Low Carbon Concrete Tunnel Linings

ITAtech Activity Group
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This report provides guidance to clients, designers and constructors to significantly reduce the carbon emissions associated with concrete tunnel linings. It has been written by the ITAtech Activity Group – Low Carbon Concrete Linings, whose membership was:

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1 >> INTRODUCTION

1.1 THE CHALLENGE WE FACE

This report has been written to address the climate emergency.

The scientific community has issued stark warnings about what could happen if we do not rise to the challenge of reducing global CO_2e (carbon dioxide equivalent) emissions (IPCC, 2023). To date, the scale and urgency of carbon reduction has not been at the pace needed to prevent catastrophic global heating. We are at risk of passing tipping points, beyond which the planet will not recover (IPCC, 2023).

A step change in our response is needed now.

1.2 WHAT WE MUST DO

The aim of all those involved in the planning, design, construction, operation and renewal of infrastructure should be to decarbonise it. This means to reduce the embodied and operational carbon produced.

The decarbonisation of infrastructure must be equitable, must be done without damaging the environment in other ways such as biodiversity loss or pollution, and using methods that maintain and improve health and safety. Any potential impacts of decarbonisation on the quality, durability or design life of structures must be carefully considered.

Sustainability is a decision-making framework that takes account of all these aspects. Considering social, economic and environmental benefits or impacts (the 'three pillars' model) is the simplest method, but there are also sustainability indexing methods, such as BREEAM (2023), ENVISION (2015) or IS Ratings (2023), that can produce scores that enable performance to be measured and comparisons to be made (Figure 1).

We must work together to reduce CO_2e emissions in tunnelling and we must do it urgently.

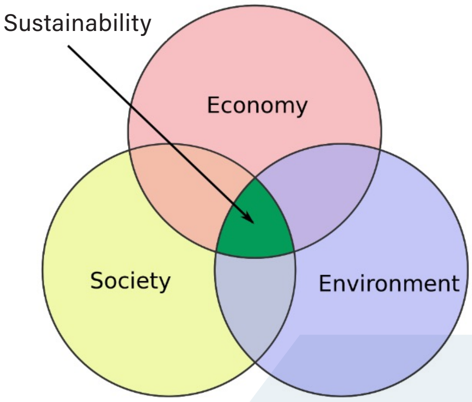

Figure 1: The three dimensions of sustainability (Nicoguaro, Wikimedia Commons).

1.3 MORE SPECIFICALLY, AS TUNNELLERS, WHAT MUST WE DO?

We are tunnellers, so we should reduce the CO_2e emissions associated with tunnelling. It is within our power and it is our responsibility. For those able to influence political decisions about whether to build new infrastructure and what form it should take, i.e., a deep or shallow tunnel, immersed tube or bored tunnel, tunnel or bridge, they should make these decisions based on sustainability, i.e., considering social, economic and environmental benefits or impacts.

For most of us, the decision has already been made to build a tunnel. But we have the ability to dramatically reduce the CO_2e emissions through intelligent specification, design and construction.

On tunnelling projects, 60-80% of the embodied CO_2e emissions are in the concrete tunnel lining (Sauer, 2016; Thomas, 2019a; Aldrian & Bantle, 2021; Wittke et al., 2022)[1]. Therefore, the easiest way for us to have the biggest positive impact is to reduce the CO_2e emissions associated with the concrete tunnel linings, and this is the focus of this report.

The production of 1 tonne of clinker for cement emits on average 842 kg of CO_2 (UN Environment et al., 2018). Less than 40% of this is related to burning fuels to heat the clay and limestone and the remainder is released by chemical reactions during calcination of the limestone. Annual global cement production accounts for approximately 8% of anthropogenic CO_2e emissions (PBL, 2016). Based on a global anthropogenic total of approximately 40 billion tonnes of CO_2e emissions per year (Our World in Data, 2023), cement production therefore causes 3.2 billion tonnes of CO_2e emissions.

The Global Cement and Concrete Association (2023) has a pathway to net zero by 2050, which involves a 'Decade to Deliver' from 2020 to 2030, followed by 'Completing the Net Zero Transition' by 2050 (Figure 2).

Firstly, we can reduce the amount of concrete consumed, through efficient design of tunnel linings and reduction of waste in construction. This needs to be considered from the inception of the project and incentivised in the project requirements and specification.

For a typical concrete, cement will have by far the greatest impact, representing typically 91% of the materials CO_2e emissions (Informationszentrum Beton GmbH, 2018). Therefore, the reduction of the use of Portland cement in concrete will have a big impact. This can be done through the use of cement replacement materials, such as GGBS (ground granulated blastfurnace slag), fly ash, silica fume, calcined clay, limestone powder, or through the use of concretes with little or no Portland cement, such as AACMs (alkali-activated cementitious materials) or geopolymers.

The second biggest source of CO_2e emissions in the lining is the reinforcement. Fibre reinforcement (ITAtech, 2016; ITA, 2020) offers an easy way to reduce this footprint in many cases.

Excavation and removal, disposal or reuse of excavated material can consume significant amounts of fuel or energy. However, the contribution of these CO_2e emissions is usually small compared to the concrete itself. For example, Sauer (2016) found for the Brenner Base Tunnel that only 16% of

[1]*These figures are for the civil engineering construction but do not generally include rail track or road surfacing, or mechanical/electrical equipment installations.*

CO_2e emissions were due to "all other construction processes", i.e., everything except the concrete. If very low carbon concrete linings begin to be used, then this element may become more important.

