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Knowledge

The Green Construction Board

Low Carbon Concrete Routemap

DRAFT FOR CONSULTATION

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Setting the agenda for a path to net zero

Low Carbon Concrete Group
The Green Construction Board

ice.org.uk

Foreword

Chris Newsome OBE
Green Construction Board member and chair

As the world digests the outcome of the UN Climate Change Conference (COP26), the publication of this Routemap towards low-carbon concrete seems ever more urgent.

Concrete is the most ubiquitous of construction materials. In the UK it accounts for 1% of greenhouse gas emissions but globally, the cement production carbon emissions associated with concrete utilisation could be as high as 8-9%.

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.

This Routemap has been created by a wide range of experts, 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.

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Introduction

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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 now, without surrendering that responsibility to the generation that follows 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, with chapter eight being a summary that includes 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 and record the progress we make in decarbonisation, as well as continuing to look to improve and adopt new or better means of carbon reduction.

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 impact in terms of carbon emissions.

It has often been the case that perceived barriers such as standards have been cited as reasons why a certain approach cannot be adopted. However, as the Routemap explains and demonstrates, most, if not all, 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 own 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 have come together as 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.

Executive summary

The concrete challenge

Concrete 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 pavers that we walk on to 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 up of three main constituents:

■ Aggregates (gravels and sands)	70%-80%
■ Cement (the active ingredient)	10%-20%
■ Water (which reacts with the cement)	5%-10%

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

Conventional Portland cement is made by heating limestone and clay and grinding it into a fine powder. The process of heating and decomposing the limestone releases about 0.86kg CO_2e[1] for every 1kg of cement produced. This is partly down to the chemical process as well as the energy involved in heating the limestone.

UK CEMENT CONSUMPTION

11.7Mt
UK cement consumption per year[1]

9Mt
CO_2e per year[2]
Equivalent to emissions from **7.2 million** cars (assumes 125g CO_2e/km and 10,000km/year)

1.5%
UK GHG emissions (2018)[3]
8% global GHG emissions (2018)

22,500,000m³
Ready-mixed concrete[2]

+

Other cement-based products
Precast concrete, mortar, architectural items, ground improvement techniques, furniture, etc

The challenge we face is how to continue to use concrete when the active ingredient in it is such a potent source of greenhouse gas emissions

A zero carbon future

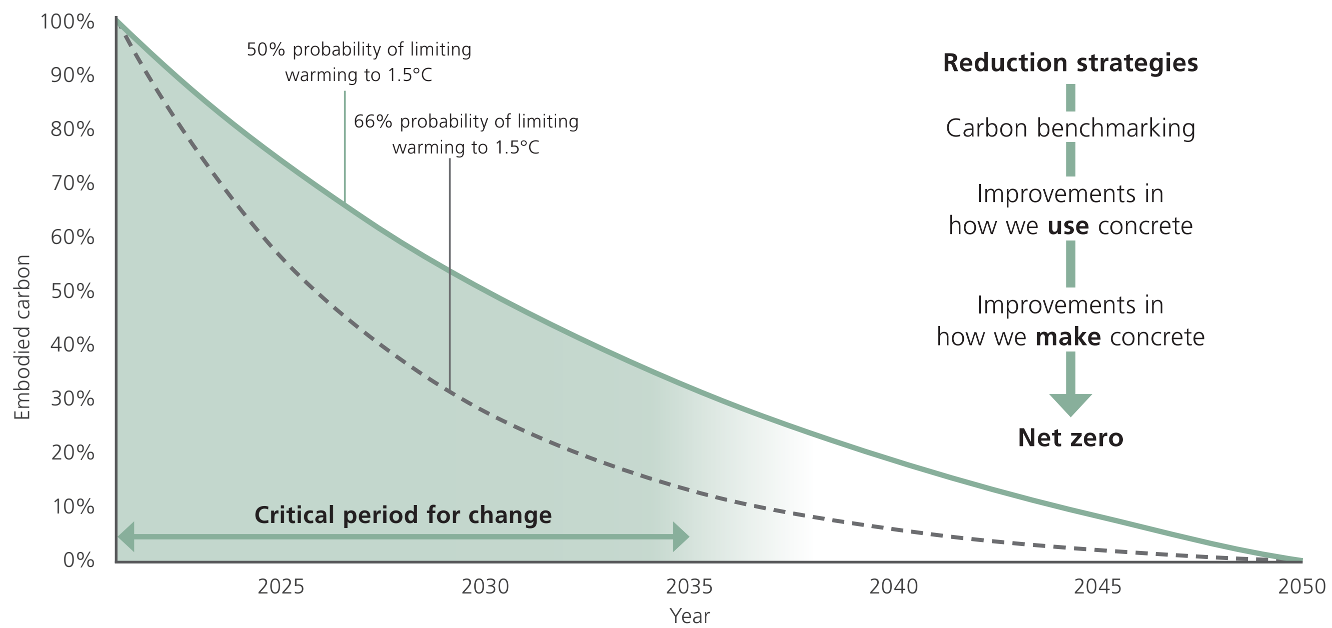


Fig 1: Idealised reduction rate for embodied carbon in concrete

The Low Carbon Concrete Routemap focuses on seven strands of knowledge that must be developed concurrently to reduce the embodied carbon of concrete. An eighth strand provides a framework of opportunities for further engagement. The ability of each strand to contribute will require continued research and development to meet the target of net zero by 2050, with the next 10-15 years being critical. The first strand covers the continuous process of accurately benchmarking concrete. Strands 2, 3 and 4 are related to the use of concrete by designers and contractors. Strands 5, 6 and 7 are related to the production of concrete. Here 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 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.

CONCRETE MIX – EMBODIED CARBON RATING CERTIFICATE

A++	<75
A+	75-125
A	125-160
B	160-190
C	190-225
D	225-275
Special	>275

B 164kg 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}	30 MPa
Cement type	IIIA
SCM	GGBS
Cement content	260kg/m³
w/c ratio	0.65
SCM content	40%
Aggregate size	20mm
Admixtures	Superplasticiser

STRENGTH CLASS *C25/30*

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 reduce significantly 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 industry and government to optimise the use of concrete for carbon.

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 standards, as well as a better understanding of performance and how and when to engage with stakeholders. 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 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.

Left: Hollowcore precast panel environmental product declaration (EPD)

Above: Concrete placement using a concrete pump

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 coordinate modernisation to allow the standardisation of the carbon intensity of concrete production with support for new technologies. 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.

6 ADOPTING NEW TECHNOLOGY

Concretes that use cement blends or contents 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 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 and the potential reduction of atmospheric CO_2. Guidance on how to use novel carbon curing technology and a better understanding of how to maximise long-term carbonation is required. Carbon sequestration 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 considered only once other carbon-saving opportunities are maximised.

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

Infographic: the Low Carbon Concrete Routemap

	2022		2024	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	Develop performance-related standards	Greater understanding of cement options embedded into engineering training
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	Reduce minimum cement content in BS 8500-2	Continuous improvements in efficiency, designing with re-used elements and for re-use
4 CONSTRUCTION AND OPERATION	Allow the concrete supplier the maximum possible flexibility to meet or beat the specified upper bound kg CO_2e/m^3	Continue to decarbonise the production of Portland cement (CEM I)	Modify batching plants to enable production of lower-carbon concretes	Reclaim cementitious material and aggregates from demolition arisings
MAKING CONCRETE				
5 OPTIMISING EXISTING TECHNOLOGY	Increase and optimise use of GGBS and PFA as an SCM	Use of current-generation AACMs and geopolymers that make use of GGBS and PFA if they can be shown to meet necessary requirements	Fly ash reclaimed from stockpiles as an SCM	AI/sensing enabled real-time adjustment to optimise mix design
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	Research and trial clay as an SCM at higher % replacement than currently permitted by BS EN 197	AACMs based on calcined clay (including metakaolin)
7 CARBON SEQUESTRATION	Identify 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 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.

kg CO_2e/m^3 or kg CO_2e/kg?

The carbon intensity or carbon coefficient of most materials is given as kg CO_2e/kg. However, concrete is generally specified and costed by volume. The embodied carbon is also often quoted by volume so that total embodied carbon can easily be calculated using readily available information on quantities. Note that concrete grade should also be stated where appropriate when considering the overall carbon of different structures.

LCCG recommendation:

- During carbon calculations, kg CO_2e/kg should be adopted.
- For general reporting and comparison with benchmarks, kg CO_2e/m^3 should be used. Many readers will be at ease with values reported in either unit.

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; that is a cradle-to-batching plant gate approach, covering modules A1-A3 in accordance with EN 15978[1]. The transport of concrete and its placement, including wastage, 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.

To calculate concrete's carbon intensity, it is important to consider the constituents and their respective contribution to the embodied carbon. Allowance should be made for transporting materials to the batching plant and batching. Fig 1.1 provides an indication of the typical distribution of embodied carbon for a structural concrete of design strength RC 25/30 for LCA (lifecycle assessment) stages A1 to A3. This has been calculated with a theoretical mix and using carbon intensity figures (carbon coefficients) from the ICE database[2] and has a total embodied carbon of 286kg CO_2e/m^3. [3]

The variety of 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. More standardised and robust approaches will emerge in the coming years; however, the current LCCG recommendation for the use of data sources to calculate embodied carbon is set out below.

1.2 Embodied carbon measuring hierarchy

Quantity of concrete:
- Record of material delivered to site
- Design information

Mix design:
- Batching records for material delivered to site
- Supplier's mix design
- Design information

Carbon intensity of constituents or concrete:
- EPDs (environmental product declarations) for the carbon coefficients of respective constituent materials
- Average industry values for the carbon coefficients of constituent materials from databases such as ICE's
- Supplier EPD for the concrete
- Generic average values for cast concrete from databases such as ICE's

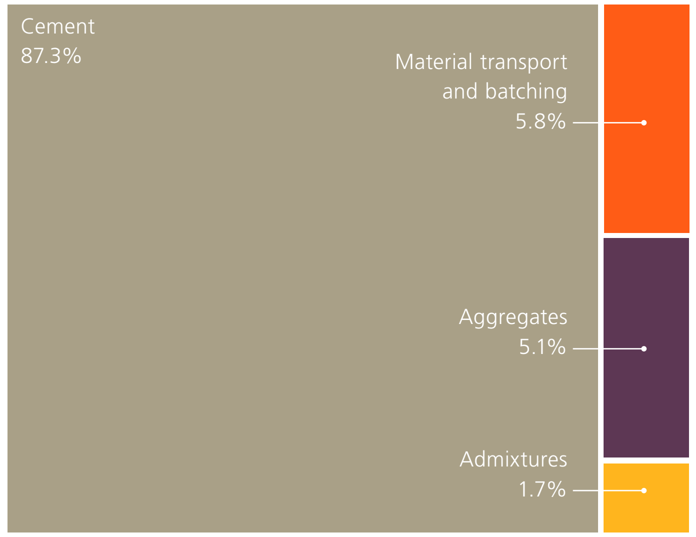


Fig 1.1: Distribution of embodied carbon in a typical structural concrete (RC25/30), LCA stages A1 to A3

Regardless of data source, it is clear from Fig 1.1 that cement is the main driver of embodied carbon in concrete today. Therefore, cement is the focus of the majority 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.

1.3 Benchmarking

Methods of defining 'low-carbon 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 define low-carbon concretes is to create thresholds based on kg CO_2e/m^3 that define high-, medium- and low-carbon concrete. This method is not well suited to capturing the change that is forecast. As the industry decarbonises, this approach will lead to misleading reporting.

In this report, 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. Note that particular performance requirements may make it impractical to use a 'very low carbon' or 'low carbon' concrete in some applications.

LCCG recommendation:

■ 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 at that time.
■ The LCCG suggests the following bands for each strength class:

Rating	Strength class fractile range
A++	0%-5%
A+	5%-20%
A	20%-40%
B	40%-60%
C	60%-80%
D	80%-95%
Special	95%-100%

*It is recognised that there may be applications where a special purpose concrete is required but that represents the lowest -carbon concrete in that situation.

