This note explains why concrete used in bridges has a high capital carbon, and discusses the factors that contribute to this.

1 Introduction

Concrete is all-but-essential in the construction of modern bridges, yet it is widely recognised as a carbon-intensive material and a driver of global heating. One part of our response to the climate crisis must be to drive down the carbon emissions associated with using concrete in bridges.

The capital carbon\(^1\) of a concrete component is equal to its volume multiplied by a carbon factor. So the clear options to save capital carbon are simply to use less concrete, or lower the carbon factor. This topic paper considers the factors that drive the carbon factor itself: the amount of greenhouse gas emissions released for each cubic metre of concrete.

Concrete is a mixture of sand, aggregate, water, admixtures, and binder. Binder is typically Portland cement (PC), or a combination of Portland cement and other supplementary cementitious materials (SCMs). Binder is by far the most carbon-intensive part of concrete and the capital carbon normally relates closely to binder content, as shown in Figure 1.

![Figure 1: Carbon factor for increasing binder content, derived from ICE Embodied Energy and Carbon Database v3.0, 2019](image)

This paper explains why cement has high capital carbon, some of the factors that influence the amount of cement used in concrete, and how we can use this knowledge to make effective choices that reduce the capital carbon of concrete in bridges. The paper is applicable to all concrete elements of a bridge: superstructure, substructure, foundations, as well as to ancillary items such as verges.

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\(^1\) Conceptually similar to embodied carbon or the capital financial cost of an asset: greenhouse gas emissions and removals associated with the creation and end-of-life treatment of an asset, network or system, and optionally with its maintenance and refurbishment (definition from PAS 2080, Carbon management in buildings and infrastructure).
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When specifying concrete, the structural engineer defines certain constraints within which the contractor and concrete supplier can operate. A structural engineer can control carbon by avoiding designing for higher strengths than needed. But when looking to improve sustainability credentials, it is not solely the structural engineer’s role to overly constrain aspects of the concrete such as cement content – the concrete mix designer must respond to this challenge. The client must also set a clear agenda and support the contractor in terms of choosing low carbon mixes, which may not always be the cheapest option. Altogether, achieving low carbon concrete is not something that can be achieved by structural engineers on their own – rather it requires engagement throughout the entire supply chain.

This paper focuses on practice in the UK and Ireland, and therefore guidance relates to the British Standard: BS 8500. A new version of BS 8500 was issued in late November 2023. A key aim of the 2023 edition is to better enable engineers to specify more sustainable concrete.

2 What makes concrete bridges different?

Concrete bridges are different to other concrete structures in several regards:

- Lifespan: bridges tend to be designed for a 100-year-plus design life, well beyond the design life for most building structures.
- Exposure: bridges are rarely clad, and usually need to be designed to withstand the effects of carbonation, freeze-thaw cycles, sulfates in the ground, and chlorides (from de-icing salts and sea water).
- Strength class: bridge superstructures are often designed using higher strength concretes, C50/60 or greater.
- Prestressing: prestressed concrete is common in bridge construction. Prestressed concrete allows longer and more slender spans, as the concrete behaves more efficiently in compression, but it typically requires higher concrete strengths. Bridge elements are often pre-cast where early strength gain is desirable to speed up production. Higher strength and early strength gain may both drive increases in the total binder content (and thus capital carbon) for a concrete mix.

3 Cement

3.1 The importance of binder in concrete

Binder is fundamental to the finished concrete being a strong, cohesive, durable solid. It reacts with water to form a paste which binds together the aggregate to form concrete. The strength of the concrete increases with a lower water/cement ratio, but a mix with a lower water/cement ratio has lower consistence. Admixtures can be used to maintain consistence with less addition of water. The quantities of binder and water used in a concrete mix depend on strength requirements (including any requirement for rapid strength gain), durability requirements, consistence, and the cement designation used.

Generally, adding more binder leads to more desirable characteristics but at the cost of an increased carbon factor. Specifying higher strength class, higher exposure classes, or high consistence will therefore normally result in an increased carbon factor of the concrete, because of the increase in binder required.
3.2 How is cement made?

Modern concretes generally use a binder which combines Portland cement and SCMs. PC is a product with high capital carbon. Cement is manufactured from calcium carbonate (limestone/chalk) and silica (clay/shale), or other chemically similar suitable raw materials. They are heated at high temperature in a rotary kiln to form clinker, rich in calcium silicates. The process of calcination of the calcium carbonate in the kiln releases carbon dioxide. The clinker is ground to a fine powder with a small proportion of gypsum (calcium sulphate), which regulates the rate of setting when the cement is mixed with water. Other minor constituent materials may also be added.

