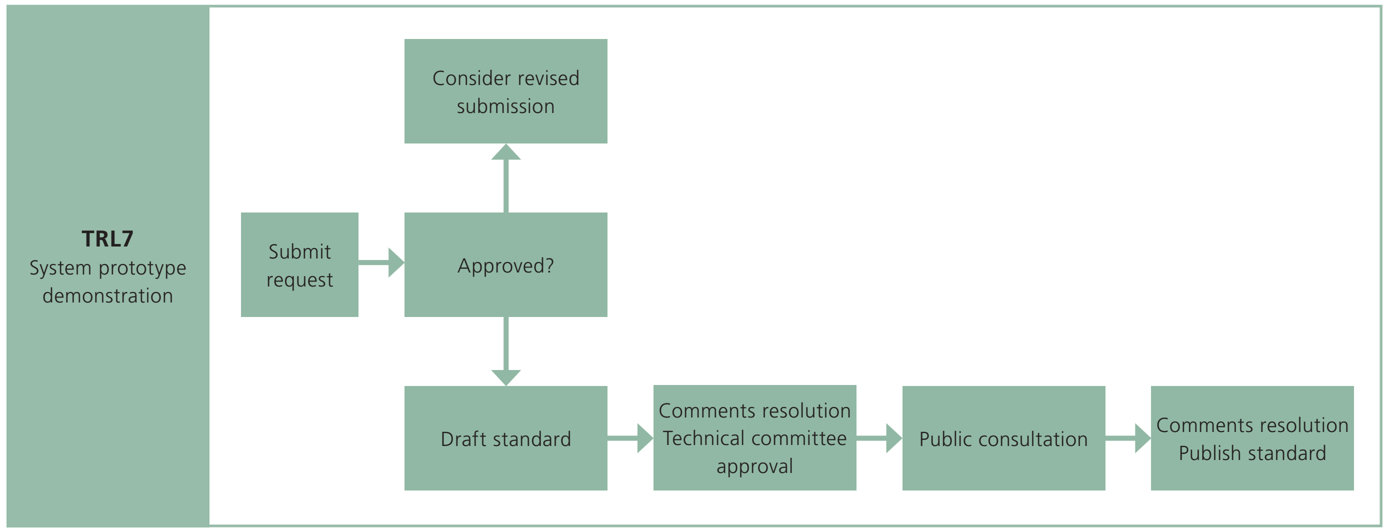


Fig 6.2: Process for gaining technical acceptance of new cements and concretes

standardisation of the new product. For cements, BS PD CEN/TR 16912:2016[4] – Guidelines for a procedure to support the European standardisation of cements – may be used. It aims to add clarity on the contents and scope of a technical dossier for cements that are not currently standardised. If the body of technical guidance or performance data is extensive, this may be transferred into a technical dossier. If existing guidance or test data is limited, a technical dossier could focus more on case studies that demonstrate a good track record of use in UK applications.

Step 3: Engagement with the standards body and technical committee

One of the key recommendations of the LCCG is the importance of collaboration and communication. The applicant is advised to engage with organisations such as the MPA, the Concrete Centre, the Concrete Society, BRE and A3CM for input and peer review at a very early stage. At this stage, they can provide useful advice and feedback on the strength of any application, although it should not be confused with formal acceptance. Without early engagement, the process may be poorly targeted.

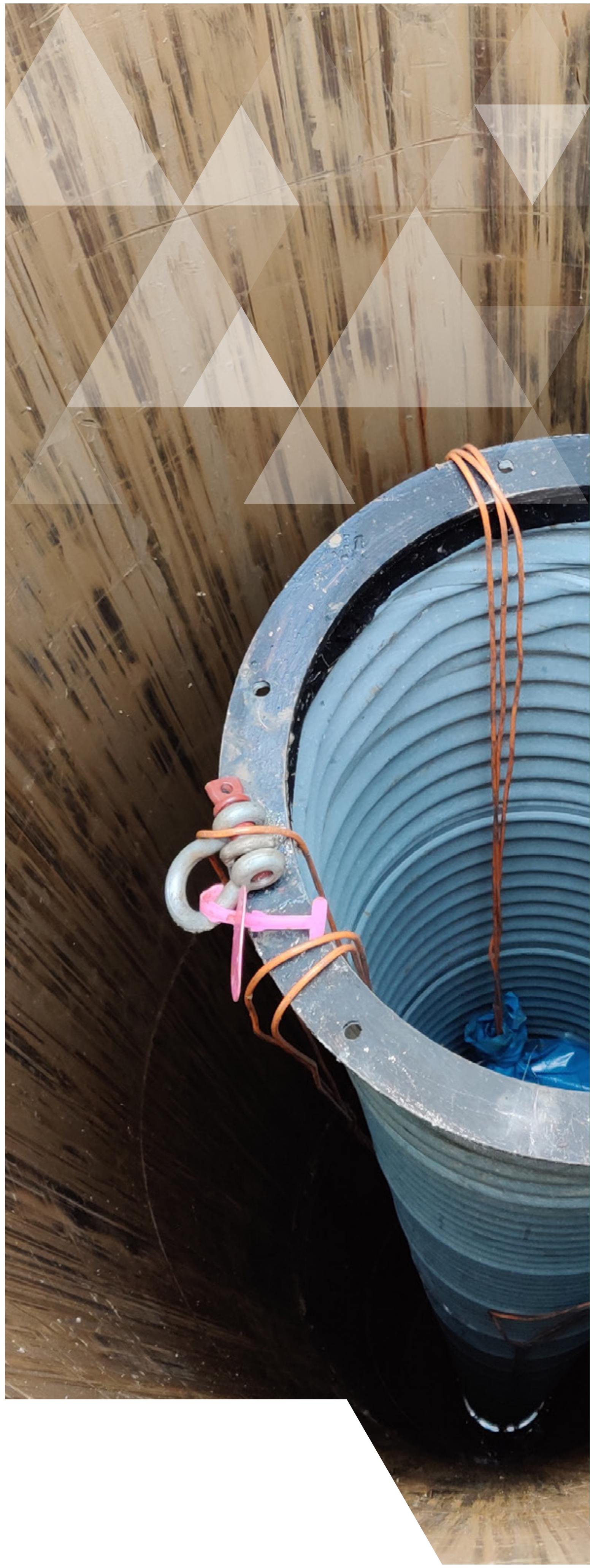
The LCCG recommends that technical committees provide feedback on any proposals that are received and that include a technical dossier, including advice on any additional information that may be required. In addition, the LCCG proposes that the MPA and/or the Concrete Centre publish a process that can be adhered to in order to facilitate and understand timelines and method of responses to applicants seeking advice and feedback.

The LCCG asks the BSI to work with its concrete and cement committees to operate and publish a transparent process for considering and accepting new cementitious materials as outlined above. This should extend to some of the standards for durability testing, many of which are designed specifically for Portland cement, or for composite cements with a low replacement level. To strengthen the transparency and dispel any perceptions that may exist regarding impartiality, the LCCG proposes that the BSI and the chair of the technical committees consider appointing a suitably qualified and experienced member of the LCCG to sit on relevant technical committees.

There is no doubt that cement chemistry and concrete technology are progressing at a pace that will be a challenge for the technical committees to keep up with. The LCCG recommends that updates are made at an appropriate frequency, that the committees are appropriately resourced and that remuneration packages become the norm for those who sit on them.

Adopting new technology

1 ISO 14001, 9001
2 BEIS (2017) Fly ash and blast furnace slag for cement manufacturing, research paper 19
3 Hibbert A, Cullen J, Drewniok M P (2022) Low Carbon Concrete Technologies (LCCT): Understanding and Implementation, ENG-TR.011, University of Cambridge
4 BSI (2016) BS PD CEN/TR 16912:2016 Guidelines for a procedure to support the European standardisation of cement



Case study: HIPER pile

The HIPER pile developed by Keltbray illustrates many of the carbon reduction themes discussed in Strands 3, 4, 5 and 6 of this Routemap.

The pile is intended for use in clays such as London Clay. The bore is formed using a conventional rotary auger. A second tool is lowered down the open shaft; this tool thrusts outward to form indentations in the clay shaft walls.

A concrete lining is then placed around the shaft's perimeter, leaving a hollow core. The lining is typically about 250mm thick and may be either a precast in-situ concrete composite or entirely cast in-situ around a sacrificial form.

Where precast units are used, these are prestressed by vertical tendons.

The pile base is formed by an 800mm-thick precast concrete unit (no hollow core). A precast unit caps the pile for connection to ground beams and columns.

The hollow core provides a means for inspection and sampling to enable assessment of the piles for potential re-use when the superstructure is eventually dismantled.

The precast units, and the cast in-situ concrete, are formed using C32/40 Wagners' Earth Friendly Concrete (EFC), an AACM concrete that does not contain any Portland cement.

The concrete has a carbon rating of A++ as defined in Strand 1 of this report (see Fig 1.2). Precast segments have sufficient strength for demoulding at 18 hours.

The hollow core is intended to be filled with water, which acts as a medium to transfer heat between the ground and pipes containing heating/cooling fluid. Two 900mm-diameter HIPER piles, each 25m deep, are estimated to provide the same ground-source heat capacity as a single 150m-deep geothermal borehole.

The HIPER pile is intended for use with pile diameters of 900mm-2,000mm.

In December 2021, after successful trials, the HIPER pile was piloted to support buildings with a planned 10-year service life at HS2 London Euston.

Following these successful trials and pilots, Keltbray has announced that the HIPER pile has been nominated for the Earthshot Prize.