Table 1.1 Distribution of CO_2e to different LCA stages[1]

To establish the appropriate carbon intensity to be used in assessing current concrete, recent UK mixes have been analysed. Amcrete, Byrne Bros, Price & Myers, Ramboll and WSP have provided information on the CO_2e of recent mixes. In total, data has been provided for 624 different normal weight concrete mixes for strengths ranging from C8/10 to C80/95. This data has been used to identify upper bounds on the kg CO_2e/m^3 for each band. As only seven of the mixes related to strength classes greater than C50/60, these have been excluded from the analysis.

Some of the data sets did not include the total volume of placed concrete for each mix. Therefore, each mix provided has been assigned equal value with respect to the frequency of use. A better representation of industry practice would be provided if the analysis included weighting to take account of the volumes placed.

The kg CO_2e/m^3 values have been calculated by each company. In most cases, the CO_2e assigned to each ingredient has been identified from industry databases such as ICE's. In some cases, EPDs for individual ingredients have been referenced.

The analysis is imperfect and the boundaries between bands are therefore approximate. However, the LCCG recommends this analysis of recent UK mixes for approximate benchmarking of project mixes. The variation in rating with strength class is summarised in fig 1.2.

The guidance should be updated annually and preferably with data from a larger number of companies. Over time, as concrete is decarbonised, the bands will cluster lower on the chart. With a more comprehensive data set, it will be possible to distinguish the carbon intensity of concrete applied in different uses (core walls, slabs, foundations, blinding, and so on).

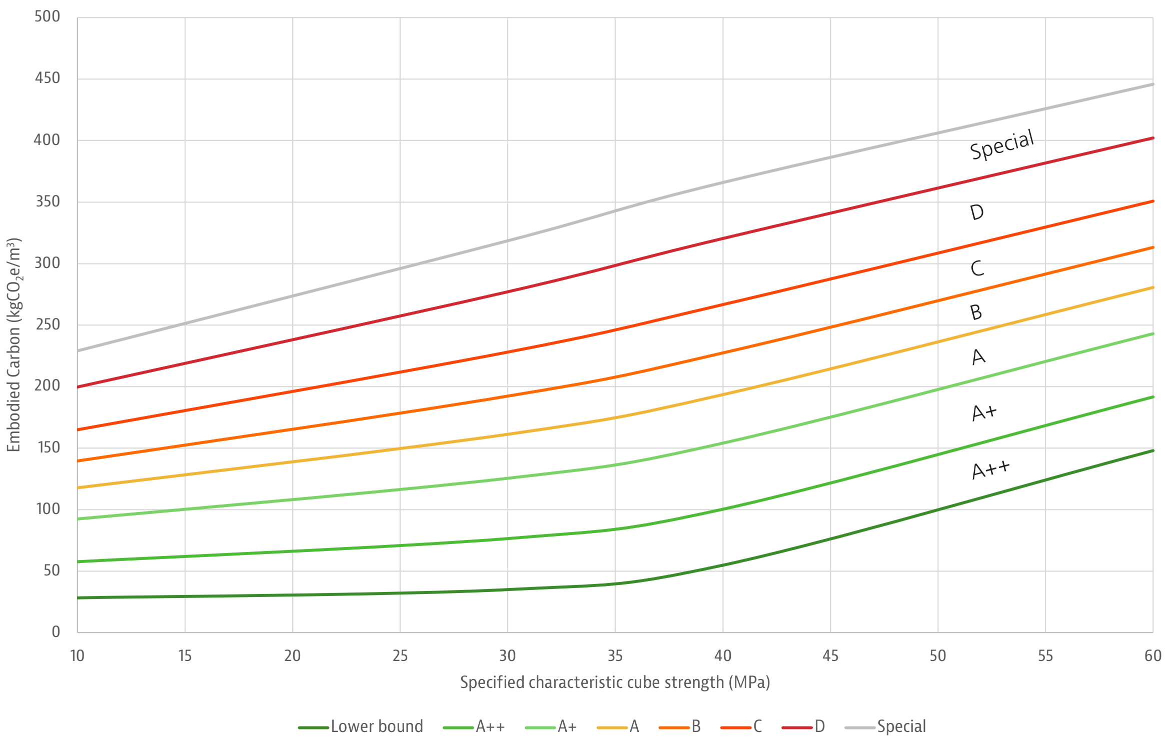
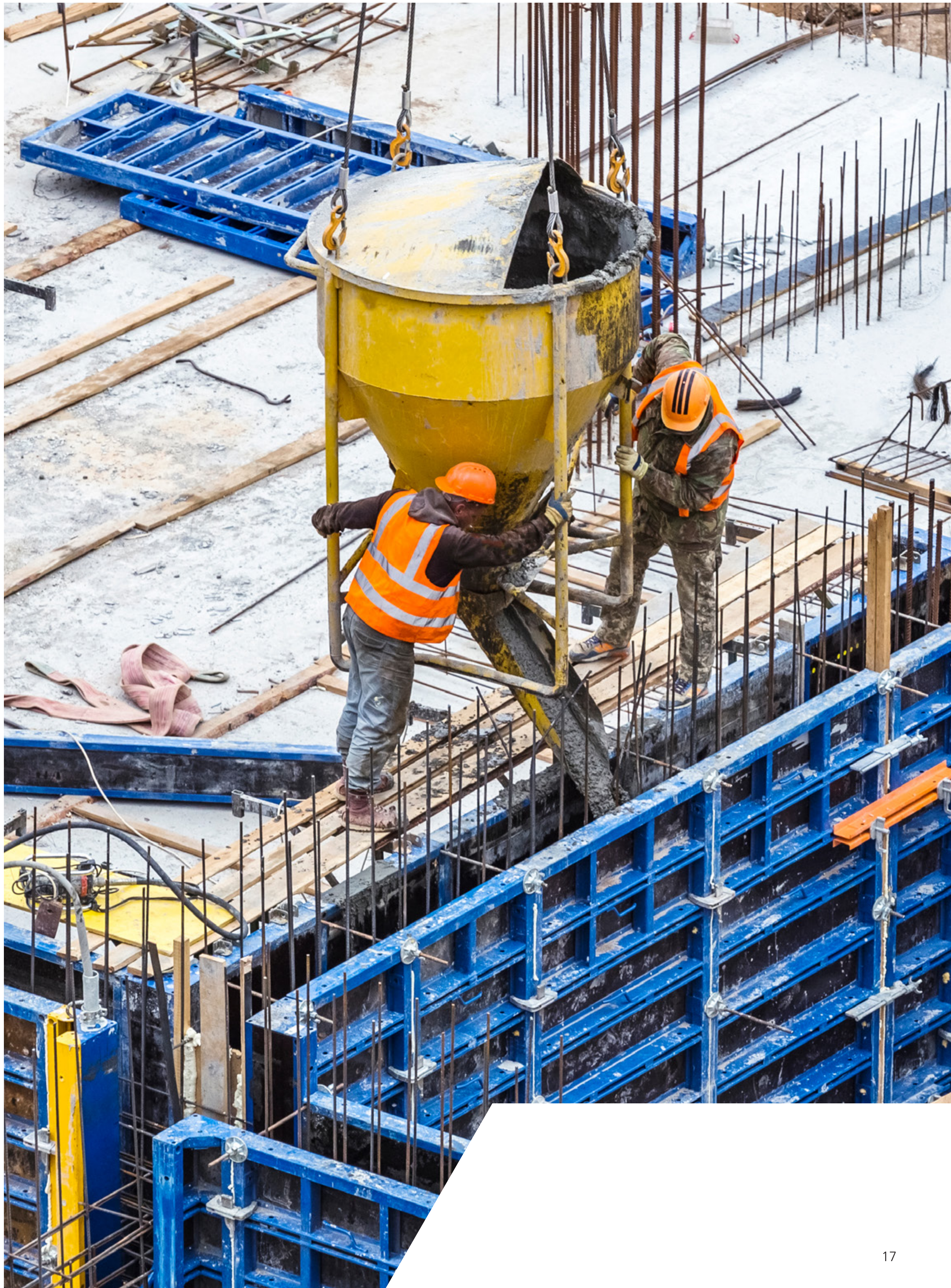
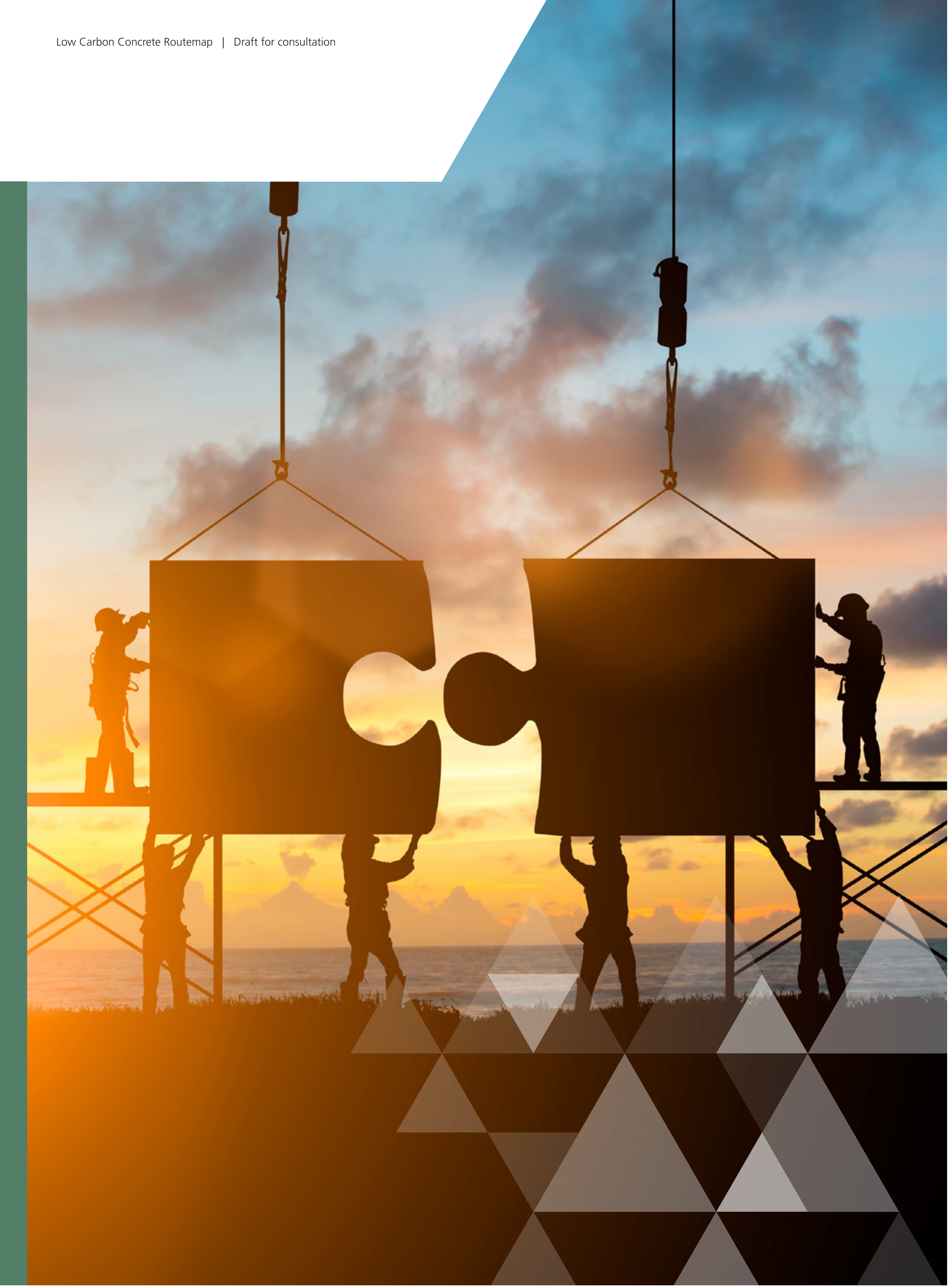


Fig 1.2: Ratings for embodied carbon, LCA stages A1 to A3





Using concrete

2 Knowledge transfer

Our Routemap to adopting lower-carbon concrete starts with something that all members of the supply chain 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 carbon 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 and emerging 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, corroborated by the survey, is a risk-averse approach to structural design. However, this is not solely the responsibility of the structural engineer. With early collaboration and knowledge sharing within the project team and supply chain, many of the 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 and should not simply look at the carbon intensity of a cement alone – alternative design approaches can yield an appropriate approach yet utilise a cement, blended or otherwise, with less material.