Carbon dioxide emissions therefore arise when generating the energy required to extract the raw materials and in the heating process, but they are also an unavoidable by-product from the process of calcination, typically comprising 60-70% of the total emissions. A flow chart of CO₂ emission during manufacture of cement clinker is provided in Figure 2.

![Flow chart showing sources of emissions during manufacture of cement clinker](Net Zero Bridges Group)

3.3 What SCMs are available?

Portland Cement content can be reduced using SCMs, which come in many forms. The most commonly used in the United Kingdom are ground granulated blast furnace slag (GGBS) and fly ash (FA), the secondary products from blast furnace steel production and coal fired power generation, respectively. Silica fume – a further SCM sometimes used – is a secondary product of silicon and ferrosilicon alloy manufacture. All of the SCMs are produced during energy and carbon-intensive processes, but because they are considered as waste products, the carbon factor of the SCM usually ignores the emissions associated with the source industry.

Currently, production of GGBS in the UK is insufficient to meet its demand as an SCM, and increasingly it is imported for use². At a global level, on average there is only sufficient supply of GGBS to replace around 10% of the PC used in concrete production³. Supply of GGBS is expected to diminish further as steel production moves away from carbon intensive processes such as the blast

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² The Structural Engineer, Volume 101, Issue 7, 2023, Pages 24-27.
³ The efficient use of GGBS in reducing global emissions, ConcreteZero, September 2023.
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furnace, with silica fume similarly affected. Supply of fly ash will diminish as coal fired power stations are decommissioned.

In the UK, limestone fines are available as an alternative SCM, typically as 10-15% of a cement blend. Limestone fines are frequently used alongside other SCMs in multi-component cements (MCCs) to achieve an overall higher proportion of PC replacement, and a reduction in GGBS dependence.

Pozzolana refers to a group of SCMs that exhibit cementitious properties when combined with lime. Pozzolana may be natural pozzolana such as volcanic ash, or natural calcined pozzolana which undergo a thermal activation process. Calcined clay is a calcined pozzolana produced via thermal treatment of clay and has lower embodied carbon than PC. Its pozzolanic properties make it suitable for blending with limestone fines. Despite being globally abundant, limited availability in the UK results from a shortage of requisite kaolin-type clays. However, importation is plausible with rising demand, and the market holds potential for growth. Ongoing research explores the viability of utilising UK-sourced waste clay.

3.4 Choice of appropriate binder

Concrete is specified to BS 8500. Further guidance is provided within Section 4. Within BS 8500, different types of cement are denoted ‘CEM’. The numeral and alphabetical notations (e.g. CEM II/A) represent the type of cement and the proportion of PC clinker required. Multi-component cements have more than one type of SCM. BS 8500:2023 expands on previous revisions of the standard to facilitate greater use of multi-component cements. A suffix applied to the cement type denotes the SCM used, as follows:

- S – GGBS
- V – fly ash
- L – limestone fines
- D – silica fume
- P – natural pozzolana
- Q – natural calcined pozzolana
- M – multi-component

It is standard practice in the UK for PC and SCMs to be mixed together at the concrete plant, as an alternative to a composite at the cement works. In such instances the equivalent cement combination is denoted with a ‘C’ designation in place of a ‘CEM’ designation (e.g. CIIA). This approach offers some greater flexibility to the concrete producer to adjust the cement blend to best suit the requirements of the concrete end use. In the future it should also enable producers to deploy more flexibly lower carbon cement combinations.

When specifying the cement designation, the structural designer takes into account the concrete’s performance requirements, encompassing fresh properties, strength (including early age specifications), and durability. The incorporation of SCMs (particularly GGBS and fly ash) in a concrete can enhance durability performance across different categories, including:

- Reduced permeability
- Reduced rate of carbonation
- Reduced rate of chloride migration
• Improved sulfate resistance
• Improved alkali-silica resistance

Technical Report 74 Cementitious Materials, Concrete Society provides detailed advice on the effects of each SCM.

SCMs possess a lower heat of hydration compared to PC. However, they demonstrate enhanced later-age strength development, leading to significant implications for their specification. To optimise cement usage, it could be feasible to specify the 56-day strength rather than the 28-day strength. Additionally, the lower heat of hydration holds relevance for specific applications. For instance, in substantial concrete pours such as pile caps, SCMs can be employed to control concrete temperatures during curing, helping to mitigate the risk of early age cracking.