Table 6.1: Carbon reduction achieved by HIPER piles relative to conventional bored cast insitu piles in London Clay

Aspect	Means of reducing carbon	Approximate % reduction in CO_2e	Notes
Indentations into London Clay	Increases shaft friction by about 40%, typically enabling a reduction in pile length of about 15% with a corresponding reduction in concrete volume	15%	
Hollow core	Reduces concrete volume	15% (900 ø) to 45% (2,000 ø)	Allowance made for solid base unit
Use of EFC as an AACM concrete[1]	Reduces the carbon intensity of the concrete	62%	LCA stages A1-A3 Reduction relative to use of CEM IIIB cement (70% GGBS)
Total reduction[1]		≈74% (900 ø) to ≈85% (2,000 ø)	LCA stages A1-A3 Reduction relative to use of CEM IIIB cement (70% GGBS)
Additional potential carbon reductions not included above			
Precast lining	Reduced over-ordering of concrete for delivery to site	noted	
Reinforcement	Use of PT tendons in place of primary longitudinal bars reduces total volume of concrete	noted	
Ground source heat storage	Reduces demand for gas or electricity	noted	Potentially substantial reduction in whole-life CO_2e, subject to assumptions about the future carbon intensity of the grid
Re-use to support subsequent generations of superstructure	Reduces future demand for concrete	noted	

1 CEM IIIB is a realistic cement for comparison for pile foundations; however, comparisons are often quoted with reference to CEM I cement (100% Portland cement).

- The reduction in CO_2e of the concrete relative to CEM I cement would be about 84%.
- The total reduction in CO_2e relative to a CEM I cement would be approximately 89% (900 ø) to approximately 94% (2,000 ø).

Case study: Seratech

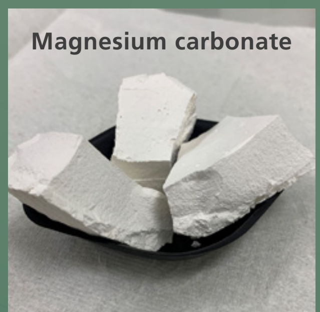
Seratech combines carbon dioxide with olivine, a widely available natural rock, to form silica (SiO_2), which may be used as an SCM in a similar manner to pozzolana or siliceous fly ash. The by-products of the reaction are magnesium carbonate and small quantities of iron oxide ('rust'). The manufacturing process sequesters carbon dioxide.

Use of the Seratech SCM to replace 35% of the Portland cement sequesters sufficient carbon dioxide to capture the CO_2 arising from the production of the 65% of the Portland cement that is not replaced. Therefore, net-zero cement can be produced by using Seratech as an SCM at replacement ratios for which guidance is already available in the relevant standards, BS EN 197 and BS 8500. Use of Seratech at greater replacement ratios results in carbon-negative cement and concrete.

There are some industrial uses for the by-product magnesium carbonate, and Seratech is actively pursuing research to explore new uses, minimising waste and improving the economic viability of the process. Alternatively, the by-products are stable and may be stored underground in perpetuity without danger of the sequestered CO_2 re-entering the atmosphere.

To date, the process has been successfully validated at lab scale and concretes produced using the SCM display similar compressive strengths to those incorporating fly ash at the same replacement level. A team at Imperial College London is currently developing a pre-pilot facility to produce the SCM in greater quantities to facilitate a thorough testing programme in a range of applications during 2022. Seratech has backing from numerous parties throughout the concrete value chain, including mineral suppliers, designers and concrete manufacturers.

With large multinational companies supporting the project, Seratech aims to have a pilot facility fully integrated into an active cement kiln by 2023, alongside large-scale trial pours at real-world sites.



Making concrete

7 Carbon sequestration, capture and use

This section explains how concrete can store carbon as well as what technologies can be adopted to capture carbon from the production of cement. It is important to recognise that some of these technologies are in development and, in many cases, are not currently commercially viable. Therefore, greater effort should be spent on optimising the quantity of concrete used and reducing its associated carbon intensity, as addressed in previous sections.

7.1 Storing carbon in concrete: upfront carbon storage

There are two technology streams for achieving this:

Portland cement concretes that carbonate with CO_2

It has been demonstrated that small quantities of CO_2 can be injected into concrete while it is being mixed. The CO_2 reacts with calcium hydroxide in the cement paste and creates calcium carbonate. The inclusion of CO_2 in this way can provide greater levels of strength and hence may allow a reduction of cement content, where strength is the driver of cement content.

The quantities of injected CO_2 are small (~0.2% by mass of cement[1]), hence for a given concrete the greatest carbon saving is likely to be in potential cement reduction. However, if this technology can be deployed at scale, alongside large-scale industrial carbon capture, then this type of technology has the potential to provide a significant carbon sink overall. It would need to be developed alongside large-scale industrial carbon capturing facilities.

Non-Portland cements that use CO_2 as a curing agent

Some non-Portland cement binders utilise CO_2 as the curing agent, rather than water. In doing so, they have the potential to use and store significant quantities of CO_2, ~230kg of CO_2/tonne cement[2]. Solidia is a leader in this field; still, there are practical limitations to using CO_2 as a curing agent, notably the need to use a CO_2-rich environment. As such, applications are currently limited to non-structural unreinforced precast elements – for example, pavers and kerbs. However, work is being undertaken to find a way to deliver CO_2 as part of ready-mix solutions (such as a liquid in the form of oxalic or citric acid[3]).

It is important that the CO_2 used for the curing is not being generated expressly for this purpose and is ideally captured from another industrial process.

Key recommendations:

- Support these technologies where possible with demonstrator projects to allow progress in this field.
- The provenance of any CO_2 used for injecting or curing must be known and not created expressly for the purpose of use in concrete.

7.2 Storing carbon in concrete: carbonation

Carbon dioxide in the air, combined with moisture, creates carbonic acid, which penetrates concrete and cementitious products and reacts with the calcium hydrate within the paste, creating calcium carbonate, sequestering CO_2.

For structural concrete containing ferrous reinforcement, carbonation is a concern for durability and the design of structural elements considers this risk of carbonation, which can reduce the alkaline environment within the concrete and increase the risk of reinforcement corrosion. However, from a carbon perspective, carbonation is a significant long-term benefit of Portland cement-based concretes.

The rate of carbonation is dependent on the concentration of carbon dioxide in the air, the exposed area of the concrete and the permeability and porosity of that concrete. It should be noted

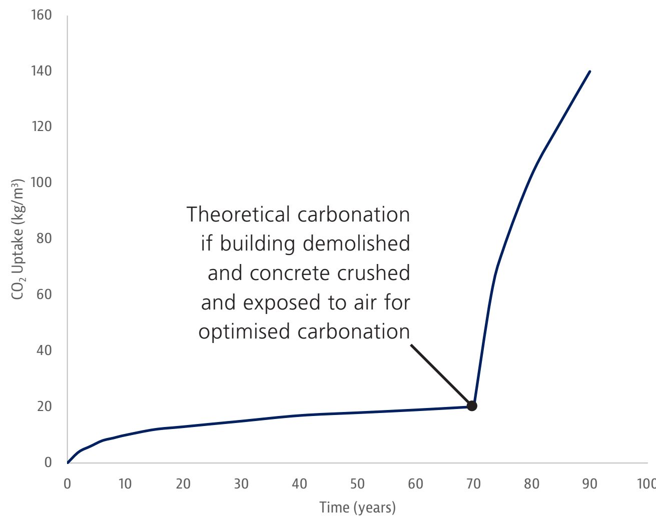


Fig 7.1: Theoretical passive carbonation for typical concrete in a building, based on model estimating CO_2 uptake over time in CP III[5]

that the concentration of CO_2 varies considerably above the global average (410ppm) and can range from 380ppm in a rural setting to 5,000ppm inside a busy building[4].

Carbonation for a given element occurs over its whole life and can be seen indicatively in Fig 7.1. In this model, carbonation during the building's life may reach about 20kg CO_2/m^3, equivalent to 5%-10% of its upfront emissions (10%-20% of cement process emissions); however, it will take at least 20-30 years to reach this level of carbonation while the building or structure is in use.

In Fig 7.1, the step change in the rate of CO_2 uptake at 70 years corresponds to cutting the concrete into small cubes, representing crushing of concrete after demolition. This demonstrates the potential to maximise long-term carbon storage to fully utilise the carbonation potential of the demolition arisings, providing they are sufficiently exposed to air.

In combination, across all cementitious products, the carbonation sink is now significant enough that it is included in the reporting of global carbon balances, and was included in the 2021 Intergovernmental Panel on Climate Change report[6]. It is estimated that the total carbonation sink is ~700 Mt per annum, broadly equivalent to half of the process emissions associated with cement[7], or about 30% of total emissions associated with cement production[8]. As with most global accounting methodologies, this figure makes significant assumptions about carbonation rates and cementitious use but national accounting methodologies are in development, including in the UK.

Regardless of global carbon balances, for a given cubic metre of concrete specified, while carbonation will ultimately capture some of the emissions associated with its production, this may not occur for many years (see Fig 7.1) and, as such, these are unlikely to address the need to severely reduce emissions in the next 5-10 years. Still, the global cementitious stock may help to act as a longer-term sink to rebalance CO_2 this century.

EN 16757 includes a methodology to calculate carbonation. There will also be a simplified methodology (with default values) in the next edition of EN 16757 (to be published in late 2022).

Key recommendations:

■ Where possible, and not in contradiction with durability requirements, make best use of carbonation by increasing exposure to CO_2-rich environments.

■ Better guidance on carbonation rates both during useful life and at the end of life would allow a better understanding of how to optimise this effect.

■ The benefits of carbonation should not drive decision-making when considering upfront embodied carbon owing to the slow uptake of CO_2. However, carbonation should be considered as part of a whole-lifecycle carbon assessment, expressed distinctly from the upfront carbon.

■ Careful planning and optimising of demolition works presents opportunities to maximise long-term carbon storage in the demolition arisings.

7.3 Capturing carbon and using and storing it from the production of cement

The carbon intensity of Portland cement is driven by three aspects:

■ Carbon associated with the electrical plant operations ~ 10%:
It can be expected that as the electrical grid decarbonises, the associated carbon emissions will reduce.

■ Carbon associated with the direct combustion of fuel to heat the raw materials ~ 40%:
Since 1998, the UK cement sector has replaced 43% of its fossil fuel usage with alternative kiln fuels[9]. There are efforts to further decarbonise thermal heating and the MPA is delivering a pilot programme with the Department for Business, Energy and Industrial Strategy to trial innovative net-zero fuel mixes. However, for net-zero fuel mixes[10] to become standard practice, investment in infrastructure and the availability of alternative fuels is required.

■ Carbon associated with the chemical decomposition of limestone powder ~ 50%:
The carbon dioxide produced through the decomposition of limestone powder is an unavoidable by-product of Portland cement chemistry. The potential capture and avoidance of emitting this CO_2 is the most important goal to produce net-zero Portland cement clinker.