2.1 How?

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: 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 24) 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 aware of. There will be low-carbon cements being introduced in forthcoming updates to standards that, based on a project's lead time, could also be considered.

In the UK there are many cements, with a wide range of CO_2 footprints, that can be specified in construction projects or concrete products. Cements can be categorised into two groups:

- 'General purpose' – i.e. those with suitability established in the UK concrete standard BS 8500
- 'Non-Portland' – 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 contains up to 95% clinker.

Non-Portland cements can also depend heavily on SCMs (secondary cementitious materials) to achieve low embodied carbon. However, 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 alkali-activated cements). Some examples of these cements include:

■ CEM III/C cements[1] contain 81%-95% GGBS and 5%-19% Portland cement clinker, but applications are limited by its slower setting. If 95% GGBS is specified, then CEM III/C cements can reduce the embodied carbon of cement by 86% versus Portland cement CEM I.

■ CEM VI cements[2] 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 Portland cement 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 will 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[2]. 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 also has a wider benefit of potentially replacing diminishing UK supplies of fly ash as it shares similar technical attributes.

■ Alkali-activated cements contain ca. 90% SCMs (that react readily in the presence of alkalis and water e.g. GGBS, fly ash, calcined clay, etc, but not limestone), and ca. 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 alkali-activated cements and concretes for construction applications. Owing to high SCM contents, very low values of embodied carbon are possible.

The Eurocodes provide a mechanism or route to use and specify non-Portland cements. This requires increased awareness of various clauses in the Eurocodes, such as EC0, BS EN 1990 cl 5.2 and D3.1d. BRE (Building Research Establishment) has outlined possible routes to demonstrate performance (IP4-16) of a non-Portland cement, and a similar approach is shown in Fig 2.3 at the end of this section.

For an example of how close collaboration between clients, engineers, contractors and concrete producers can remove a barrier, and show the suitability of an AACM concrete for permanent piled foundations, see case study [editor's note: this case study is being reviewed by the relevant partners and shall be included in the final draft].

Whatever cement is used, to achieve a lower-carbon concrete it is recommended to use a performance-based specification – one that resists stipulating minimum cement content, water-to-cement ratios and even the proportion of SCM, which would provide the concrete producer with more flexibility to offer a lower-carbon concrete. This change of specification behaviour is supported by organisations including RILEM[2] and BRE[3].

Any new and emerging technology needs to demonstrate high performance in comparison with an existing mix design for that given application and environment. This is significant, as in order to demonstrate equal or better performance, time and commercial viability from research to delivery are required (see Fig 2.5, page 26).

2.2 Why?

To deliver the lowest possible carbon concrete for a project or application, it is important that all members of the project team, including the client, 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 or binder type. Availability of the materials used in low-carbon cements will also influence specification. For example, 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; in the medium term it may become commercially viable to recover stockpiled FA and new binder technologies will become commercially viable and enter the market.

There are UK-sourced alternatives, such as calcined clay, silica fume and limestone, that have the potential to utilise vegetable ashes and other technologies. However, for these to be available at scale, the infrastructure needs to be in place to recover, manufacture, deliver and batch these alternative SCMs. 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 concrete 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.

There is already significant evidence in the form of research and durability data for many new cementitious materials.

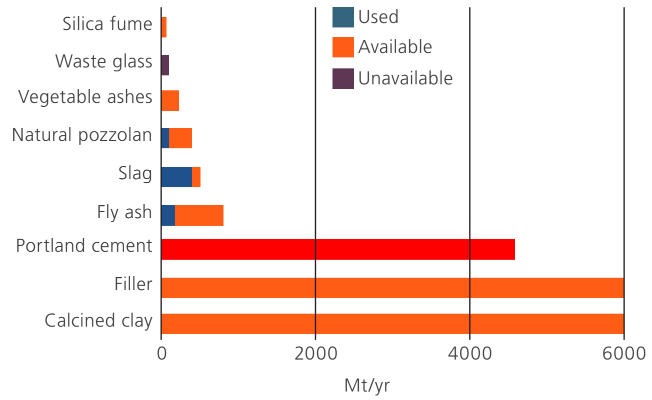


Fig 2.1: Use and estimated availability of possible SCMs and fillers (Scrivener, 2018)

2.3 What?

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 MPA Factsheet 18, ICE's database and environmental product declarations from sources including One Click LCA. Half of survey respondents did not feel that 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.

The LCCG recommends a collaborative approach early in a project to harness the shared experiences and lessons learnt from lower-carbon technologies. 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 promotes the use of product-specific EPDs that detail the accurate embodied carbon for each mix design, and provision of carbon data at a project level. (See Setting the benchmark, p15.)

The tendency is to compare one mix design against another. However, identifying the most appropriate lowest-carbon mix can be more complicated than that. To assess the carbon credentials of any mix design, another 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 in order to achieve a concrete with a strength class of C32/40, whereas a Portland cement-based mix design may require only 200kg of GGBS.

Therefore, a balance 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, the 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 it will need to perform safely, not just for the construction period but also 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 at the end of this section). In this regard, assessment of the TRL could be challenged depending on what evidence is available at the time; therefore, for new and emerging technologies it is advised that structural engineers are consulted at an early stage to program a robust testing regime to demonstrate suitability.

If the concrete is required for temporary works, the process of acceptance of a niche cement 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 the project teams to build confidence in the use of the new technology.

2.4 When?

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 lower-carbon 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 for the Zero Carbon World Tiger Team project, for Network Rail, HS2 and i3P.

Key recommendations:

- The recommendation of the LCCG is that clients are best placed to provide leadership and that the supply chain is more than ready to meet the challenge.

2.5 Who?

Collaboration is the key to successfully introducing new and emerging technologies, through to standards approval and finally implementation or adoption, regardless of whether the new 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 and knowledge 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 and information.

This guidance contains a number of case studies, and the LCCG encourages clients and project teams to publish and promote case studies featuring low-carbon concretes.

There is also a role for established training providers, such as professional institutions 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 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 and timely manner.

Table 2.1: Material supply and demand figures (Assi et al, 2020; Alberic et al, 2017)

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.

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.

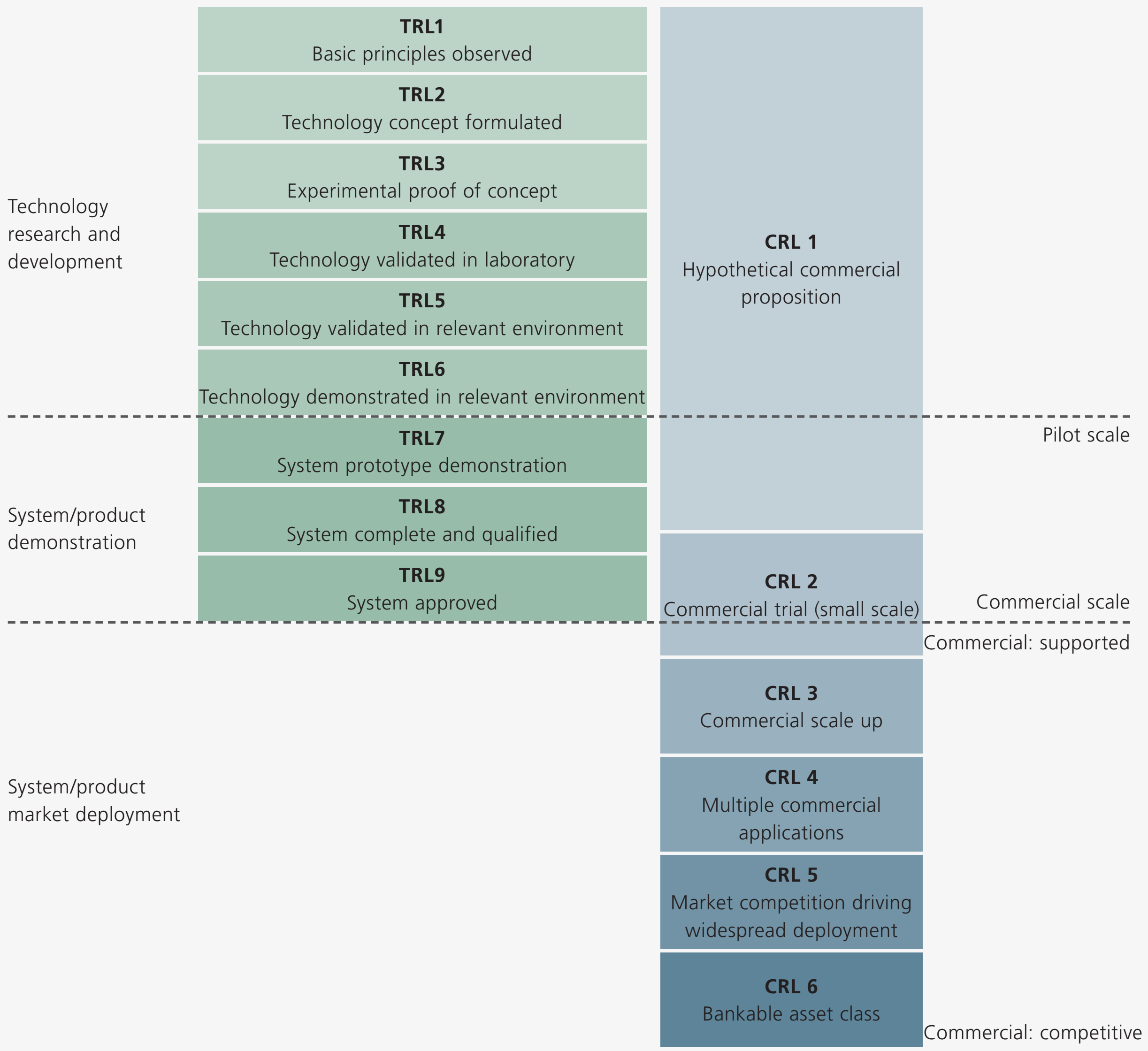


Fig 2.3: Technology readiness for low-carbon concrete
This diagram expands on the key stages of technology readiness when bringing a new lower-carbon concrete technology to market.