In contrast, some applications will require early strength gain – such as programme critical activities or a precast factory where earlier formwork striking will enable commercial benefits. In these instances, mix designs will often have a higher total binder content to compensate for the SCM’s slower rate of strength gain.

3.5 Embodied carbon of binder

Figure 3 illustrates the how the different constituent components contribute to the embodied carbon for a typical cubic metre of reinforced concrete. Cement is by far the main contributor – making it a clear focal point when seeking to specify more sustainable concrete.

Figure 3: Typical make-up of embodied carbon in reinforced concrete (source: Paul Astle / The Structural Engineer, Volume 99, Issue 2, 2021, used with permission)

Increasing the proportion of GGBS and other SCMs will nominally reduce the embodied carbon of cement, as shown in Table 1. While the use of a higher proportion of SCMs will lead to a lower capital carbon for any given volume of concrete, the limited availability of SCMs should deter designers from specifying very high levels (e.g. CEM III/B), solely for carbon savings, where there is
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no need for their specific performance attributes. Concentrating use of the finite quantity of SCMs in this manner is unlikely to reduce carbon emissions at a global level\(^4\), even if the individual project can claim to have reduced its carbon. This practice may even lead to an overall increase in global carbon emissions, if overall binder use increases; for example, to meet early-age strength requirements while maintaining a high proportion of slag, or if the SCMs require transportation over long distances. In contrast, more extensive use of multi-component cements, as facilitated by BS 8500:2023, offers the opportunity to better utilise the palate of SCMs available and derive lower concrete mixes without overreliance on GGBS and fly ash.

*Table 1: Embodied carbon (kgCO₂e/tonne) range for different cements - includes transport of all constituent materials to the cement works but not transport to concrete plant*\(^5\)

<table>
<thead>
<tr>
<th>Cement (Factory made cement)</th>
<th>Low – High Content (%)</th>
<th>Main SCM</th>
<th>Embodied carbon (kg CO₂e/tonne)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEM I Portland Cement</td>
<td>-</td>
<td>-</td>
<td>912</td>
</tr>
<tr>
<td>CEM II/A-LL or L Portland Limestone Cement</td>
<td>6 – 20</td>
<td>Limestone</td>
<td>860 - 738</td>
</tr>
<tr>
<td>CEM II/A-V Portland fly-ash cement</td>
<td>6 – 20</td>
<td>Fly ash</td>
<td>858 -730</td>
</tr>
<tr>
<td>CEM II/B-V Portland fly-ash cement</td>
<td>21 – 35</td>
<td>Fly ash</td>
<td>721 - 595</td>
</tr>
<tr>
<td>CEM II/B-S Portland slag cement</td>
<td>21 – 35</td>
<td>GGBS</td>
<td>729 - 607</td>
</tr>
<tr>
<td>CEM III/A Blast furnace cement</td>
<td>36 – 65</td>
<td>GGBS</td>
<td>599 - 346</td>
</tr>
<tr>
<td>CEM III/B Blast furnace cement</td>
<td>66 – 80</td>
<td>GGBS</td>
<td>338 - 216</td>
</tr>
<tr>
<td>CEM IV/B-V Pozzolanic (siliceous fly ash) cement</td>
<td>36 – 55</td>
<td>Fly ash</td>
<td>585 - 413</td>
</tr>
</tbody>
</table>

4 Specifying concrete

BS 8500-1 introduces five approaches to the specification of concrete:

(a) Designated concretes
(b) Designed concretes
(c) Prescribed concretes
(d) Standardised prescribed concretes
(e) Proprietary concretes

Specification of concrete for bridges will typically fall under the second category ‘Designed concretes’, thus they form the focus of this note. Bridge designers will usually provide the contractor

\(^4\) *The efficient use of GGBS in reducing global emissions*, ConcreteZero, September 2023.
\(^5\) Values derived from *ICE Cement, Mortar and Concrete Model* - V1.1 Beta - 28 Nov 2019. Similar sources available, such as *Fact Sheet 18*, Mineral Products Association, September 2019.
a designed concrete specification outlining the exposure class, strength class, consistence class, cement type, minimum cement content, and maximum water/cement ratio intended to achieve the required concrete performance. The contractor then considers early age strength requirements and more specific consistence requirements (such as pumping, placing, and compaction) before passing their own specification to the concrete supplier. The concrete supplier prepares a mix design that complies with this specification.