Capturing carbon dioxide

If we are to continue to produce and use Portland cement, which is recognised as an excellent binder and accounts for the majority of cement consumption, then we must find a way to capture and use or store the associated carbon from fuel combustion and chemical decomposition of limestone powder, to avoid their unabated emissions.

There are several technologies for capturing carbon, each at different levels of technological and commercial readiness. Direct separation, post-combustion and oxyfuel carbon capture are the main technologies under consideration today. Both direct separation and oxyfuel systems create near-pure exhaust streams of carbon dioxide, reducing the complexity of scrubbing CO_2 from mixed exhaust gases, as in post-combustion carbon capture.

Direct-separation systems currently capture the emissions from the limestone decomposition, whereas oxyfuel systems capture the emissions from fuel combustion and calcination (where the fuel is combusted with oxygen rather than air). Post-combustion systems, while requiring scrubbing, capture CO_2 from mixed flue gases combined from the fuel combustion and limestone decomposition.

It should be noted that there are no carbon capture systems that capture 100% of the CO_2 produced in place, so there will be residual emissions from the process, but efficiencies of about 90% capture are possible. Carbon capture technologies are currently energy intensive, and this energy must also come from a renewable source to avoid further emissions.

Using carbon dioxide

Direct use of carbon dioxide is a more favourable outcome than storage because there may be fewer processes, it does not carry long-term risk and it may be commercially viable if CO_2 can be sold to meet industrial needs. It should be noted that using CO_2 from cement production is only a viable approach to reducing global CO_2 emissions where it is avoiding another industrial source of CO_2.

A more integrated use of CO_2 from cement production would be to use it within the concrete industry. For example, if captured carbon dioxide were used with technology being developed by Seratech then this would allow production of an SCM and the sequestration of the carbon dioxide associated with the Portland cement component. There is also the potential to use captured carbon dioxide in the production of aggregates, where the aggregates could then be used in the concrete. If these technologies can be fully proven at commercial scale then they offer the potential for carbon-neutral concrete, or possibly even a carbon-negative concrete.

Storing carbon dioxide

If carbon dioxide cannot be used then it must be stored in a stable long-term location without risk of leakage e.g. a sealed geological reservoir. While there has been considerable discussion about carbon capture and storage (CCS) in the media and industry, there has been little development other than test exemplars of carbon capture at individual cement plants. There is not currently a commercial business case, although the UK Government is exploring ways to incentivise commercial carbon storage. Current costs for CCS are in the range of US$50-70/t$CO_2$ for a cement kiln[11], which would increase cement production costs by about 30%-60%[12]. The cost of storing captured carbon may reduce in price and present a viable net-zero solution to Portland cement production; however, given the costs and uncertainty, industry focus needs to be on measures that reduce the demand for concrete and cement, avoiding emissions in the first place.

Key recommendations:

■ CCUS (carbon capture and use or storage) may offer a way to reduce the net carbon intensity of Portland cement to near zero and allow it to continue to be specified in a net-zero future. Carbon dioxide may also be used and stored in the production of concrete, a potential carbon sink. However, technology development is required and the commercial environment does not yet exist to allow the large-scale roll-out of this technology.

■ CCUS should not be considered a certainty as a means to achieve net-zero concrete and there needs to be a focus on activities that can avoid emissions more quickly and with less risk, identified in Strands 2-6.

■ The industry, government and academia need to work together to aggressively drive the creation of the right commercial and regulatory environment to incentivise the development of technologies associated with the capture, transportation, use and long-term storage of CO_2.

Carbon sequestration, carbon and use

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Low Carbon Concrete Routemap

8 Next steps in the decarbonisation of concrete

Strands 1-7 of this report set out currently available methods of reducing carbon in concrete and identify further development required to enable additional reductions in the future.

Strand 8 summarises what can be done to reduce carbon in concrete at scale in the UK. This includes steps that can be taken now, and steps that need to be taken to enable future additional carbon reductions. The focus of Strand 8 is on actions that will be taken in the next 10 to 15 years. These actions will make an important contribution to delivering net-zero concrete at scale.

Engagement across the UK concrete industry and supply chain will be required to achieve the carbon reductions that are both necessary and possible. Everyone is invited to participate to make reductions now and enable further reductions in the years ahead.

8.1 Vision for the UK

The Government has set out a vision for the UK to reach net zero by 2050. It has set in motion the mechanisms to enshrine in law a reduction in carbon emissions of 78% by 2035 and 100% by 2050, both relative to 1990 levels. The Low Carbon Concrete Group was established by the Green Construction Board in January 2020 to demonstrate how these ambitious targets could be achieved, for concrete used in UK construction.

Since then, in October 2021 the government published the Net Zero Strategy and the UK Net Zero Research and Innovation Framework. The strategy includes commitments to drive procurement of 'green cement', and CCUS. The framework recognises the research need for decarbonisation of construction and that lower-carbon cement/concrete should be a research priority.

8.2 Aim of the Green Construction Board Low Carbon Concrete Group

Our aim is not just to identify potential areas for carbon reduction at scale in UK concrete, but to signpost what can be done, where it can be achieved, how it is possible and, just as important, by whom.

To achieve that aim, we have identified key strategic objectives and actions that will, when combined, substantially contribute to achieving the 2050 target. The LCCG has proposed an ambitious yet practical timeline for achieving these specified objectives and actions. The objectives and actions identified by the LCCG are not exhaustive. Additional but as yet unspecified tasks will also contribute towards achieving the 2035 and 2050 goals for carbon reduction. The clear message from the LCCG is that we have no time for continued complacency. The climate emergency is real, and although 2050 is cited as the year to achieve net zero, in reality we have until between 2030 and 2035 to realise the changes needed to enable net zero by 2050.

8.3 There is an opportunity, and need, for all to engage

There are opportunities for the Government, regulators, researchers, institutions and entrepreneurs to help the UK construction industry to achieve the reductions in carbon that are required between now and net zero in 2050, or sooner. Without their support, the UK construction industry is unlikely to achieve the required reductions.

To realise the required reductions of carbon emissions, there is a necessity for collaboration across the supply chain, clear client signalling on carbon reduction targets and robust third-party EPDs for ingredients and concrete.

8.4 Decarbonising concrete at scale in the UK

There are many ways of decarbonising concrete construction. Some methods work well in other territories but rely on the use of materials that are not available at scale in the UK.

The recommendations and opportunities listed here are focused on the means, methods and technologies that could credibly deliver reductions in the carbon of concrete construction, at scale, in the UK. We have discussed in Strands 1-7 what should be done and when. Further technologies that can be adopted at scale may emerge and these should also be developed. Future revisions of this guidance will be able to include those further technologies that are viable.

Table 8.1: Next steps in the decarbonisation of concrete

	Item	1. Benchmarking	2. Knowledge transfer	3. Design and specification	4. Supply and construction	5. Optimising existing technology	6. Adopting new technology	7. Carbon sequestration	Opportunity	Impact	Start date	Example products
Government Leadership	A1								As part of the transition to a green economy, provide support to the Concrete Decarbonisation Task Force, including financial support	5	2022	
	A2								Encourage and enable pilots of new low-carbon concrete materials and technologies with a focus on enabling rapid scale-up of successful technologies. Mandate piloting on publicly funded projects	5	2023	
	A3								Work with the Task Force to provide clear guidance to the concrete industry on targets and timescales for emission reductions	5	2023	
	A4								Legislate to create an economic incentive to reduce embodied carbon	5	2023	
	A5								Legislate to require accurate measurement and public reporting of embodied carbon on all projects over a certain construction value	4	2023	
	A6								Develop a cross-party political consensus on the measures that will be in place for the long term to guide the decarbonisation of the industry. This will inform the planning of alterations to existing facilities and the construction of new infrastructure	5	2022	
Clients Signalling	B1								Define product requirements including use of the LCCG benchmark rating criteria and commit to buying concretes that meet the criteria	5	2022	
	B2								Add a requirement for procurement to take account of CO_2e	5	2022	
	B3								Encourage the use of carbon-reducing SCMs other than GGBS	3	2022	
	B4								Define any financial value of CO_2e reduction. Acknowledge the cost to designers and contractors of doing things that vary from 'business as usual'	5	2022	
Task force Coordination	C1								Formation of a Concrete Decarbonisation Task Force to coordinate and communicate the development of low-carbon technologies and initiatives	5	2022	
	C2								Develop and deliver a coordinated programme for tests, trial and pilots with a focus on enabling rapid scale-up of successful technologies	5	2023	
	C3								Develop guidance to the industry on targets and timescales for emission reductions	5	2023	
	C4								Creation of a one-stop low-carbon concrete portal where the industry can find up-to-date guidance	4	2023	
	C5								Create a central database for reporting concrete use for future benchmarking	3	2023	
Engineers Design and specification	D1								Include voids, coffers or profile sections to reduce concrete volume in thick or planar concrete sections (slabs, rafts, diaphragm walls, profiled retaining wave walls)	4	2022	
	D2								Increase utilisation factors and assess design optimisation	4	2022	
	D3								Make use of EN 1992 provisions to reduce material partial factors based on quality control and reduced deviations	1	2022	
	D4								Take account in design of the real strength of concrete arising from the cement content that is required for workability and early strength gain	1	2022	
	D5								Specify reinforcement that will not corrode and define the real lifetime of RC elements	1	2022	
	D6								Specify an upper bound on kg CO_2e/m^3. Consider contractual incentives if a lower carbon content is achieved. Allow the concrete supplier the maximum possible flexibility to meet or beat the specified upper-bound kg CO_2e/m^3	3	2022	

> The Government has set the vision and defined the goals for decarbonisation. It is our moral and professional obligation to establish the framework and then work to achieve the goals. The world is demanding change, and that demand creates opportunities and incentives for business to deliver decarbonisation.

Concrete is made of a combination of cement, aggregates, water and admixtures. At present, a large majority of the carbon emissions of UK concrete are attributable to the cement. Therefore, at present, the focus is on reducing the quantity of cement used and reducing the carbon footprint of the cement.