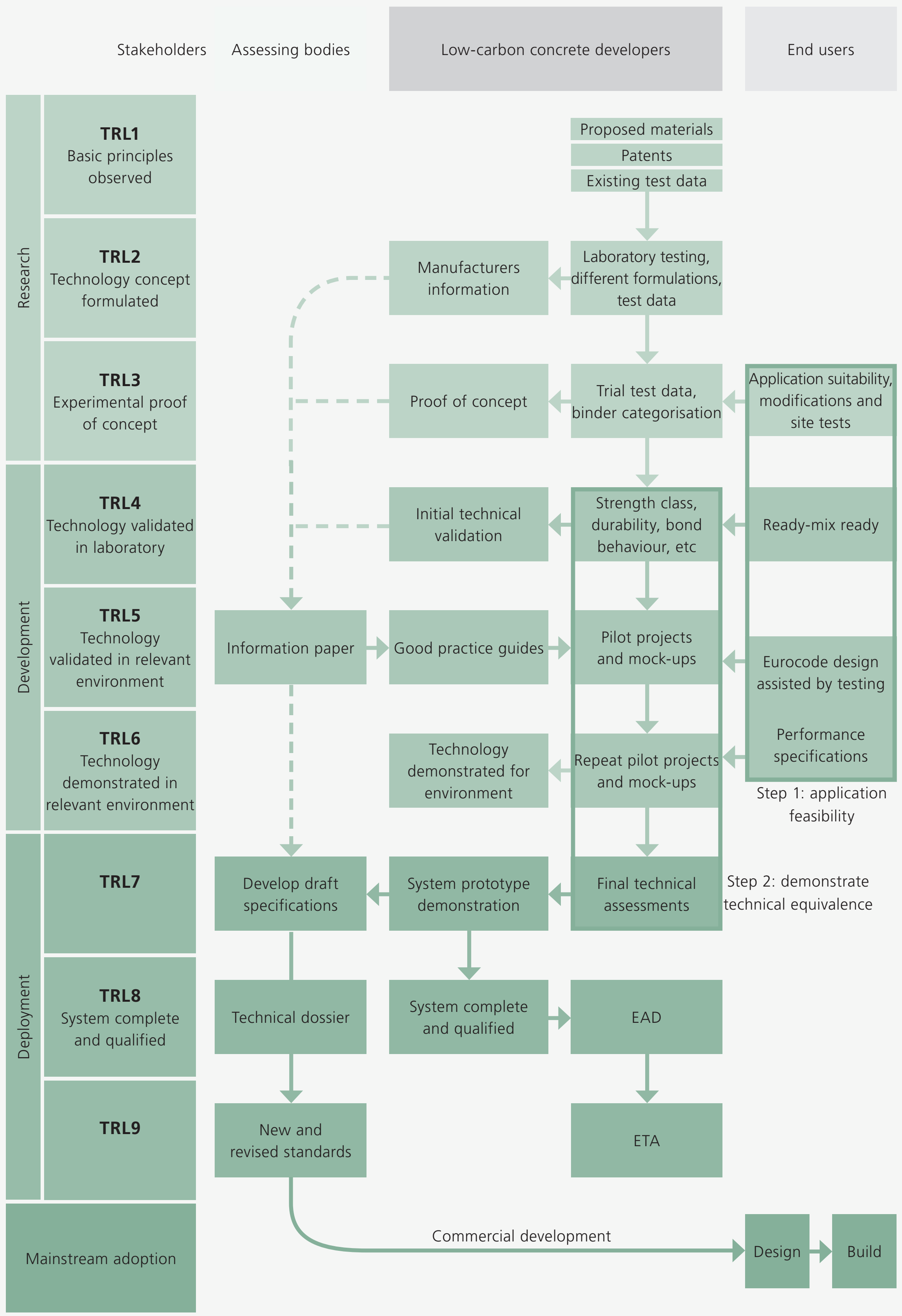


Fig 2.4: Step 1 – Application feasibility assessment

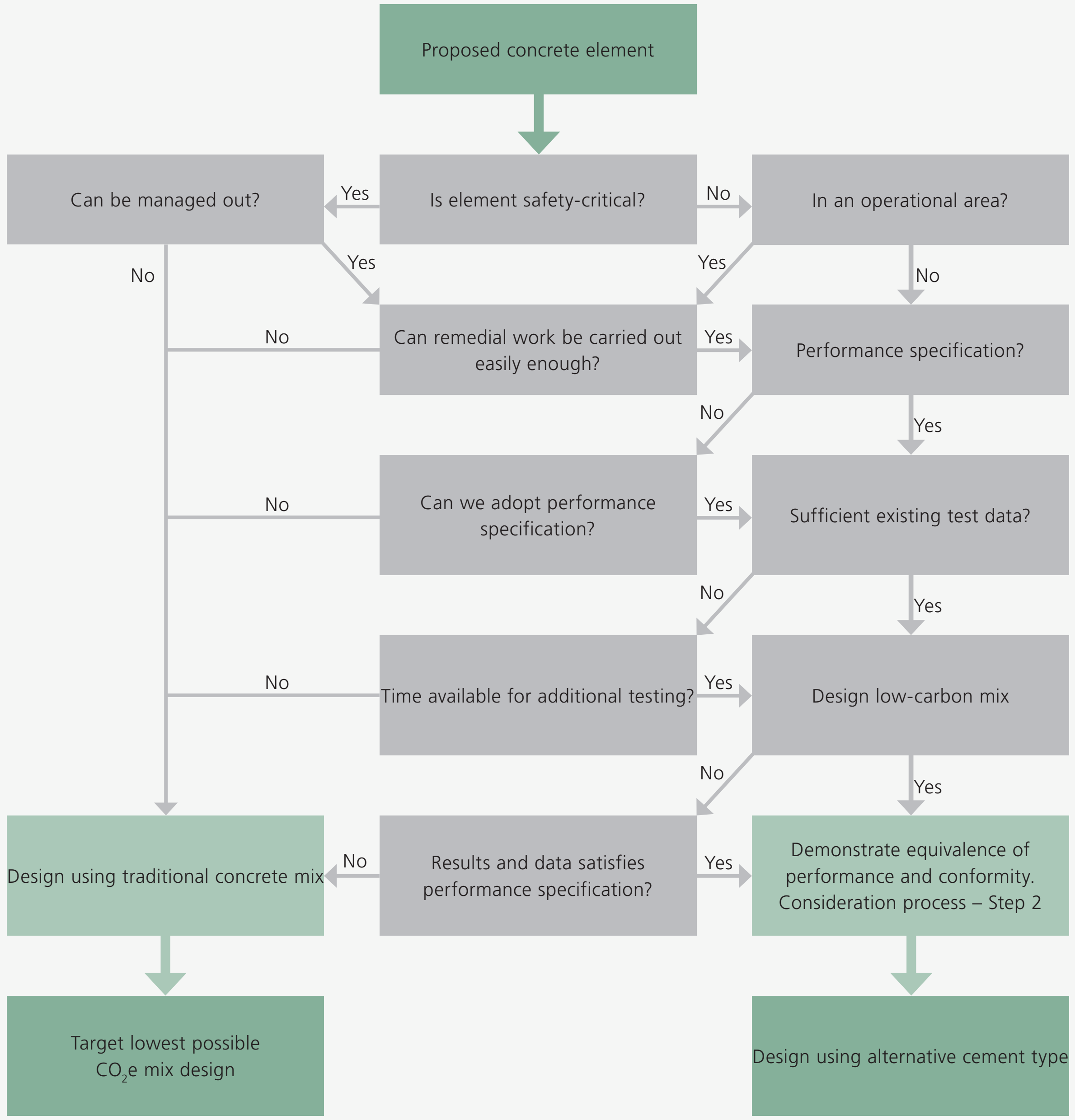
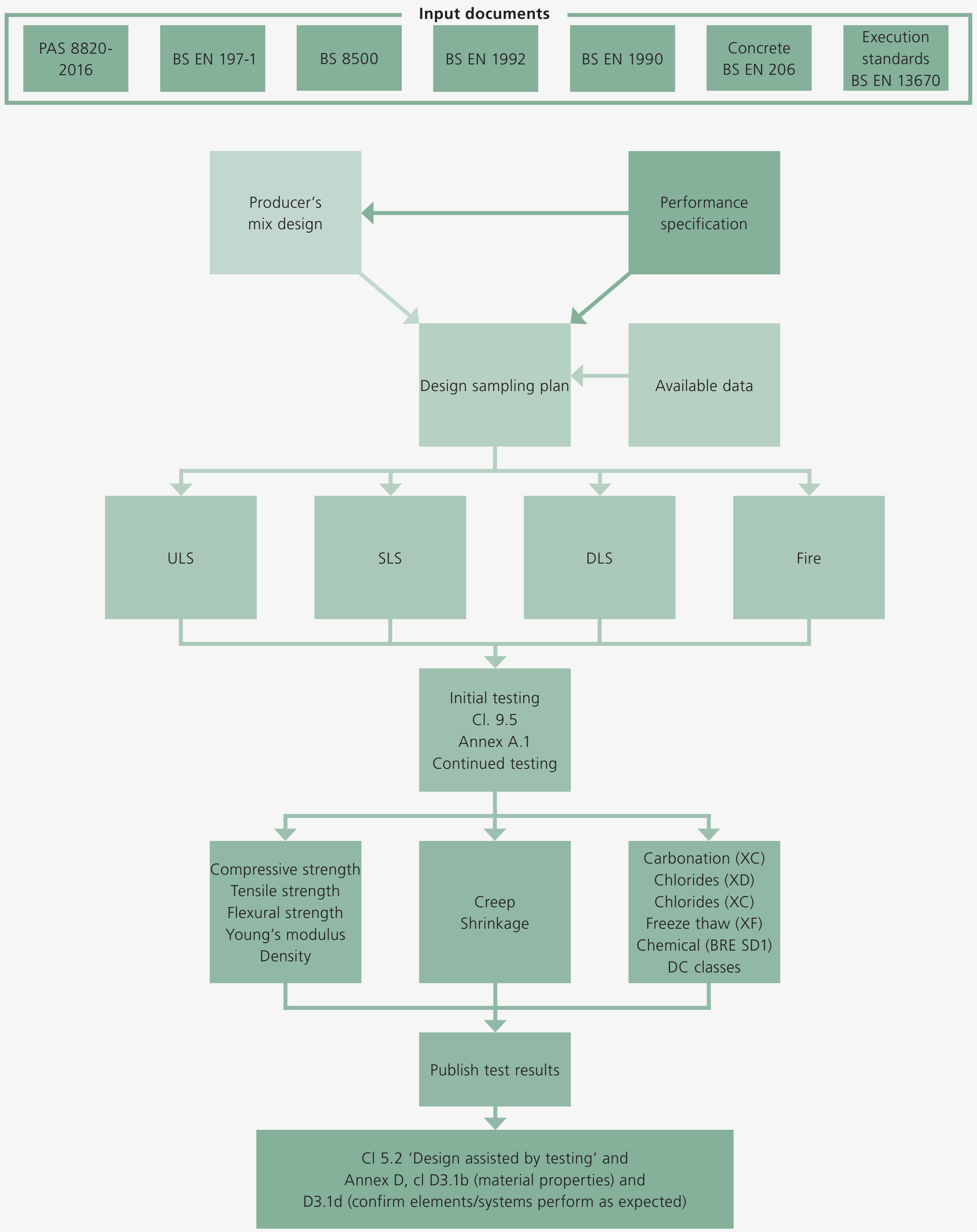
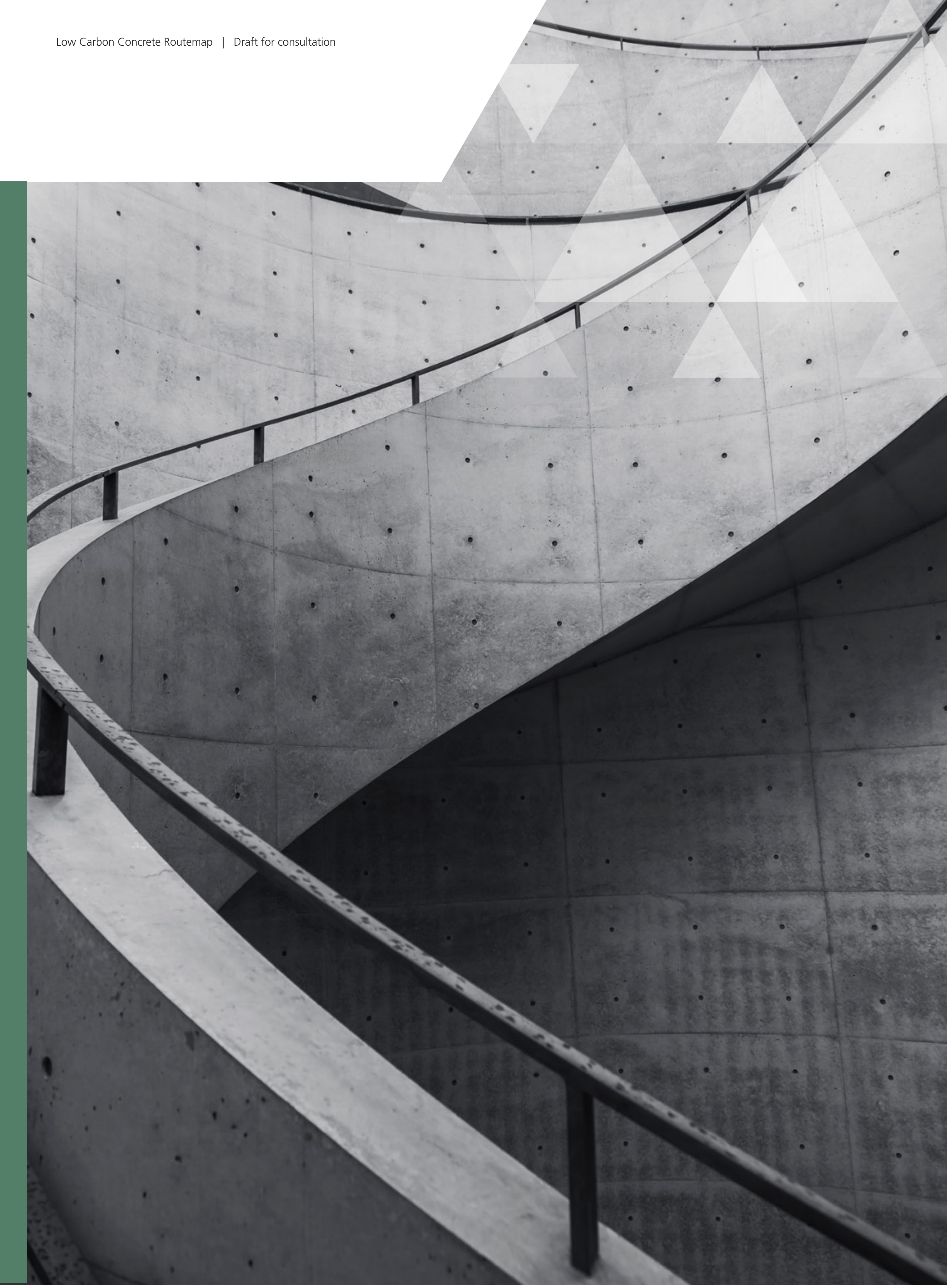


Fig 2.5: Step 2 – Demonstrating technical equivalence





Using concrete

3 Design and specification

To minimise CO_2e, the design team should use concrete with the lowest carbon intensity that is suitable for the particular performance requirements in the intended application. The design should be optimised to use materials efficiently to achieve the lowest practical whole-life CO_2e.