Specifying higher strength concretes than are necessary for structural performance may lead to the supplier adding more binder (if the binder content is not controlled by other factors), thereby increasing the embodied carbon of the mix. Durability performance is assured by the presence of a cover layer of dense, alkaline concrete between any steel reinforcement and the outside face of the concrete. Specifying more onerous exposure classes will lead to thicker cover, and more binder being required in the concrete (again, if other factors don’t control the binder content). Where the water/cement ratio is limited for durability, or a high consistence is required, the supplier may increase binder further to meet these criteria. Similar enhancements to the consistence can be achieved through use of admixtures.

To achieve the lowest cement content and hence lowest carbon factor for any given situation, the designers of the structure, the contractor, and the concrete supplier need to collaborate and achieve a common understanding of what is required, and identify whether alternative requirements, specifications or mix design can reduce the total binder content, particularly the quantity of PC clinker. Without this understanding, setting arbitrary maximum cement contents, minimising strength class, and reconsidering exposure classes may not have the expected outcome.

To facilitate collaboration, the designer, typically the initial specifier of material requirements, can suggest a target limit for embodied carbon per m³ of supplied concrete. This limit encompasses cradle-to-gate emissions, or A1 to A3 Modules. Valuable guidance for establishing this limit is available in the Low Carbon Concrete Routemap and NZBG’s Guidance Note: Carbon Calculations for Bridges. It is advisable for the designer to discuss and secure the client’s early support for this approach, initiating proactive conversations with the supply chain. Caution is essential to prevent a simplistic response to these targets, such as merely increasing the levels of SCMs within the concrete.

5 Conclusions

Binder is the most important component in concrete from a carbon perspective, and Portland cement contributes the most to the overall carbon footprint of the binder. The following key points are noted:

- Specifying as little binder as is possible to satisfy the performance and constructability requirements will minimise the capital carbon of the concrete.
- Varying the performance and constructability requirements may reduce the binder content, but only if the factors dominating the final binder content are properly recognised.
- SCMs should not be specified in excess if local supply of the SCM is constrained and the SCM is not needed for the performance of the concrete. High use of constrained SCMs in any given project is unlikely to decrease global carbon emissions.
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• Clients, designers, and contractors should be aware that specifying stronger concrete, more onerous exposure classes, high consistence, or rapid strength gain all have the potential to increase the carbon factor.

• Bridges often require high durability, and high strength (or high early age strength gain) concretes which require high binder content. Durability requirements may necessitate SCMs in bridges, as can the need to control heat of hydration in large elements like pile caps. Thus constrained SCM usage for a given bridge element may already exceed what is worthwhile to include from the perspective of sustainability.

• Engagement with the full supply chain, from client to concrete supplier, is necessary to achieve low carbon concrete.

• Use less volume of concrete through design efficiency.

6 Glossary

• **Carbon factor**: a value for a material which describes the amount of carbon (and other greenhouse gas) emissions which will be released when a single unit of the material is used.

• **Capital carbon**: refers to emissions associated with the creation of an asset.

• **Consistence**: the degree to which a fresh concrete is mobile, measured as a slump or flow class. Higher consistence concretes can be pumped and require less vibration to achieve effective compaction.

• **Binder**: the mixture of Portland cement and SCMs which reacts with water to form the matrix holding together the sand and aggregate in concrete, and which gives concrete its strength. Binders include both pre-blended composite common cements and cement combinations produced in the concrete mixer, identified using CEM or C designations respectively, as set out in BS 8500.

• **SCM**: supplementary cementitious material, a material used in place of Portland Cement in binder. BS 8500-2 Table 1 lists many types of SCM but the primary two in the UK are:
  o **GGBS**: a supplementary cementitious material produced by grinding blast furnace slag, a waste product from the steel industry.
  o **FA**: a supplementary cementitious material produced by processing fly ash derived from the burning of coal.

7 Further reading

This note is only an introduction to the subject, and the following sources are recommended for anyone wishing to read further:

• **Specifying Sustainable Concrete**, Concrete Centre, February 2020.

• **Low Carbon Concrete Routemap**, Low Carbon Concrete Group, April 2022

• **The efficient use of GGBS in reducing global emissions**, ConcreteZero, September 2023.

• **Technical Report 74 Cementitious Materials**, Concrete Society, December 2011

• **Concrete Futures, Concrete Centre**, Spring 2023

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