As the cement is decarbonised, the carbon intensity of the other ingredients, transport and site works become more significant fractions of the carbon content of the concrete. This is already the case for a small proportion of commercially available concretes that use current-generation AACMs, or a high proportion of GGBS as a SCM. In parallel with reducing the carbon footprint of the cement, action can, and must, be taken to decarbonise the other ingredients, transport, and site works.

The focus of this Routemap and the identified next steps is on reducing the carbon content of concrete through LCA stages A1 to A3. However, the whole-life carbon context must also be considered. This includes transport to site, site works and the carbon intensity of rebar in reinforced concrete, as well as carbon emissions, or carbon sequestration, in service and at end of life. There is a need for further guidance on all of these items.

The limits of current practice

Using GGBS as an SCM to replace Portland cement is the current 'go-to' method for reducing the carbon intensity of concrete in the UK. GGBS is a finite resource with UK availability forecast to reduce, potentially rapidly if other nations increase their use of GGBS as an SCM. Use of GGBS as the go-to method for decarbonising concrete in the UK may only be possible in the short to medium term.

Current annual global production of GGBS is about 10% of annual global cement use:

■ Use of GGBS to replace Portland cement often requires an increase in the total cement content (kg/m^3). The percentage increase in total cement content is usually greater for higher strength classes with GGBS replacement rates above 50%. GGBS used to increase the total cement content in these mixes is not available for use in other mixes that would require a smaller percentage increase in total cement content. Those other mixes may therefore use more Portland cement. Therefore, if the use of GGBS leads to a substantial increase in total cement content, it may result in a low carbon rating for that mix but an overall increase in the global use of Portland cement, with an associated increase in GHG emissions.

Use of GGBS to decarbonise concrete is only appropriate if to do so reduces global GHG emissions:

■ Guidance is required on the most carbon-effective use of GGBS as an SCM or AACM in the UK. In the absence of such guidance, it may be appropriate to base decisions on the UK availability of GGBS: if GGBS is not readily available, increasing the total cement content by more than about 10% to enable a higher percentage of GGBS may result in increased global use of Portland cement with an associated increase in global GHG emissions.

Similar considerations may apply to the use of other SCMs with limited availability.

If you can't 'do nothing', use less

Sometimes the use of new concrete can be avoided – for example, by design to avoid site works, re-use of existing concrete structures and elements, or use of alternative lower-carbon materials.

Where new concrete is needed, substantial reductions in project GHG emissions can quickly be achieved by reducing the volume of concrete used. This could be one of the most effective ways of rapidly reducing carbon emissions from concrete. However, regulatory action may be required to create an economic case for material minimisation before widescale adoption.

The volume of new concrete required can often be substantially reduced by the use of efficient forms. 'Flat slabs', solid rafts and retaining walls without buttresses are rarely carbon-efficient forms of construction. Optimisation of the applied loading, serviceability criteria and structural analysis can also significantly reduce the volume of concrete required.

Table 8.1: Next steps in the decarbonisation of concrete (continued)

	Item	1. Benchmarking	2. Knowledge transfer	3. Design and specification	4. Supply and construction	5. Optimising existing technology	6. Adopting new technology	7. Carbon sequestration	Opportunity	Impact	Start date	Example products
Engineers Design and specification (continued)	D7		■	■			■		Identify elements suitable for the use of new and emerging low-carbon concrete. Encourage the use of these concretes for these elements	3	2022	
	D8			■	■				When identity testing, ensure quality control methods are communicated to batching plant so cement content is not increased for reduced results	1	2022	
	D9			■					Require reporting of the as-batched kg CO_2e/m^3	3	2024	
	D10			■	■	■			Use fibre reinforcement instead of bar/mesh reinforcement	1	2022	
	D11			■	■	■			Review selection of SLS design criteria (e.g. criteria for loading, deflection limits or crack widths can sometimes be relaxed)	2	2022	
Contractors (Tier 1 and 2) Site works	E1				■				Adopt working methods that reduce the required consistence (slump/flow) of concrete	2	2022	
	E2				■				Adopt working methods that reduce the requirement for early strength gain	3	2022	
	E3			■	■				Avoid use of sacrificial concrete in temporary works (e.g. ballast systems to be precast and re-usable, sand blinding instead of concrete blinding, etc)	3	2022	
	E4			■	■				Minimise waste, including through use of BIM to avoid over-ordering	3	2022	
	E5				■	■		■	Plan demolition works to maximise carbon take-up by concrete demolition arisings	2	2022	
	E6				■				Reclaim cementitious material from demolition arisings	2	2026	SmartCrusher
Supply chain Cement manufacture and concrete batching	F1					■			Continue to decarbonise the production of Portland cement (CEM I)	1	2022	
	F2		■		■	■			Calculation of as-built CO_2e based on as-batched ingredients and volumes mixed or dispatched to site	3	2022	
	F3				■	■	■		Modify batching plants to enable production of lower-carbon concretes. For example, add silos for alternative SCMs, add dispensers for AACM activators	5	2022	
	F4				■	■	■		Propose alternative lower-carbon concretes/mixes to clients, including as pilots	4	2022	
	F5			■		■			Increase and optimise use of GGBS and FA as an SCM in cements already in current standards (BS EN 197)	3	2022	CEM III/B, CEM III/C
	F6					■			Increase use of ternary (three-part) and quaternary (four-part) multi-component cements already in current standards (BS EN 197)	2	2022	CEM VI(S-P), CEM VI(S-L), CEM II/C-M
	F7					■			Extending the use of limestone powder in cements within the current standards (BS EN 197)	2	2022	CEM II/B-L, CEM II-B-LL
	F8					■	■		Use of current-generation AACMs and geopolymers that make use of GGBS and FA if they can be shown to meet necessary requirements	3	2022	Cemfree, EFC, ECOPact, Virtua Abs Zero, LoCem
	F9		■		■	■			CO_2e calculations to be based on kg CO_2e/kg of ingredients as used (i.e. based on actual processing, not industry database values)	2	2026	
	F10		■		■	■			AI/sensing enabled real-time adjustments to optimise mix design	2	From 2022	Concrete DNA (Converge)
All Reporting	G1	■	■		■	■			Public reporting of kg CO_2e/m^3 based on material batched and dispatched to site, improving on EN 15804. Include assessment against LCCG benchmark	4	From 2022	
	G2	■	■						Periodic updating of LCCG benchmark and guidance	3	From 2022	
	G3			■					Designers to report on optimisation and utilisation for all concrete elements as standard practice	3	From 2024	

Alterations to the method of factory or site works can reduce requirements for early strength gain or consistence and thereby enable reductions in the quantity of cement required per unit volume of concrete.

Reduce the carbon intensity of ingredients

In the short to medium term, use of alternative SCMs, such as limestone powder, stockpiled fly ash, calcined clay and volcanic ash can be increased to reduce the carbon intensity of cement. This is possible within the guidance provided in the current editions of BS EN 197 and BS 8500. The recent publication of BS EN 197-5 provides information on additional cements that use limestone powder and calcined clay to reduce reliance on GGBS. It is expected that BS 8500 will be updated in 2023 to include the BS EN 197-5 cements. Until BS 8500 is updated, design assisted by testing may be used to demonstrate performance of concretes made with these cements. The MPA advises that it can make available test data on the performance of BS EN 197-5 cements.

Limestone powder is in principle available now, although many batching plants may need to add a silo before they are able to offer limestone powder as an SCM. The UK Quality Ash Association coordinates ongoing research into the use of fly ash from stockpiles and can advise on this. Calcined clay is not currently produced at scale in the UK, although it could be imported, as could volcanic ash. The MPA and several universities are researching sources of calcined clay in the UK, with reports expected in 2023.

Aggregates that sequester captured carbon are now available and may be suitable for use on selected projects. Some products use materials that also have other uses that reduce global GHG emissions. Users should ensure that the aggregate feedstock materials would not deliver greater reductions in GHG emissions in other uses.

Fibre reinforcement, GFRP and BFRP rebar and unreinforced concrete provide low-carbon alternatives to traditional steel reinforcement in some conditions. These options are available now.

Longer term, there appear to be four themes to reducing the carbon intensity of ingredients:

■ Ongoing decarbonisation of the manufacture of Portland cement. However, since emission of CO_2 is inherent in the processing of limestone during manufacture, there are limits to how far this can be taken without reliance on carbon capture.

■ Development of next-generation AACM concretes that are not reliant on GGBS, and that use 'green energy' in the manufacture of the ingredients.

■ Use of carbon-negative synthetic materials as SCMs, AACMs and aggregate. Carbon-negative synthetic SCMs and AACMs are in the early stages of moving from laboratory tests to site trials and pilots. Used at scale, and with suitable carbon infrastructure, they offer the potential to make new concrete a carbon sink; part of the solution instead of part of the problem.

■ Use of 'green energy' for the extraction and processing of aggregates and water and the manufacture of admixtures.

In addition, further decarbonisation of, or methods for omitting, reinforcement will be required.

Measure, report, share and compare

Accurate measurement of embodied carbon, public reporting and comparison against similar projects will be central to driving the decarbonisation of UK concrete. Regulation to require accurate measurement and public reporting will increase participation.

8.5 Carbon capture has a role to play

Carbon capture and use or storage (CCUS) will have a role to play. However, CCUS is only one of the many methods of reducing carbon emissions into the atmosphere. We also need to employ other emission reduction activities: carbon that is not emitted does not need to be captured. CCUS should not be relied upon as the sole solution.

8.6 Actions required

Table 8.1 (opposite) summarises the next steps that the LCCG has identified in the ongoing decarbonisation of concrete in the UK. The table includes target timescales against each action. The timescales are necessarily estimates as some actions will be achieved more quickly while others may take longer to achieve, such as demonstrating durability properties of new concretes. An independent task force with funding is required to coordinate and drive the actions identified. This will deliver clarity to the supply chain on targets and timescales for decarbonisation and new technologies.

The task force will need to work with Government and industry to develop and deliver a coordinated programme for tests, trials and pilots. The focus must be on enabling rapid scale-up of successful technologies that deliver reductions in carbon emissions.