To achieve this, the design team should adopt best practice in selection of the structural form and general arrangement to reduce structural demand. 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 used.

'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 removing formwork/moulds often dictate in service concrete strengths that exceed the specified strength as used in the design calculations. Before commencing detailed design, the designer should engage and collaborate with a concrete technologist, a concrete contractor and a concrete supplier on the construction requirements and the minimum associated in-service strength of the concrete.

In addition, higher-strength grades, typically at 28 days, are often specified with the assumption that they will be more durable, but this is based on assumptions from plain Portland cement concretes containing little or no SCM content. Although the mainstream perception is that a high-strength concrete improves quality and durability, concrete technology is proving that 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. 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 concrete specification should include the project requirements for the carbon intensity of the mix. The specification should provide maximum possible flexibility to the mix designer to satisfy the project requirements, taking account of the ingredients available in the batching plant.

3.1 A hierarchy for design to minimise whole-life CO_2e

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

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

Table 3.1: Distribution of structural CO_2e to different LCA stages[1]

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 for ease of disassembly and re-use or reclamation of complete elements or materials at the end of life

Design and detailing for a long life is achieved by following industry guidance on details and mix design appropriate to the service environment. If industry guidance is followed, the CO_2e arising from requirements for structural maintenance during the design service life is usually minimal. Any benefits owing 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.

To reduce the CO_2e that will arise during LCA stages C and D, the design should facilitate eventual disassembly and re-use of elements, or separation of materials for re-use or recycling. 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 greenhouse gas 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. For example, a sway frame with a raised ridge relative to the eaves is a more efficient form than a flat roof arrangement.

For building structures, optimising the overall form for structural efficiency typically reduces the area of the external envelope and also reduces peak wind pressures. Such secondary effects can deliver additional reductions in greenhouse gas emissions.

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

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 LCA stages A1-A3 embodied carbon 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

3.3 Optimise elements for embodied carbon, considering the balance between reinforcement and concrete quantities and the carbon intensity of materials

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 foamed concrete. In some cases, this can reduce the concrete volume by more than 50%.

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).

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.

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 reported for 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[2] 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.

One part of a structure or element may be on the verge of failure while the rest remains far from failure. 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 around 30%. It is anticipated that similar reductions in CO_2e may be possible by increasing optimisation.

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 workability, reduce time to striking formwork or demoulding, mix grade simplification, 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 by the designer.

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.

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[3] and partial factors[4]. 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%[5]. 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[6].

Analysis methods
Substantial reductions in design actions may be achieved by using more accurate analysis methods. 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, or use of a yield line[7] or reliability analysis[8] to calculate the design section resistance. Reductions in the design actions enable the quantities of concrete or reinforcement to be reduced.

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.

3.4 Be flexible and collaborate with contractors and suppliers to use a wider range of concretes that meet the requirements

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 weight of cement required, 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 and will need to be in accordance with the relevant standards.

It should be recognised that there will be a greater range of lower-carbon cement blends 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 cement blends 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.

With a more flexible approach to specification, testing may be viewed as a necessary safety net to ensure compliance. Conformity control[9] and identity testing[10] are essential methods of demonstrating that a concrete conforms not just to the design from the concrete producer but also 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.

However, it is likely that engineers are setting onerous identity testing regimes as a means of risk reduction, which consequently provides the catalyst for concrete producers and contractors to include more cement in the mix design. This is clearly counterproductive if seeking to utilise a lower-carbon concrete. This practice is exacerbated by the failure of test samples, which more often is the result of poorly sampled and cured concrete cubes than a defective concrete.

To overcome the unintentional consequences of an overcautious testing regime, it is important that engineers collaborate with contractors and suppliers to agree an appropriate level of identity testing, if required, and ensure that the cement content is not increased to satisfy identity testing.

The specification of a low-carbon concrete is a collaborative effort. It is important for 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.

3.5 Request embodied carbon in concrete mixes and specify an upper limit

The Benchmarking section (Strand 1) of this document 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. However, these are typically based on generic reference mix designs that may be adjusted to meet project-specific requirements .

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. Carbon intensities based on mix designs should be verified by supplier reporting of the carbon intensity of the concrete as batched. Where possible, the carbon calculations based on mix designs and batching records should obtain the CO_2e values of the mix ingredients from product-specific EPDs.

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

The Benchmarking section 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[11] 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.

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.

Case study: Network Rail precast concrete optimisation

Many of the principles described here have been applied to reduce the embodied carbon of the precast concrete platform slabs used by Network Rail.

The form has been modified so that spanning units taper towards each end where the bending moment reduces.

Use of coffers on the soffit was reviewed. Since the units were only 65mm-90mm thick, the reduction in concrete volumes did not warrant the extra complexity of construction that would be required. Guidance in Economic Concrete Frame Elements[12] suggests use of ribbed sections in cast in-situ elements of 250mm or more, while ribs and recesses are sometimes incorporated into precast elements that are only 100mm thick.

The tapered form improves optimisation for bending and shear. The arrangement of reinforcement has been developed to increase utilisation and the layout has been optimised.

The structural design was based on a C40/50 mix. To satisfy the requirements for placement in the moulds and demoulding, the actual cement content used was originally consistent with a structural design based on a C50/60 mix. In this case, instead of designing for a higher strength of concrete, the mix design and demoulding arrangements have been modified so that the cement content can be reduced.

Measurements of cast units and the coefficient of variation of the concrete strength have been used to demonstrate that the partial factors for concrete and steel reinforcement could be reduced from 1.5 to 1.35 and 1.15 to 1.1 respectively[13].

Assessment of the weights of cast units and a review of the accuracy of analysis and verification methods, which included load testing[14], has demonstrated that the partial factor for self weight could be reduced from 1.35 to 1.05[15].

The original design was based on bending moments and shear loads estimated using manual estimation of point load dispersal into beam strips; this was replaced by a finite element model. Designs using steel reinforcement were additionally assessed using a yield line analysis.

The above measures, in conjunction with switching to a high-GGBS cement and BFRP (basalt) reinforcement instead of stainless steel, have achieved a reduction of 60% in the CO_2e attributable to LCA stages A1 to A3.

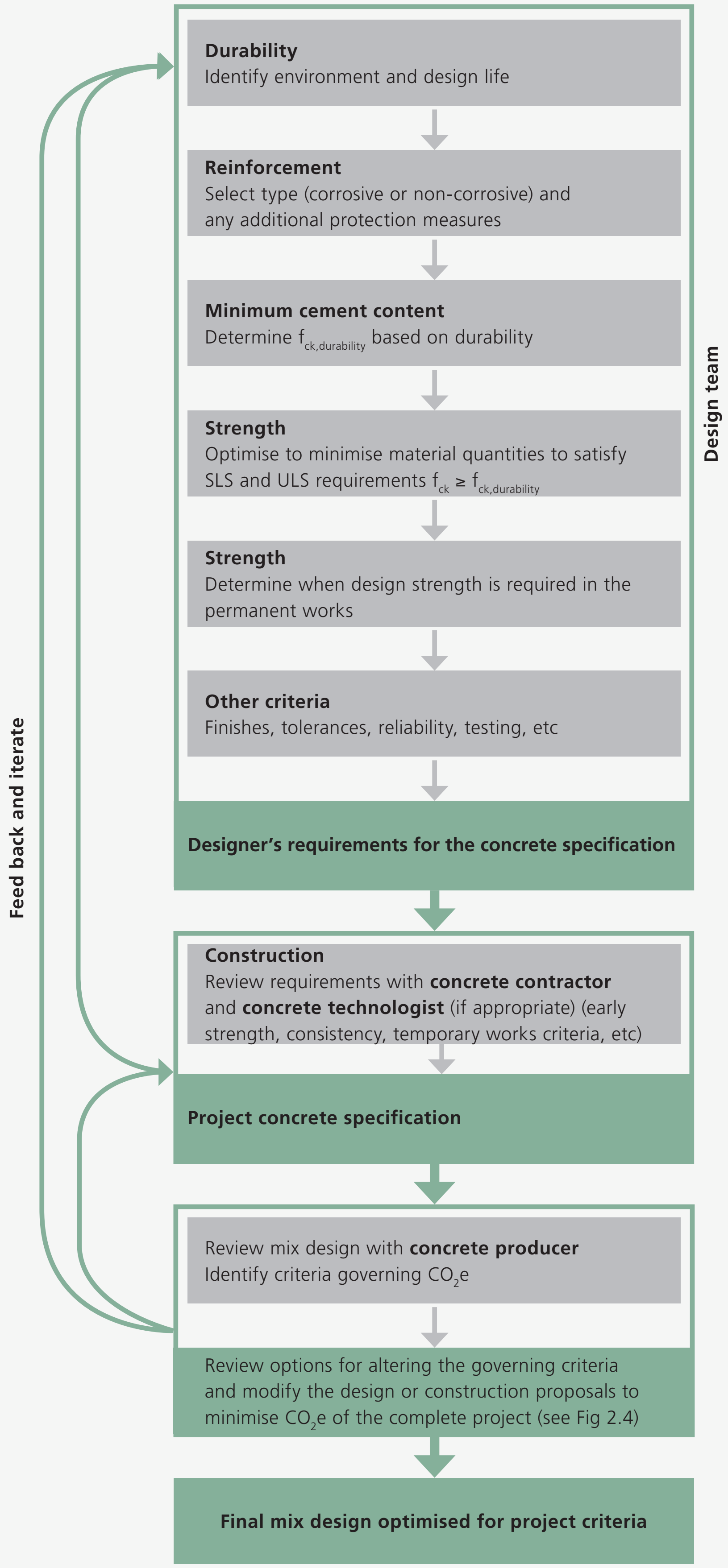
Publication by concrete suppliers, and preferably by individual batching plants, of the carbon intensity of their mixes will help project teams to identify suppliers that are able to meet specified limits on concrete CO_2e.

3.6 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 not be the absolute lowest in order 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.

> 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.

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



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 concrete 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[4].

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. Amendment to BS EN 13369:2018 (Common rules for precast concrete products)[4] may also offer an opportunity to embed minimum 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.

[Editor’s note: case study to follow on Wagners EFC with > 70% reduction in CO2e relative to 30% PFA mix and early age strength which matches the requirements for demoulding at 18 hours. This case study is being reviewed by the relevant partners and shall be included in the final draft.]

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, concrete cast in-situ waste is estimated to be approximately 5%[9] and globally it is estimated that more than 125 million tonnes of fresh, unhardened 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 recommendations promoted by the Get it Right Initiative[10] should be adopted wherever possible to reduce waste caused by construction errors.

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.

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 8km. In 2019, the average delivery distance for all concrete was 48km and the average delivery distance for all raw materials for concrete was 49km[1]. 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 transport emissions. There can also be limitations associated with the size and sophistication of the concrete plant.

Aggregate availability

Aggregates form the bulk of the mass of concrete and while they are typically inert, their size, shape and porosity play a significant role in the water demand and hence cement demand of a given concrete. Table 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 and secondary aggregates is often highlighted by project teams to satisfy BREEAM credits as well as the assumption that it must lower carbon. While there are definite advantages to the use of these materials, they are not necessarily beneficial with respect to the impact on cement content and can actually increase the cement demand compared with a locally sourced natural aggregate.

The properties of concrete with recycled aggregates are strongly influenced both by its type and proportion on 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[11].

During the concrete design, secondary aggregates, recycled coarse aggregates and crushed concrete aggregates should be considered; however, the aggregate quality, processing and transport should be compared with natural or crushed aggregates to assess the overall project carbon and cost benefit.

Cement type availability

The current cement standard BS EN 197-1[12] includes five main types of cements and 27 types of common 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 (L, LL). Most common 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 (Fig 4.1). Used with the concrete standards EN 206 and BS 8500, a wide range of solutions that can lower the embodied carbon of concrete can be provided.

However, not all batching plants will have access to the full variety of potential cement blends. As such, similarly to aggregates, project teams should review what potential blends 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 new cement blends while ensuring a smooth transition and phasing out of pure or high Portland cement blends.

Mineral combination	Plain	Water reducing additive	Superplasticiser
Basalt/crushed rock fines/04 nat sand	440	390	370
Basalt/04 nat sand	390	330	350
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 (w/c = 0.5) for a mid-range concrete with 04/20 aggregates and an S3 slump class

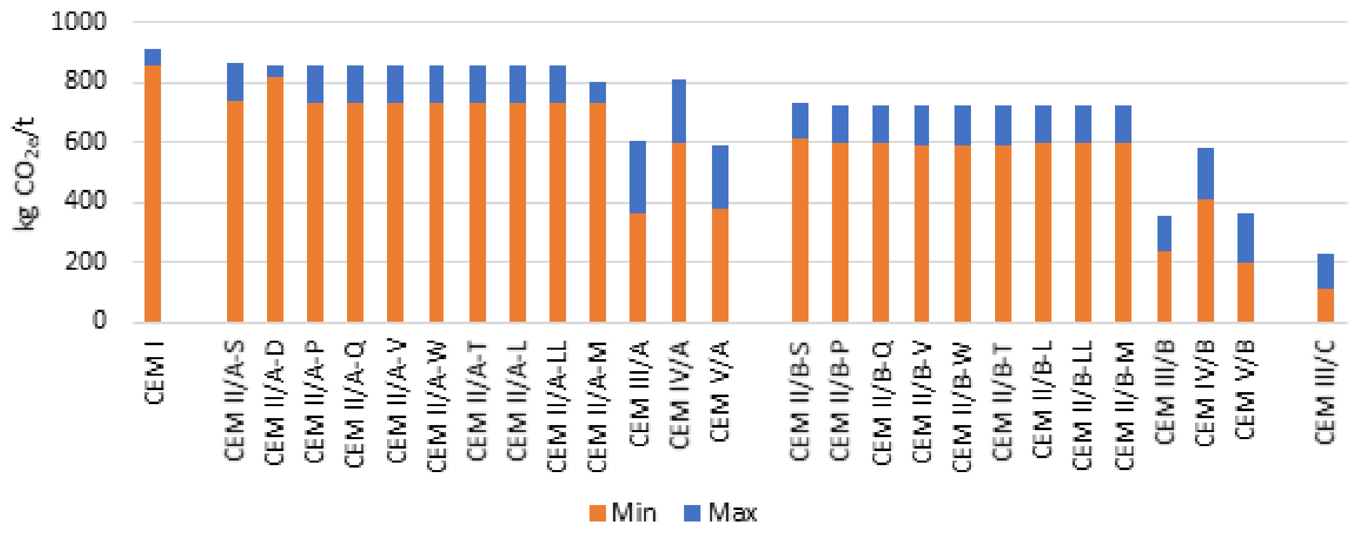


Fig 4.1: Cradle-to-gate carbon by cement types included in BS EN 197-1[12]

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 cement blends 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 – for example, altering an element to allow it to act in the temporary case, or considering how it could be optimised.

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 types and sizes, 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)[13].

There can also be construction 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)[14].

The speed at which a slab develops the necessary strength is a function of cement type, cement content, temperature and curing method. Using cement blends with 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 4.2, the impact on strength gain can be relatively small and may not be significant enough to affect strike times. Furthermore, by using accelerating admixtures, it is possible to mitigate the reduction in the rate of strength development (see Fig 4.3, which provides test data from a recent investigation).

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. 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.

Key recommendations:

- Workability requirements tested at an early stage to avoid locking in the requirement for additional cement in a mix.
- 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 and the appointment of a concrete technologist to respond appropriately 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 the 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 efficient and 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.

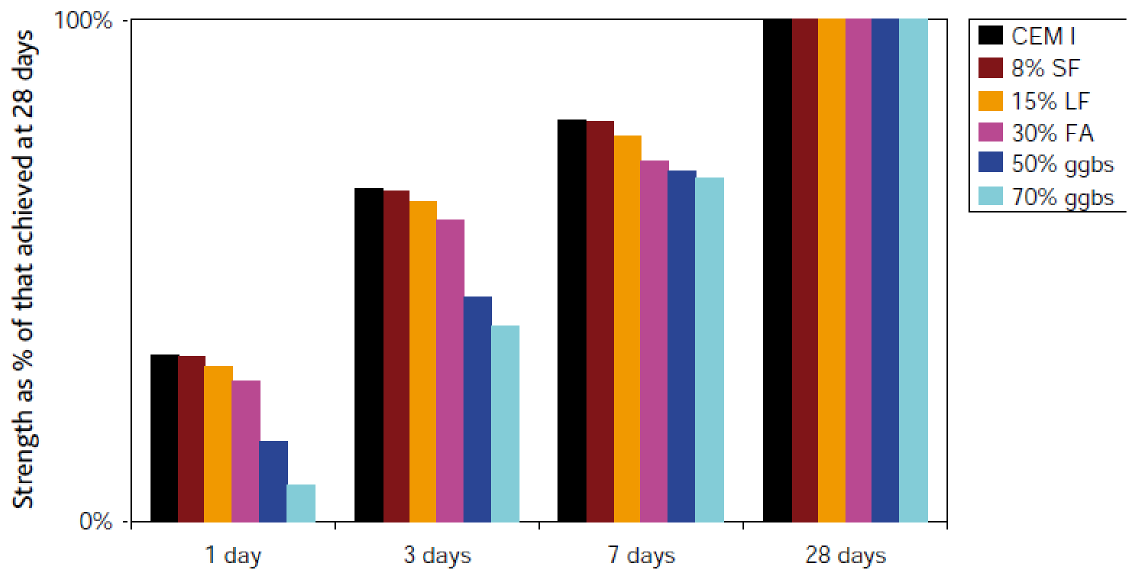


Fig 4.2: Indicative early strengths shown as percentage of 28-day strength (TR74, cementitious materials[15])

Notes:

1. The relative strengths are indicative and will vary significantly, with mix design and materials
2. The early-strengths are relative to 28-day strength
3. The cementitious content required to achieve a specified 28-day strength will not be the same for the different combinations
4. This graph is derived from experience and data contributed by the authors of this report

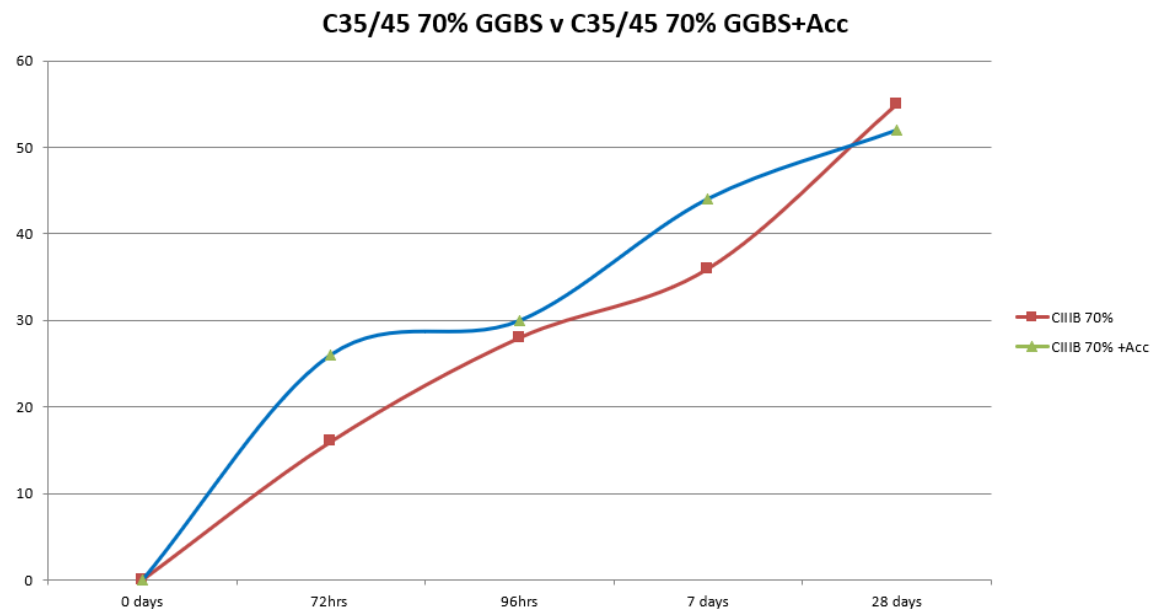


Fig 4.3: Impact of the use of accelerating additives to mitigate the use of SCMs

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_2 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 secondary cementitious materials 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 which 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]. The non-clinker ingredients include SCMs such as GGBS, fly ash, calcined clay and limestone. With the emergence of EN 197-5, these cements

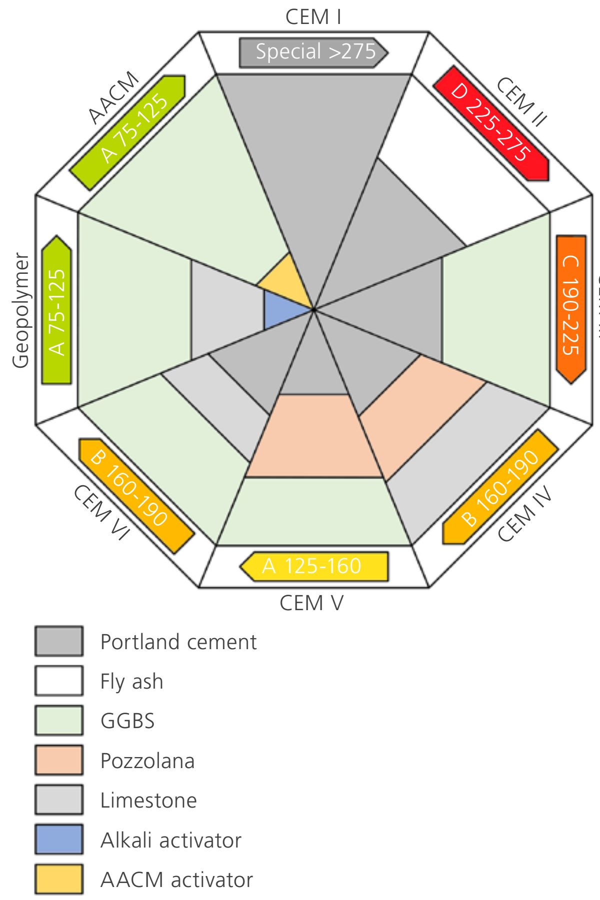


Fig 5.1: Typical carbon content of concretes made with different cements

are permitted to include limestone fines as part of the cementitious content.

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) only provides guidance for a subset of the EN 197-1 and BS EN 14216 cements, which 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 establish a British Standard for AACM and geopolymer cements and activators.