The principles underlying the actions listed in Table 8.1 can be broadly summarised as:

■ Use the minimum practical quantity of new concrete

■ Minimise the cement content

■ Reduce the carbon intensity of the cement and other constituent materials

■ In due course, capture and use (or store) any residual carbon emissions

The Government should provide specific guidance to the concrete industry on targets and timescales for emission reductions. These may be defined in conjunction with the task force. The industry requires a framework, defined by government, which creates an economic incentive for reducing embodied carbon. Development of a cross-party political consensus on the measures that will be in place for the long term to guide the decarbonisation of the concrete industry would be particularly useful. This would

Table 8.1 Next steps in the decarbonisation of concrete (continued)

	Item	1. Benchmarking	2. Knowledge transfer	3 Design and specification	4. Supply and construction	5. Optimising existing technology	6. Adopting new technology	7. Carbon sequestration	Opportunity	Impact	Start date	Example products
All Piloting	H1				■			■	Central database of pilots required and reporting of findings	4	From 2022	
	H2			■	■		■		Expectation that large projects will include pilots of ways to reduce concrete CO_2e (design, specification, types of concrete, batching, site works, demolition)	3	From 2024	
	H3				■			■	Establish pilots of CO_2 capture at cement works	5	From 2026	
Industry bodies and researchers Publish guidance	J1		■				■		Assessment of risk and consequence levels and conditions where the use of different concretes should be accepted/expected	4	2022	
	J2	■	■	■	■		■		Demonstrating satisfactory performance of materials and products that are not yet included in codes and standards	4	2025	
	J3			■		■			Selection of the SLS performance criteria to minimise CO_2e (applied loads and limits on deflection, crack widths and vibration)	2	2025	
	J4			■		■			Reduce minimum cement contents listed in BS 8500	2	2024	
	J5		■	■	■	■			Target m^3 concrete/m^2 floor for buildings to minimise concrete use	2	2025	
	J6		■	■		■			Methods for calculating and reporting utilisation and optimisation of concrete structures	1	2025	
	J7			■					When non-corrosive reinforcement should be used	1	2023	
	J8			■	■		■		Accelerated test methods to determine long-term properties of new concrete products	5	2025	
	J9		■	■					Performance-related standards for concrete works	3	2023	
	J10		■		■		■		Identify future requirements for concrete by use across the UK to inform targeting of new facilities and products	1	2025	
	J11		■		■	■			Construction methods/formwork that make economic use of efficient/voided forms	4	2024	
	J12		■	■	■				Working methods to maximise carbon take-up by concrete demolition arisings	2	2024	
	J13		■	■	■	■			Optimal use of GGBS and FA in the UK to maximise global reduction of carbon emissions	3	2023	
	J14					■	■		Convert PAS 8820-2016 to a British Standard – AACM/Geopolymer Activator Standard	2	2023	
	J15					■			Use of fly ash reclaimed from stockpiles as a SCM	4	2023	
	J16						■		Identification of clays in the UK with mineralogy suitable for calcining to use as cementitious materials (SCM or AACM)	5	2023 - 2024	
	J17						■		Use of limestone powder as a SCM at higher percentage replacement than currently permitted by BS EN 197	2	2025	
	J18						■		Use of tertiary and quaternary mixes beyond the guidance already provided in BS EN 197 and BS 8500 to reduce the proportion of clinker and also GGBS	2	2025	
	J19						■		Use of calcined clay as a SCM at higher percentage replacement than currently permitted by BS EN 197	3	2026	
	J20						■		Use of AACMs based on calcined clay (including metakaolin)	5	From 2026	

inform the planning of alterations to existing facilities and the construction of new infrastructure.

8.7 Limiting warming to 1.5C

To limit warming to 1.5C carbon requires emissions in 2035 to be reduced by two-thirds relative to 2018[1] levels, with net zero achieved by 2050. These targets are challenging but necessary. There is no spare capacity for additional carbon emissions. The UK concrete industry must reduce GHG emissions. By acting quickly to decarbonise, there is potential to be knowledge leaders with opportunities to export skills and products.

8.8 Potential reductions in GHG emissions

Figs 8.1 to 8.3 summarise the reduction in GHG emissions from the UK concrete industry for three potential routes. They also show HM Government (HMG) targets for carbon emissions[1] and the additional annual sequestration required to meet HMG targets, or how far the emission reductions are ahead of the HMG targets.

Each of the routes assumes that a different combination of the opportunities listed in Table 8.1 is successfully developed. All three routes assume further optimisation of current practice and technology to reduce the volume of concrete required to deliver a particular utility, to reduce the cement content (kg/m^3) of the concrete that is used, and to reduce the carbon intensity of Portland cement. In addition:

- Route 1 is based on successful use of fly ash from stockpiles and adoption at scale of mixes that use limestone powder, calcined clay and/or volcanic ash as SCMs.
- Route 2 is based on the developments underlying Route 1 and successful development and adoption of AACMs based on calcined clays or volcanic ash.
- Route 3 is based on the developments underlying Route 1 and successful sequestration of captured carbon dioxide within concrete. The captured carbon dioxide is used to manufacture carbon-negative synthetic SCMs, AACMs and aggregates; for direct injection of carbon dioxide into fresh concrete; and for concretes that cure by carbonation.

Figs 8.4 to 8.6 summarise the volumes of new concrete made each year with different binder types for each of Routes 1, 2 and 3. For clarity of presentation, the figures indicate that GGBS and fly ash are not used in combination with each other or in combination with limestone powder, calcined clay or volcanic ash. In practice, combinations of SCMs will be used within concretes.

The cumulative GHG emissions avoided relative to continuing with current practice is shown in Fig 8.7 for each route from 2022 to 2050. The quantities are based on CO_2e generated before any sequestration using CCS. The figure includes the LCCG estimate of the cumulative GHG emissions associated with implementation of the measures described in the MPA Roadmap[2]. Fig 8.8 shows the cumulative financial value of the avoided GHG emissions. The value is calculated using the BEIS 'central carbon values' (£/tCO_2e) for valuing impacts resulting from policy interventions[3]. The figure demonstrates the enormous value to society that could be achieved through implementation of the opportunities described in Table 8.1.

Each of the three routes is potentially possible. However, to hit the emissions shown on the charts, any of the routes, including Route 1, will require motivation and substantial effort from across the industry.

Route 3 demonstrates that by the early 2040s new concrete could be a net carbon sink. Concrete could be a part of the solution instead of a part of the problem.

All three routes suggest that the UK concrete industry's GHG emissions are likely to exceed HMG targets until at least the mid-2030s. If Route 3 can be accelerated, it may be possible to meet the HMG targets before 2040.

While there is potential that in the long-term, production of concrete may act a carbon sink, until the required materials, technologies and practice have been proved, plans for external CCUS should continue to be developed.

Achieving the reductions in GHG emissions of any of Routes 1, 2 or 3 will require, over the next 10 to 20 years, large-scale change in the UK concrete industry and successful development of emerging technologies. This is ambitious, perhaps of similar ambition to the development of multiple Covid-19 vaccines in only 10 months.

8.9 A moral and professional obligation

The UK Government has set the vision and defined the goals for decarbonisation. It is our moral and professional obligation to establish the framework and then work to achieve the goals. The world is demanding change, and that demand creates opportunities and incentives for business to deliver decarbonisation.

> "The task force will need to work with Government and industry to develop and deliver a coordinated programme for tests, trials and pilots. The focus must be on enabling rapid scale-up of successful technologies that deliver reductions in carbon emissions."

Table 8.1: Next steps in the decarbonisation of concrete (continued)

	Item	1. Benchmarking	2. Knowledge transfer	3 Design and specification	4. Supply and construction	5: Optimising existing technology	6. Adopting new technology	7. Carbon sequestration	Opportunity	Impact	Start date	Example products
Industry bodies and researchers Publish guidance (continued)	J21						■		Use of graphene in concrete to enable reductions in volume of concrete and/or cement content	3	From 2024	
	J22						■		Optimal use of cementitious materials reclaimed from demolition arisings as a SCM	3	From 2026	
	J23						■	■	Optimal use of concretes that contain sequestered CO_2	2	From 2024	
	J24						■	■	Use of synthetic aggregates that sequester CO_2 during manufacture	3	From 2024	
	J25						■	■	Use of concretes that cure by carbonation	2	From 2024	
	J26						■	■	Use of synthetic SCMs that sequester CO_2 during manufacture	5	From 2027	
	J27						■	■	Use of synthetic AACMs that sequester CO_2 during manufacture	5	From 2027	
Researchers and entrepreneurs Develop and roll out new products	K1		■		■	■			Formwork and construction methods that make economic use of efficient/voided forms	4	From 2024	
	K2					■			Concrete mixes tuned to use of fly ash reclaimed from local stock piles	4	From 2024	
	K3						■		Concrete mixes that use UK-sourced calcined clay, or imported volcanic ash, as an SCM	4	From 2026	
	K4						■		Concrete mixes that use UK-sourced calcined clay, or imported volcanic ash, as an AACM	5	From 2026	BanahCEM (no longer trading)
	K5						■		Proprietary mixes using graphene to enable reductions in volume of concrete and/or cement content	3	From 2024	
	K6						■	■	Concretes that contain sequestered CO_2	2	From 2024	CarbonCure
	K7						■	■	Synthetic aggregates that sequester CO_2 during manufacture	3	From 2024	Blue Planet Aggregates, OCO Technologies
	K8						■	■	Concretes that cure by carbonation	2	From 2024	Solidia Concrete
	K9						■	■	Synthetic SCMs and AACMs that sequester CO_2 during manufacture	5	From 2030	Solidia SCM, Seratech
	K10			■					Alternatives to current-generation steel rebar	2	From 2022	

Fig 8.1: Route 1 – Optimise current practice and technology (including limestone powder, calcined clay and natural pozzolana as SCMs) – annual GHG emissions