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.

Commercial availability of secondary cementitious materials used for the manufacture of all cements varies over time, sometimes rapidly. 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 supplementary cementitious materials other than GGBS and fly ash where possible

Fig 5.2 summarises global availability of cementitious materials. Clays and limestone 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.

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 FA 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 FA as an SCM.

The use of GGBS or FA 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 FA is fully utilised, use of GGBS or FA in any one mix may not reduce overall global greenhouse gas emissions. Where possible, a project should consider cements and other types of SCM for which there is potential for surplus local supply.

In the UK, there is scope to rapidly increase the use of limestone fines to the limits defined in BS EN 197-5.
In 2021, the Mineral Products Association, 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 fines (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 SCMs. Research is in progress to identify suitable UK clays. Most calcined clays are understood to perform similarly to FA, 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 governed by the minimum cement contents prescribed by standards such as BRE SD 1:2005 and BS 8500-1:2015+A2:2019.

Although concrete technology has evolved and improved in recent years, the prescribed values in BS 8500-1 have remained fairly static. The LCCG would support 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

The cement content should be sufficient to meet the performance requirements for:
- Exposure class (interpretation of BS 8500 tables needs engineering judgment for temporary works)
- Early strength gain
- Workability (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.

What's more, owing to operational considerations, cement contents in practice may exceed the designed values. The parameters that determine the minimum cement content should be identified early and, if time allows, tested to see if it will be possible to reduce the cement content. Testing may demonstrate that the performance requirements can be met with cement contents that are lower than those quoted in BS 8500-1. Once the cement content has been determined, the design should be developed to make maximum benefit of the concrete properties arising.

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 template is provided in the National Structural Concrete Specification[5] and should be included in procurement documentation.
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 additional measures to reduce the cement content, so as to reduce embodied carbon while providing the required performance.

> "Concrete technologists and the concrete producers' technical teams are best placed to understand and influence the performance of their materials – it is imperative that they are afforded the opportunity to influence the mix design rather than simply develop a prescriptive design."

5.4 Summary: optimising mix design

Parameter	Adjustments that may be considered
Early strength gain	Is it possible to keep formwork in place for longer? Can the factory casting sequence be adjusted so that precast elements can be removed from the mould later? Can an alternative method of demoulding be used?
Workability (slump or flow)	Is it possible to use an alternative method of placement or compaction? Is it possible to replace crushed aggregate with rounded aggregate – probably marine sourced?
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? Would the addition of small quantities of silica fume increase durability by filling pores and reducing permeability of the concrete? Can the concrete be protected from the environment, for example by using an external barrier system? Do we need a strict minimum cement content for service life of a structure that is considerably less than 50 years? 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 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.

Making concrete

6 Adopting new technology

Cement is the binding component in concrete, as obvious as it may sound – without it, the composite material will simply not work as it is designed and intended. The cement component is already varied but is currently dominated by Portland-based cements. 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.

In Section 2.1 (page 19), we discussed how to demonstrate the performance of cements that are not listed in BS EN 197-1 and consequently are not identified 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 sourced supply chain with ethical treatment of people and the environment. 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 (see section 5.2, page 44). 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; however, BEIS technical research paper 19 forecasts ongoing surplus availability.

Concrete comprises more than just cements and, as such, we should consider the requirement for other constituents such as aggregates, reinforcement and so on. These interdependencies are complex – they vary from product to product and are influenced by local availability and other project needs.

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

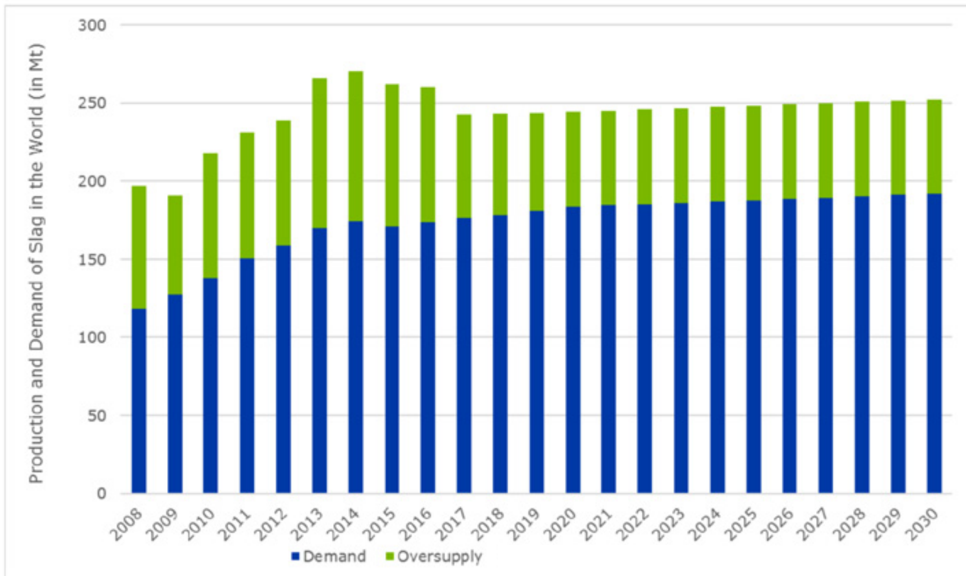


Fig 6.1: Global production and demand of GGBS (Mt) reproduced from fly ash and blast-furnace slag for cement manufacturing. BEIS technical research paper 19, 2017

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[1]. Below is an extract reproduced with permission from the authors, Hibbert, Cullen and Drewniok, 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 bodies 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.

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.

Market opportunities
There must be a market opportunity for a technology for it to reach commercialisation. The highest level of market opportunity is when the technology can be produced at scale and compete with existing alternatives due to demand-pull, rather than technology-push drivers.

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

- BBA (British Board of Agrément) certification
- Inclusion in a European assessment document (EAD) which forms a harmonised technical specification published by the European Organisation for Technical Assessment (EOTA)
- Completion of a European technical assessment (ETA) by the Technical Assessment Body for the respective product area.

There is no exact timeline for the above and the processes to be followed 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.

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 upon 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 should include a clear and concise proposal for standardisation of the new product. For cements, CEN/TR 16912:2016[2] – 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 MPA and The Concrete Centre for input and peer review at a very early stage. At this stage, the MPA and Concrete Centre can provide very 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. In order 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. Therefore, 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.

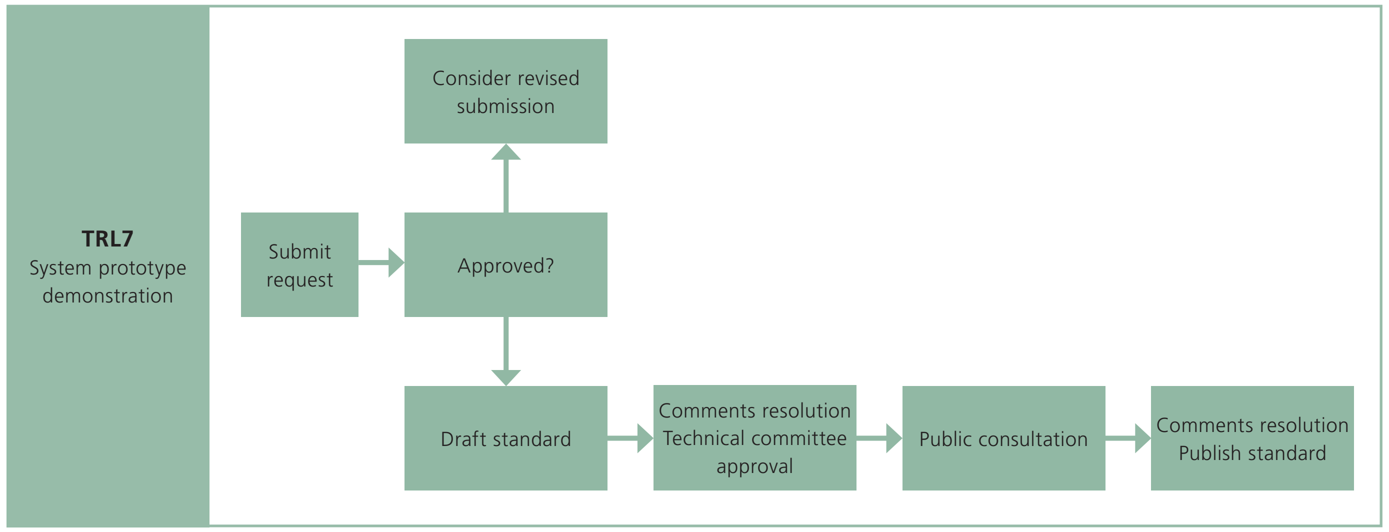


Fig 6.2: Process for gaining technical acceptance of new cements and concretes

Making concrete

7 Carbon sequestration, capture and use

This section considers how concrete can store carbon as well as what technologies can be adopted to sequester carbon from the production of concrete and 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, before relying on technologies that sequester the carbon dioxide once it has already been emitted.

7.1 Storing carbon in concrete: upfront carbon storage

Carbon dioxide can be utilised within concrete when it is mixed and cured. 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. As such, the principal carbon benefit of this technology is that it can reduce the cement content, rather than the storage of the injected CO_2, which is in very small quantities (~0.2% by mass of cement[1]).

There remain some ongoing queries with respect to the durability implications of such technology. It is also important that the CO_2 used in this process is from a captured source rather than having been created expressly for this purpose.

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, up to 300kg 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 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]).

As above, 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 Long-term carbon storage: 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 the risk of carbonation, which can reduce the alkaline environment within the concrete and increase the risk of reinforcement corrosion. However, from a carbon perspective, this effect is a significant long-term benefit of Portland cement-based concretes.

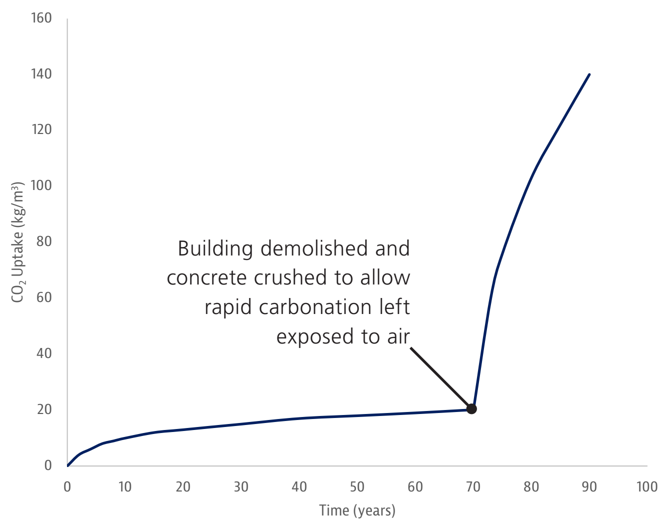


Fig 7.1: Indicative carbonation for typical concrete in a building, based on model estimating CO_2 uptake over time in CP III[5]

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 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.

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 is included in the 2021 Intergovernmental Panel on Climate Change report[6]. It is estimated that the total carbonation sink is 733 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]. This figure makes significant assumptions about rates of carbonation and the availability of cementitious materials.

Regardless of global carbon balances, for a given cubic meter 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.

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 CO2. However, the should be considered as part of a whole-lifecycle carbon assessment, where they are expressed distinctly from the upfront carbon.
■ Careful planning of demolition works presents real 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 limestone ~ 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 Mineral Products Association is delivering a pilot programme with BEIS 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. It is therefore likely that some of the emissions associated with thermal heating will need to be dealt with directly until alternative low-carbon alternatives are available at scale.

■ Carbon associated with the chemical decomposition of limestone ~ 50%:
The carbon emitted through the decomposition of limestone is an unavoidable by-product of Portland cement production. These emissions must be dealt with, too, if we are to continue to use significant quantities of Portland cement and reach net zero.

Capturing carbon

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, 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 (where the fuel is combusted with oxygen rather than air). Post-combustion systems, while requiring scrubbing, can capture CO_2 from mixed flue gases combined from the fuel combustion and limestone decomposition.