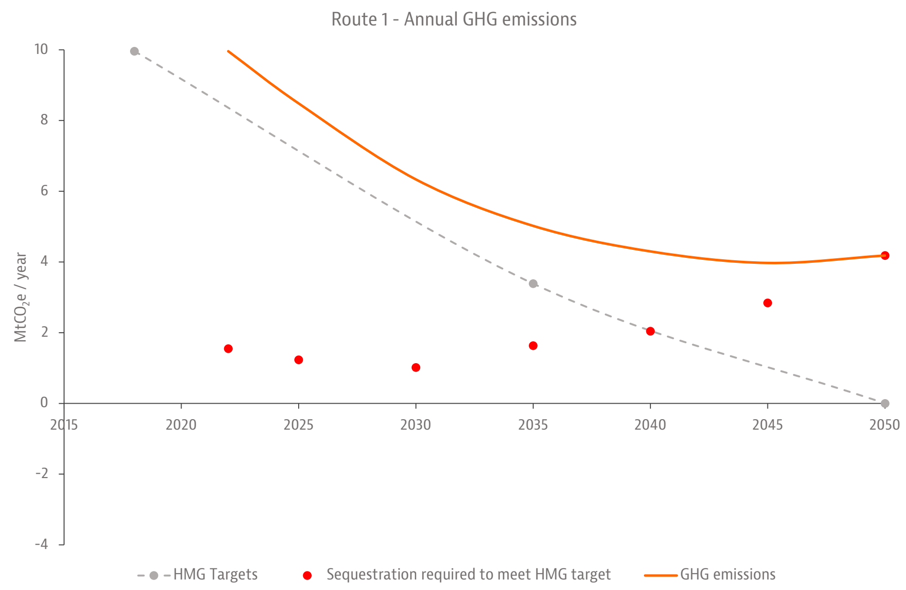


Fig 8.2: Route 2 – Optimise current practice and adopt AACMs based on calcined clays and natural pozzolana – annual GHG emissions

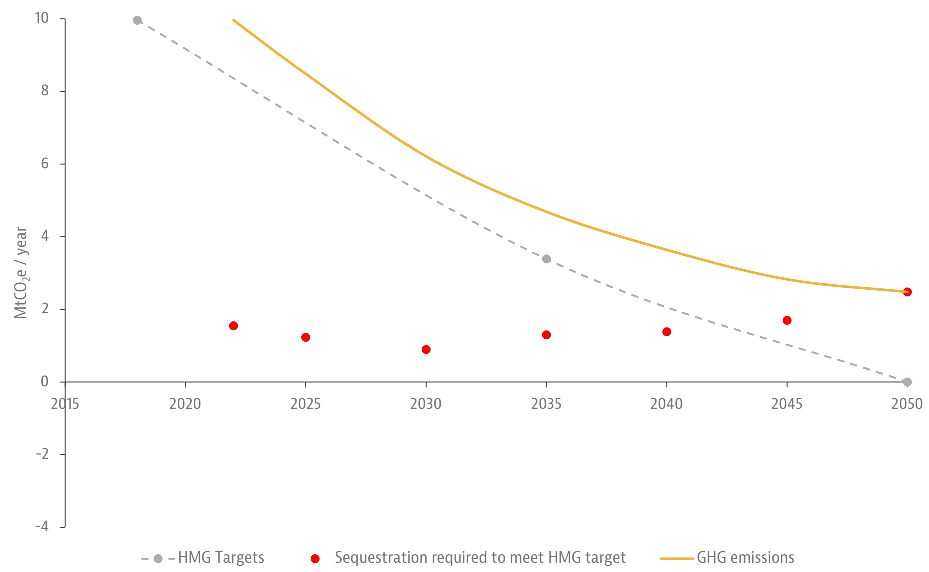


Fig 8.3: Route 3 – Optimise current practice, and adopt sequestration within concrete – annual GHG emissions

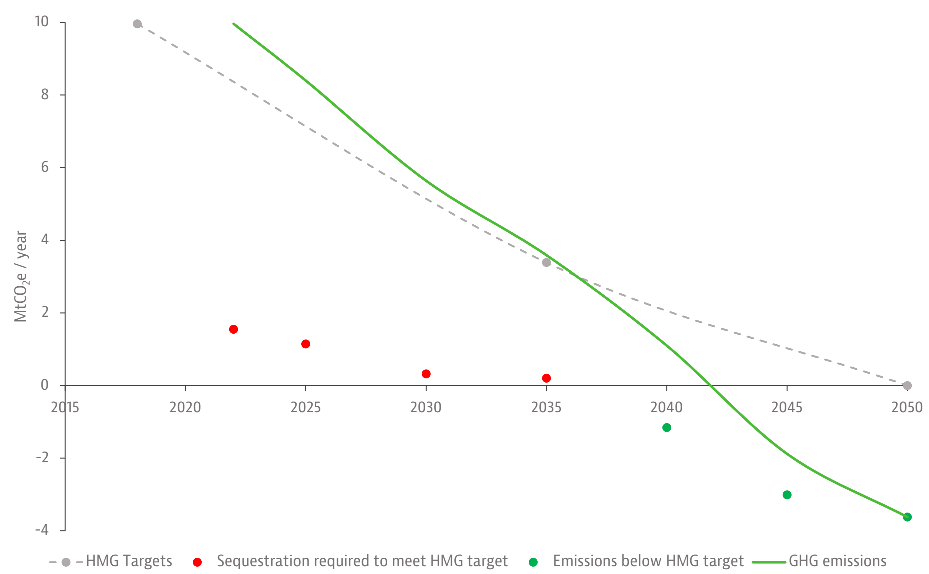


Fig 8.4: Route 1 – Optimise current practice and technology (including limestone, calcined clay and volcanic ash as SCMs) – concrete quantities by cement type

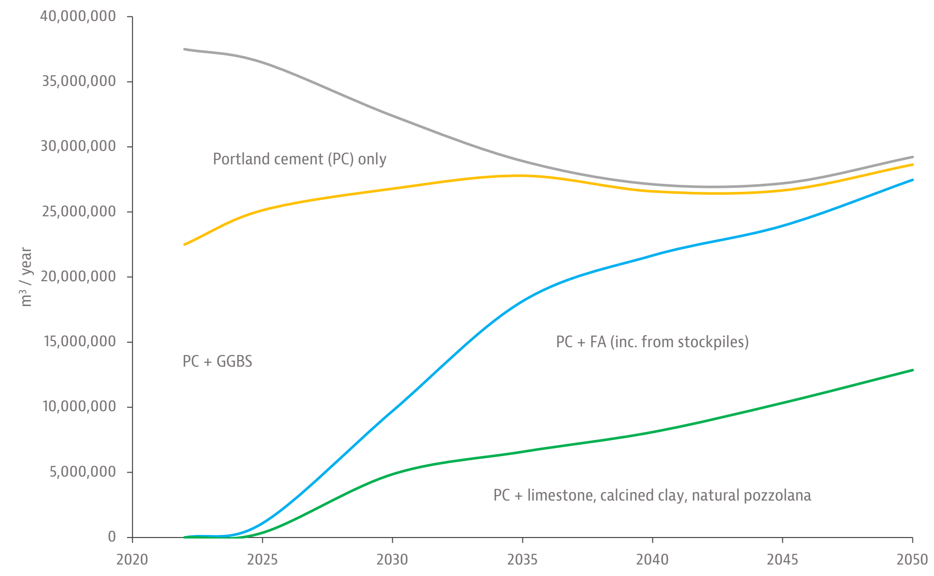


Fig 8.5: Route 2 – Optimise current practice and adopt AACMs based on calcined clays and natural pozzolana – concrete quantities by cement type

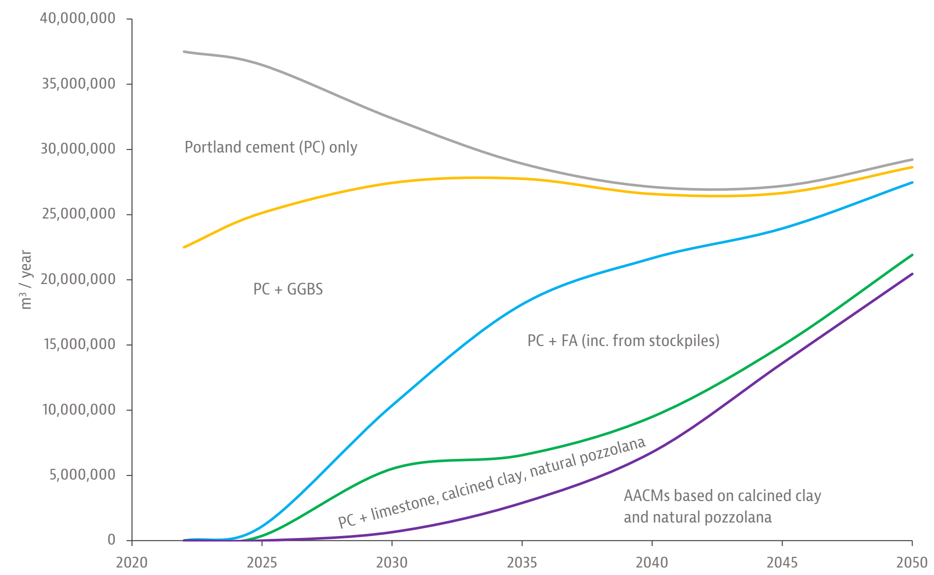


Fig 8.6: Route 3 – Optimise current practice, and adopt sequestration within concrete – concrete quantities by cement type

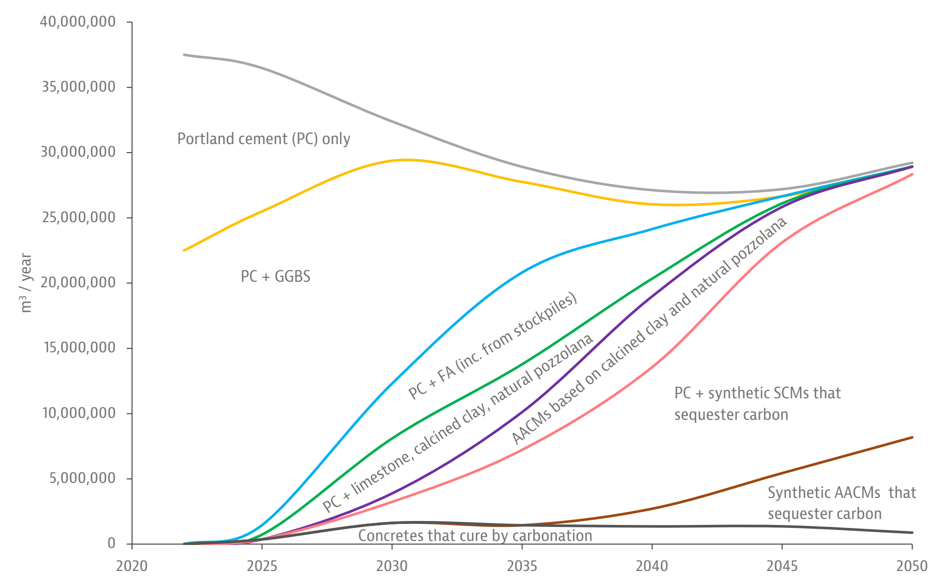


Fig 8.7: Cumulative avoided GHG emissions (before CCS)

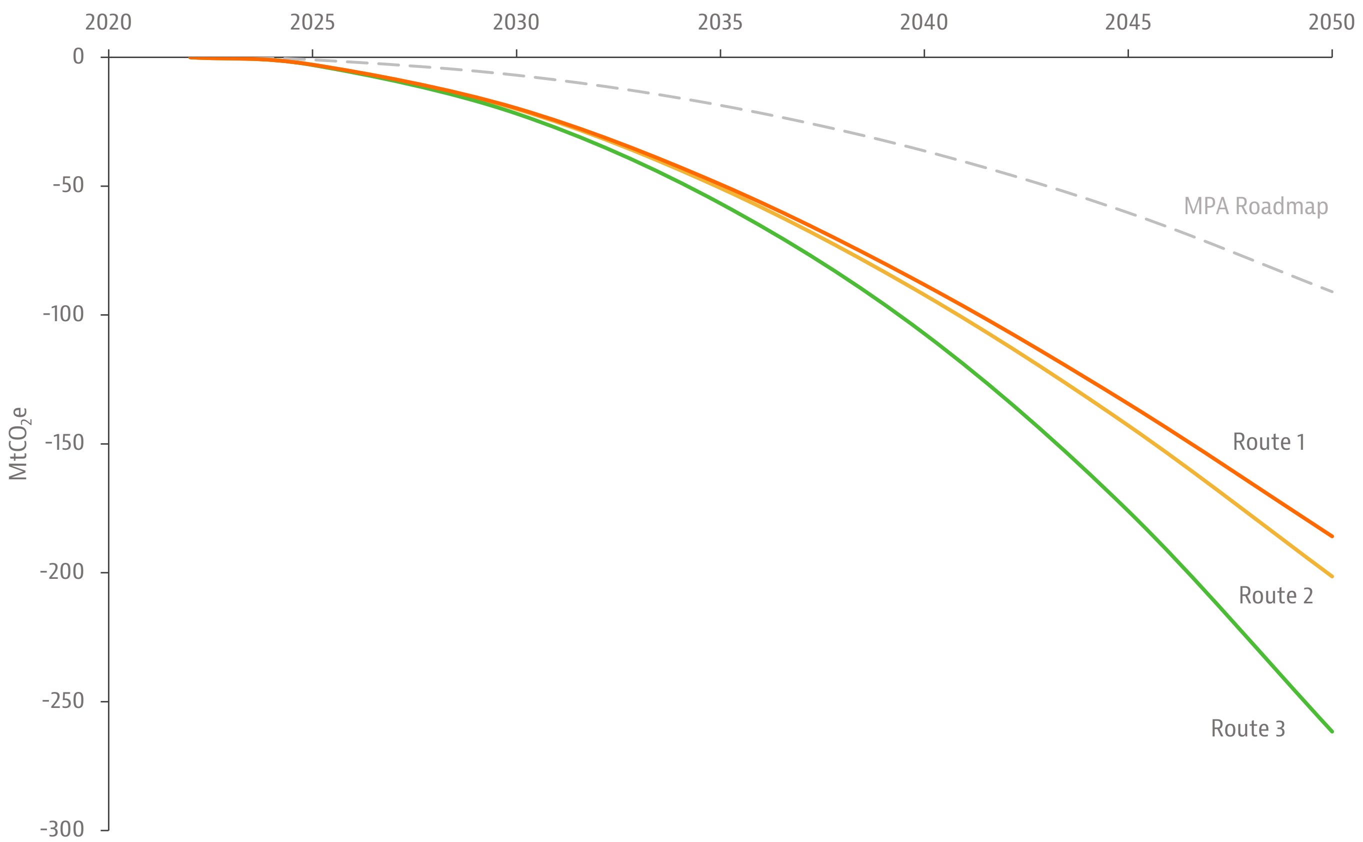
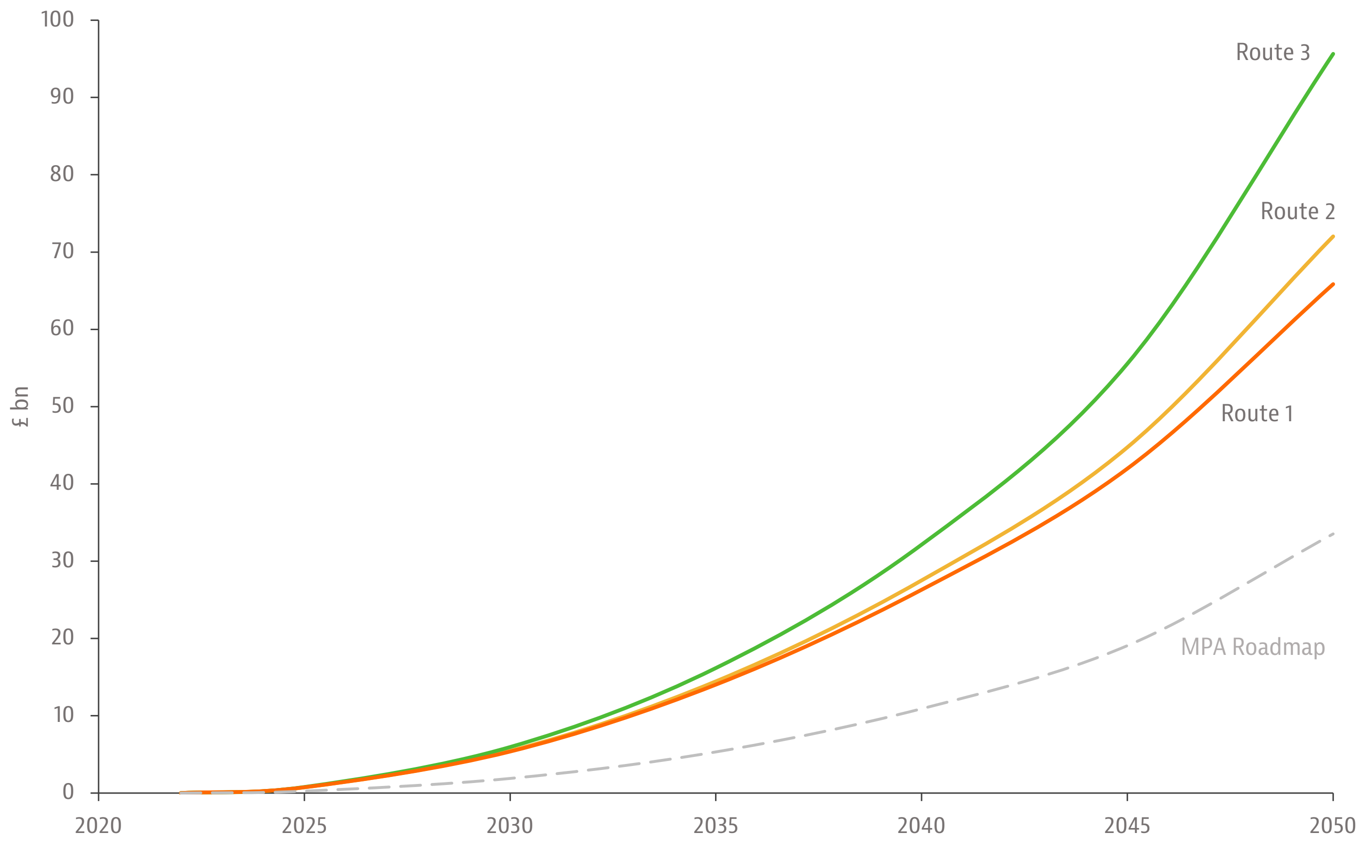


Fig 8.8: Cumulative value of avoided GHG emissions



Notes on Figs 8.1 to 8.8

The GHG emissions reported in Figs 8.1 to 8.3 and 8.7 are for LCA stages A1 to A3 (ready-mix: cradle to batching plant gate, precast: cradle to mould).

All of the analyses assume that new concrete is required to deliver new utility which increases each year in line with economic growth (1.4% p.a. real growth as forecast by HM Government from 2019 to 2050)[4].

Reductions in the overall volume of new concrete used each year, despite increasing utility constructed, are principally down to form optimisation, increased use of voids and unbound fillers, and design optimisation. There are also small contributions from reducing waste and sacrificial concrete.

The volume of new concrete required in 2022 is based on the 90 Mt/year (37,500,000 m^3/year) quoted in the MPA Roadmap[2] as the total quantity of concrete (ready-mix and precast) produced in the UK in 2018. In the absence of more recent data, this value has been used as an estimate of UK concrete production in 2022. Similarly, total LCA stages A1 to A3 GHG emissions in 2022 are taken as unchanged since 2018.

GHG emissions are calculated based on the carbon intensity of the concrete and the volume of new concrete.

For clarity of presentation, the figures indicate that GGBS and FA are not used in combination with each other or in combination with limestone, calcined clay or volcanic ash. In practice, combinations of SCMs will be used within concretes.

Any carbon dioxide that is produced during the manufacture of Portland cement is included in the total GHG emissions shown in the figures. The carbon intensity of Portland cement is assumed to reduce by 20% between 2022 and 2050 (16% due to fuel swapping plus 4% due to decarbonisation of the grid). This is consistent with the MPA Roadmap[2].

The carbon intensity of transport, batching and aggregates is assumed to reduce by 70% between 2022 and 2050. The carbon intensity of other ingredients is assumed to remain unchanged between 2022 and 2050.

Average replacement of Portland cement with SCMs in 2022 is taken as 18%. This is consistent with the figure quoted in The Concrete Centre Guide to Specifying Sustainable Concrete[5].

To generate 18% SCM use, the analysis assumes 30% use of GGBS to replace Portland cement in 60% of UK concrete in 2022. After that, in concretes that use GGBS, the proportion of GGBS is modelled as increasing to 50% by 2035.