It should be noted that there are currently no operational carbon capture systems that capture 100% of the CO_2 emitted 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

Direct use of carbon dioxide is a more favourable outcome than storage because it involves fewer processes, does not carry long-term risk and may be commercially viable if CO_2 can be sold to meet industrial needs.

As noted above, carbon use for injection in ready-mix concrete, or for carbon curing, should come from industrial sources and, as such, some captured emissions from cement production could be used in concrete production – although this would require technology development to ensure that carbon was locked into concrete without any unabated emissions during curing.

Storing carbon

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 at individual cement plants. This is because currently there is no commercial incentive to invest in the technology to store carbon. 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 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. However, technology development is required, particularly with storage, and the commercial environment does not yet exist to allow the large-scale roll-out of this technology within the timeframe required for action in the cement industry.
■ 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.

[Editor's note: case study to follow on CCS at Norcem Brevik. This case study is being reviewed by the relevant partners and shall be included in the final draft.]

> "If we are to continue to 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, to avoid their unabated emissions."

8 Next steps in the decarbonisation of concrete

> 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.

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 in the UK.

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.

8.2 Aims of the Green Construction Board's 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 towards 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 a need and opportunity 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. Ready-mix producers should provide batch records for each delivery that calculates the embodied carbon for that delivery.

8.4 Decarbonising concrete at scale in the UK

There are very many ways of reducing the carbon of concrete construction. Some methods of decarbonising concrete construction 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 will credibly deliver reductions in the carbon of concrete construction, at scale and across the UK. We have discussed in Strands 1-7 of this Routemap 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.

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 footprint 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 and geopolymers, 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.

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.

8.6 Actions required

Table 8.1 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 cement types. A task force with funding is required to coordinate and drive the actions identified.

The principles underlying the actions listed in Table 8.1 (see overleaf) can be broadly summarised as: use the minimum practical quantity of concrete, reduce the carbon intensity of cement and other constituent materials including reinforcement and, in due course, capture and use (or storage) of any residual carbon emissions.

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 industry would be particularly useful. This would inform the planning of alterations to existing facilities and the construction of new infrastructure.

8.7 A moral and professional obligation

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. Decarbonisation of the UK concrete industry can be supported by:

- Industry and public education campaigns
- Enabling research and the development of guidance
- Provision of grants or low-cost loans to industry to enable change to facilities and processes
- The creation of commercial incentives to decarbonise.

Table 1: Next steps in the decarbonisation of concrete in the UK

	Item	1. Benchmarking	2. Knowledge transfer	3. Design and specification	4. Construction and operation	5. Optimising existing technology	6. Adopting new technology	7. Carbon sequestration	Opportunity	Impact	Start date	Example products
Client signalling	A1	■							Clients define product requirements using the LCCG benchmark rating criteria and commit to buying concretes that meet the criteria	5	2022	
Task force	B1		■						Formation of a Concrete Decarbonisation Task Force to coordinate and communicate the development of low-carbon technologies and initiatives	4	2022	
Design and specification	C1			■					Include voids, coffers or profile sections to reduce concrete volume in thick or planar concrete sections (slabs, rafts, diaphragm walls)	4	2022	
	C2			■					Increase utilisation factors and assess design optimisation	3	2022	
	C3			■					Make use of EN 1992 provisions to reduce material partial factors based on quality control and reduced deviations	1	2022	
	C4			■	■				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	
	C5			■					Specify reinforcement which will not corrode and define the real lifetime of RC elements	1	2022	
	C6			■					Include an upper bound on kg CO_2e/m^3 in the specification	3	2022	
	C7			■	■				Allow the concrete supplier the maximum possible flexibility to meet or beat the specified upper bound kg CO_2e/m^3	3	2022	
	C8		■	■			■		Identify elements suitable for the use of new and emerging low-carbon concrete. Encourage the use of these concretes for these elements	3	2022	
	C9			■	■				When identity testing, ensure quality control methods are communicated to batching plant so cement content is not increased for reduced results	2	2022	
	C10			■					Require reporting of the as batched kg CO_2e/m^3	3	2024	
Site works	D1				■				Adopt working methods that reduce the required slump/flow of concrete	2	2022	
	D2				■				Adopt working methods that reduce the requirement for early strength gain	3	2022	
	D3			■	■				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	
	D4			■	■				Minimise waste, including through use of BIM to avoid over-ordering	3	2022	
	D5				■	■		■	Plan demolition works to maximise carbon take-up by concrete demolition arisings	2	2022	
	D6				■				Reclaim cementitious material and aggregates from demolition arisings	2	2026	SmartCrusher
Cement manufacture and concrete batching	E1					■			Continue to decarbonise the production of Portland cement (CEM I)	1	2022	
	E2	■			■	■			Calculation of as built CO_2e based on as batched ingredients and volumes mixed or dispatched to site	3	2022	
	E3				■	■	■		Modify batching plants to enable production of lower-carbon concretes. For example, add silos for alternative SCMs, add dispensers for AACM activators	4	2022	
	E4				■	■	■		Propose alternative lower-carbon concretes/mixes to clients, including as pilots	4	2022	
	E5			■		■			Increase and optimise use of GGBS and FA as an SCM in blended cements already in current standards (BS EN 197)	3	2022	CEM III/B, CEM III/C
	E6					■			Increase use of tertiary (three-part) and quaternary (four-part) blended cements already in current standards (BS EN 197)	1	2022	CEM VI(S-P), CEM VI(S-L), CEM II/C-M
	E7					■			Extending the use of limestone fines as a blended cement within the current standards (BS EN 197)	1	2022	CEM II/B-L, CEM II-B-LL
	E8					■	■		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
	E9	■			■	■			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	
Reporting	F1	■	■		■	■			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	
	F2	■	■						Periodic updating of LCCG benchmark and guidance	3	From 2022	
	F3			■					Designers to report on optimisation and utilisation for all concrete elements as standard practice	3	From 2024	
Piloting	G1				■			■	Central database of pilots required and reporting of findings	4	From 2022	
	G2			■	■		■		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	
	G3				■			■	Establish pilots of CO_2 capture at cement works	5	From 2026	
Developing technologies and preparing/ publicising guidance	H1						■		Tertiary and quaternary mixes beyond the guidance already provided in BS EN 197 and BS 8500, reducing the clinker proportion	1	From 2025	CEM II/C-M
	H2						■		Limestone fines as a SCM at higher % replacement than currently permitted by BS EN 197	1	From 2022	
	H3						■		Identification of clays in the UK with mineralogy suitable for calcining to use as cementitious materials (SCM or AACM)	5	From 2022	
	H4		■	■					Develop performance-related standards for concrete works	3	From 2022	
	H5					■	■		Convert PAS 8820-2016 to a British Standard – AACM/Geopolymer Activator Standard	2	From 2022	
	H6			■					When non-corrosive reinforcement should be used	1	From 2022	
	H7		■				■		Assessment of risk and consequence levels and conditions where the use of different concretes should be accepted/expected	4	From 2022	
	H8		■	■	■				Working methods to maximise carbon take-up by concrete demolition arisings	2	From 2022	
	H9		■	■			■		Availability and remuneration of competent persons to develop the guidance	3	From 2022	
	H10			■		■			Reduce minimum cement contents listed in BS 8500-2	4	From 2024	
	H11						■	■	Concretes that contain sequestered CO_2	4	From 2024	CarbonCure
	H12					■			Fly ash reclaimed from stockpiles as a SCM	3	From 2024	
	H13						■	■	Synthetic aggregates that sequester CO_2 during manufacture	2	From 2024	Carbon8
	H14						■		Use of graphene in concrete	3	From 2024	
	H15						■	■	Concretes that cure by carbonation	2	From 2024	Solidia Concrete
	H16		■		■	■			Construction methods/formwork that make economic use of efficient/ voided forms	4	From 2024	
	H17				■			■	Identify optimal locations for factories that will make use of captured CO_2	3	From 2024	
	H18						■		Calcined clay as a SCM at higher percentage replacement than currently permitted by BS EN 197	4	From 2026	
	H19						■		AACMs based on calcined clay (including metakaolin)	4	From 2026	BanahCEM (no longer trading)
	H20						■		Use of cementitious materials reclaimed from demolition arisings as a SCM	3	From 2026	
	H21						■	■	Synthetic SCMs that sequester CO_2 during manufacture	5	From 2030	Solidia SCM, Seratech
	H22						■	■	Synthetic AACMs that sequester CO_2 during manufacture	5	From 2030	Seratech

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 material	AACM	Alkali-activated cements are materials that gain strength by means of a chemical reaction between a source of alkali and an aluminate-rich material e.g. GGBS, FA or natural pozzolans such as calcined clay.
Binder		A binder is a material used to form materials into a cohesive whole, as a means of providing structural stability. Binding agents harden chemically or mechanically and in the process bond fibres, filler powder and other substances together.
Building Research Establishment	BRE	A UK centre of building science, owned by charitable organisation the BRE Trust.
Building Research Establishment Environmental Assessment Method	BREEAM	BREEAM is 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.
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 global warming potential expressed in equivalent carbon dioxide emissions.
Carbon intensity	kg CO_2e/kg	The upfront embodied carbon of a material or product relative to its weight.
Carbon neutral		All carbon emissions are balanced with offsets based on carbon removals or avoided emissions.
Carbon offset		'Carbon offset' means emission reductions or removals achieved by one entity can be used to compensate (offset) emissions from another entity.
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		Carbonation is the reaction of carbon dioxide (CO_2) in the environment with the calcium hydroxide – $Ca(OH)_2$ – in the cement paste. CO_2 is absorbed by the concrete during its use and end-of-life phases of its lifecycle.
Cement		A finely ground inorganic material which, when mixed with water, forms a paste that sets and hardens by means of hydration reactions and processes and which, 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, the one that confers hydraulic properties to cement.
Commercial readiness index		An index to consider commercial readiness to reflect commercial pressures beyond 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 strategy to tackle climate change.
Durability		Durability describes how a material resists mechanical or chemical degradation.
Embodied carbon		The total greenhouse gas emissions and removals associated with materials and construction processes throughout the whole lifecycle, including disposal.
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	Fly ash or pulverised fuel ash is the fine ash carried out with the flue gases from a furnace during the combustion process. Fly ash can also mean ash from furnaces other than coal-fired power station furnaces.
Geopolymer		Geopolymer cements are 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	Created in 2011, the Green Construction Board is the sustainability workstream of the Construction Leadership Council (CLC).
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.
Lifecycle assessment	LCA	An assessment of the environmental impacts of products, processes or services, through production, usage and disposal.
Megapascals	MPa	The metric unit use 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.
National Structural Concrete Specification	NSCS	The NSCS Standard Specification provides a base concrete specification with standard clauses on execution, materials and construction.

TERM	ACRONYM	DEFINITION
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. Minimising emissions should always be prioritised over offsetting.
Non-Portland cement binders		A term used to designate alternatives to existing general-purpose cements but whose suitability is not yet established in 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). It also contains smaller amounts of magnesium oxide (MgO) and oxides of the alkali metals potassium (K_2O) and sodium (Na_2O). It is produced by grinding clinker with gypsum (which controls setting) to a fine powder.
Pozzolan		A siliceous and aluminous material that, in the presence of moisture, chemically reacts with calcium hydroxide to form compounds possessing cementitious properties; such as calcined (kaolinate) clays, fly ash, volcanic ash and silica fume.
Parts per million	PPM	Parts per million is the number of units of mass of a 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	Arise from reprocessing materials that have previously been used in construction.
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		Aggregates that are usually by-products of other industrial processes that have not previously been used in construction.
Secondary cementitious materials	SCM	Materials that may be used to replace a proportion of Portland cement, CEM I or clinker in blended cements or concrete. When added at the concrete mixing plant, such SCMs are referred to as 'cementitious additions' as they are added to high clinker CEM I. SCMs may be naturally occurring with minimal processing or may arise from wastes or by-products from other industries.
Technology readiness level	TRL	A type of measurement system used to assess the maturity level of a technology.
UK Quality Ash Association	UKQAA	A 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.
Water-cement ratio		The ratio of the amount of water to the amount of cement in a concrete mixture.
Whole-life carbon		The sum of all asset-related greenhouse gas emissions and removals, both operational and embodied, over the lifecycle of an asset, including disposal.

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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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