For all other SCMs, the 2022 proportion is 20%, which increases to 40% by 2050.

The MPA Roadmap does not define the rate at which reductions in GHG emissions are achieved. The LCCG analyses assume a linear reduction from 2022 to 2050.

A copy of the analyses used to generate the figures can be obtained from the LCCG.

Next steps in the decarbonisation of concrete

1 HMG Industrial Decarbonisation Strategy CP339 March 2021, p.14: Indicative roadmap to net-zero UK industry
2 MPA (2020) UK Concrete and Cement Industry Roadmap to Beyond Net Zero
3 BEIS, Valuation of greenhouse gas emissions: for policy appraisal and evaluation (Annex 1), 2 September 2021
4 HMG Department for International Trade, Global Trade Outlook, September 2021, p56: UK 2019-2050 56% real growth
5 MPA, Specifying Sustainable Concrete, February 2019

Low Carbon Concrete Routemap

Glossary

TERM	ACRONYM	DEFINITION
Admixture		An additive to the concrete mix used to modify the properties of concrete in its freshly mixed, setting or hardened states. The most common admixtures are plasticisers, superplasticisers and water reducers, which improve workability or reduce water demand.
Alkali-activated cementitious materials	AACM	Materials that gain strength by means of a chemical reaction between a source of alkali and an aluminate-rich material e.g. GGBS, fly ash or natural pozzolans such as calcined clay.
Building Research Establishment	BRE	A UK centre of building science, owned by charitable organisation the BRE Trust.
Building Research Establishment Environmental Assessment Method	BREEAM	A standardised assessment methodology for the environmental performance of buildings through design, specification, construction and operation.
British Standards Institution	BSI	The national standards body of the UK.
Carbon		In this report, 'carbon' refers to the carbon emissions associated with a material as opposed to the element carbon (see: embodied carbon).
Carbon dioxide	CO_2	A colourless, odourless and non-combustible gas. It is the most common greenhouse gas that contributes to global warming.
Carbon dioxide equivalent	CO_2e	A standard unit for measuring the global warming potential of atmospheric pollutants (see: GWP), expressed in equivalent carbon dioxide emissions.
Carbon intensity	kg CO_2e/kg	Cradle-to-gate embodied carbon of a material or product relative to its weight (modules A1-A3 according to BS EN 15978)
Carbon neutral		All carbon emissions are balanced with offsets based on carbon removals or avoided emissions.
Carbon offset		A procedure by which emission reductions or removals achieved by one entity can be used to compensate (offset) emissions from another entity (see also: ref[1])
Carbon sequestration		The storage of carbon in a place (a sink) where it will remain. Types of sequestration include 'geological', where CO_2 is captured and buried underground, and 'biological', where CO_2 is absorbed during the growth of plants and trees. The carbonation of concrete is also sequestration, as is the production of concrete using CO_2.
Carbonation		The reaction of carbon dioxide (CO_2) – either from the environment or applied artificially with the calcium hydroxide – $Ca(OH)_2$ – in the cement paste, in any stage of the lifecycle.
Cement		A material used to form materials into a cohesive whole, as a means of providing structural stability. In the context of concrete, cement refers to finely ground inorganic material that, when mixed with water, forms a paste that sets and hardens by means of hydration reactions and processes and that, after hardening, retains its strength and stability even under water.
Cement content		The quantity of cement used per unit volume of concrete, normally expressed as kg/m^3.
Comité Européen de Normalisation	CEN	The European Committee for Standardisation.
Clinker		A nodular material made by heating limestone and clay at a temperature of about 1,400C-1,500C. It is the basic ingredient of Portland cement, that confers hydraulic properties to cement.
Commercial readiness index	CRI	An index to consider commercial readiness to reflect commercial pressures beyond the technical readiness level.
Curing		Curing is the process of preventing the loss of moisture from fresh concrete while maintaining a satisfactory temperature regime.
Department for Business, Energy and Industrial Strategy	BEIS	UK Government department overseeing national industrial strategy, including tackling climate change.
Durability		How a material resists mechanical or chemical degradation to fulfil its intended purpose.
Embodied carbon		The total greenhouse gas emissions and removals associated with materials and construction processes throughout the whole lifecycle, including disposal (modules A1-A5, B1-B5, C1-C4 according to BS EN 15978).
Environmental product declaration	EPD	An independently verified and registered document that communicates transparent and comparable information about the lifecycle environmental impact of a product.
Engineering and Physical Sciences Research Council	EPSRC	The main funding body for engineering and physical sciences research in the UK.
European assessment documents	EAD (ETA)	The European technical assessment (ETA) is an alternative for construction products not covered by a harmonised standard. It is a document providing information on their performance assessment. The procedure is established in the construction products regulation and offers a way for manufacturers to draw up the declaration of performance and affix the CE marking.
Fly ash/pulverised fuel ash	FA/PFA	The fine ash collected from the flue gases of a (predominantly) coal-fired furnace during the combustion process. Fly ash can also mean ash from furnaces other than coal-fired power station furnaces (FA/PFA for concrete see: BS EN 450-1, municipal and industrial waste incineration ashes do not conform to BS EN 450-1).
General purpose cements		Cements with suitability established in the UK concrete standard BS 8500.
Geopolymer		Particular examples of 'alkali-activated pozzolanic cements' or 'alkali-activated latent hydraulic cements'.
Global Cement and Concrete Association	GCCA	A trade association for the cement and concrete sector across the world. GCCA's membership consists of cement producers from across the globe working towards a membership that accounts for 50% of global cement production capacity.
Global warming potential	GWP	A measure of how much heat a gas traps in the atmosphere relative to carbon dioxide over 100 years, where carbon dioxide = 1.0.
Green Construction Board	GCB	The sustainability workstream of the Construction Leadership Council (CLC), created in 2011.
Ground granulated blast-furnace slag	GGBS	An SCM whose main use is in concrete as a Portland cement replacement to help reduce permeability and improve durability. It is a by-product from the blast-furnaces used to make iron.
Hydration		The chemical reaction between cement and water that causes concrete or other cement-based materials to harden.
Intergovernmental Panel on Climate Change	IPCC	The UN body for assessing the science related to climate change.
Life Cycle Assessment	LCA	An assessment of the environmental impacts of products, processes or services, through raw materials acquisition, production, usage and disposal (see: ISO 14044 or BS EN 15978).
Megapascals	MPa	The SI (International System of Units) unit for stress, equivalent to N/mm^2.
Mineral Products Association	MPA	The trade association for the aggregates, asphalt, cement, concrete, dimension stone, lime, mortar and silica sand industries.

TERM	ACRONYM	DEFINITION
National Structural Concrete Specification	NSCS	A base concrete specification with standard clauses on execution, materials and construction.
Net zero carbon		Where the sum total of all asset- or product-related greenhouse gas emissions, both operational and embodied, over its lifecycle including disposal plus offsets equals zero (see also: ref[1]).
Other cements		A term used to designate potential alternatives to existing general purpose cements whose suitability is not yet established in the UK concrete standard BS 8500.
Portland cement (CEM I)	PC (CEM I)	A mixture of compounds formed from the oxides of calcium (CaO), silicon (SiO_2), aluminium (Al_2O_3) and iron (Fe_2O_3), predominantly comprising hydraulic calcium silicates, which react and harden in contact with water. It is produced by grinding Portland cement clinker with a source of calcium sulphate to yield a fine powder. It is classified as the common cement type CEM I according to BS EN 197-1.
Pozzolan		A siliceous and aluminous material that, in the presence of moisture, chemically reacts with calcium hydroxide to form compounds possessing cementitious properties. Examples include calcined kaolinite clays, fly ash, volcanic ash and silica fume.
Parts per million	PPM	The number of units of mass of a constituent (or contaminant) per million units of total mass.
Publicly Available Specifications	PAS	Documents written by BSI in conjunction with external organisations and with a view to supporting certification schemes. The designation has been widened to include privately commissioned standards. PAS are generally fast-track documents that serve to address issues in the interim between identifying a market need and proposing/developing a British or European standard.
Recycled aggregates	RA, RCA	Aggregates that arise from reprocessing inorganic or mineral materials that have previously been used in construction (see also: BS EN 12620).
Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages	RILEM	Founded in 1947, the International Union of Laboratories and Experts in Construction Materials, Systems and Structures promotes scientific cooperation in the area of construction materials and structures.
Secondary aggregates	SA	Aggregates that are usually by-products of other industrial processes that have not previously been used in construction.
Secondary cementitious materials	SCM	Cement constituents other than Portland cement clinker as defined in EN 197-1 clause 5.2. SCMs which are added at concrete batching plants are referred to as 'additions' (in accordance with BS 8500-2 clauses 4.4.2, 4.4.3 or 4.4.4). SCMs may be produced from naturally occurring materials with minimal processing or may arise from wastes or by-products from other industries.
Technology readiness level	TRL	A measurement system used to assess the maturity level of a technology.
UKCA marking	UKCA	The UK Conformity Assessed marking used for goods being placed on the market in Great Britain (England, Wales and Scotland).
UK Quality Ash Association	UKQAA	A UK trade body that represents members involved in the supply or use of fly ash from pulverised coal-fired power stations.
Upfront embodied carbon		The sum of the greenhouse gas emissions associated with materials and construction processes up to practical completion (A1-A5 according to BS EN 15978).
Water-cement ratio	w/c	The ratio of the amount of freely available water to the amount of cement in the fresh concrete, defined on a mass basis. Note: where fly ash and silica fume are added at the concrete batching plant using the k-value concept, the w/c ratio should be adjusted appropriately in accordance with BS 8500-2 clause 4.4.4.
Whole-life carbon	WLC	The sum of all asset-related greenhouse gas emissions and removals, both operational and embodied, over the lifecycle of an asset, including disposal (see also: ref[1]).

1 Anderson J et al (2021) Improving Consistency in Whole Life Carbon Assessment and Reporting: Carbon Definitions for the Built Environment, Buildings and Infrastructure, Sturgris S, WLCN, LETI, RIBA

Low Carbon Concrete Routemap

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The Low Carbon Concrete Group (LCCG), formed of professionals from the concrete and cement industry, academia, engineers and clients, has been brought together by the Green Construction Board in its role as the sustainability workstream of the Construction Leadership Council.

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