There are also ways to reduce CO_2e emissions related to the use of concrete, such as transportation of raw materials and the concrete itself and the energy consumption of plant and equipment used in the construction process. However, the contribution of these CO_2e emissions is usually small compared to the concrete itself. Aldrian et al. (2023) found that batching, transport and application of sprayed concrete was only 2.5% of total CO_2e emissions.

The biggest reductions in CO_2e emissions can be achieved during the planning and concept design stage. It is important, therefore, to try to quantify the CO_2e emissions related to different options in a pragmatic way as early as possible. If for whatever reason the CO_2e emissions are not considered in the early design stages, then they should still be considered at later stages.

We should use every lever available to reduce CO_2e emissions, but we should focus first on the areas we can make the biggest difference. In most cases this will be to reduce the volume of concrete in tunnel linings, and to reduce the Portland cement content of that concrete.

1.4 SCOPE OF THIS REPORT

Tunnels are essential infrastructure that provide mass transportation, hydroelectric power plants, sewerage, potable water supply and other utilities that can improve quality of life, the economy, public health and the environment.

Tunnels can, at a network and system level, reduce CO_2e emissions. For example, by providing fast and efficient train or metro services, car use can be reduced. Or, by providing a shorter, flatter route, a tunnel through a mountain can reduce journey times, energy consumption and air pollution.

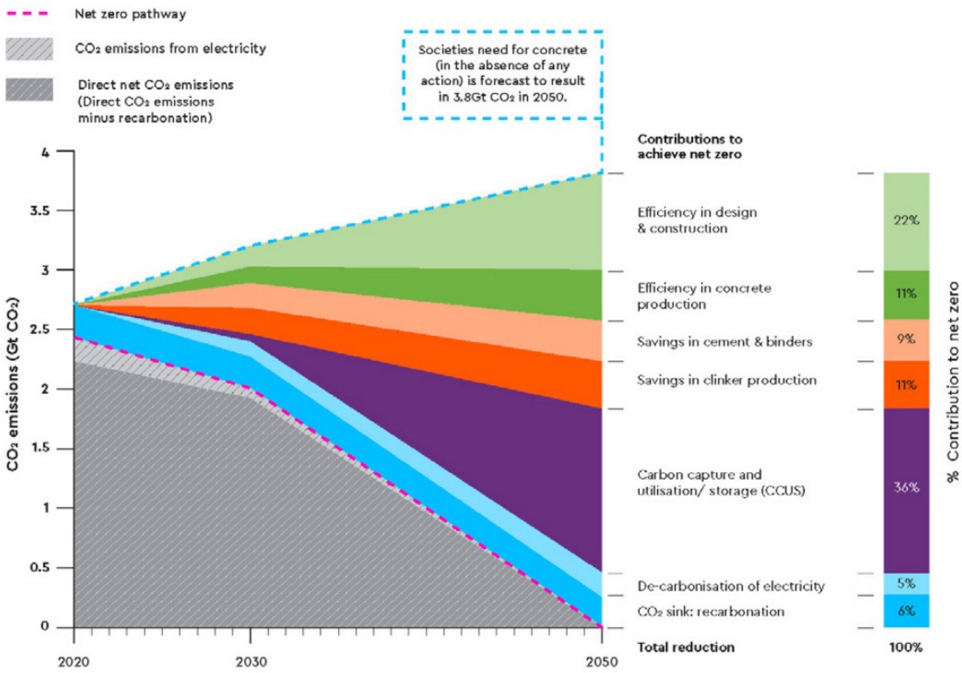

Figure 2: Net Zero Roadmap (Global Cement and Concrete Association, 2023).

Compared to other potential solutions, e.g. a bridge or surface option, tunnels are often more resilient and durable, require less maintenance, and have less impact on the environment.

The big picture – looking at the system and network levels – is really important, but once we have decided to build a tunnel, then we must build it with the lowest CO_2e emissions possible.

Most tunnels are constructed with concrete tunnel linings. Other lining types, such as timber, steel or cast iron, are only used in special cases and represent a tiny proportion of the total length of tunnels in the world. Therefore, the easiest way to have the biggest impact is to reduce the CO_2e emissions associated with the concrete tunnel linings, and this is the focus of this report.

The report will provide guidance on how to reduce CO_2e emissions for all types of concrete tunnel linings, including:

- Precast concrete segmental linings,
- Annulus grout,
- Sprayed concrete, and
- Cast-in-place concrete.

Note that this report does not include grouting for ground improvement, or rockbolting, both of which could be considered part of the lining/support system. If applied systematically to large volumes of ground, these can make a significant contribution to CO_2e emissions.

If the global tunnelling industry implements the recommendations of this report, huge reductions in CO_2e emissions will be achieved.

Best practice in different parts of the world is at different levels, but even within a country or sector the way things are done on different projects can be very different. Improving practice will depend on leadership by the government or by the client/owner; legislating, requiring or incentivising carbon reductions.

Globally, very few tunnelling projects use any kind of sustainability indexing or carbon accounting (Aldrian et al., 2022). This needs to change because it is difficult to provide incentives unless something is being benchmarked and measured in an independent and repeatable way. However, the lack of client leadership, sustainability indexing, carbon reduction targets or commercial incentives on a project should not stop us. As engineers with a professional duty to protect the environment and the public, we should still be doing the right thing and reducing carbon, but a lack of client leadership does make it harder and we cannot always be successful in influencing clients to do the right thing.

Nevertheless, on many projects, there are easy 'quick wins' to be made that would often reduce cost and improve quality and durability. For example, the average **sprayed concrete** contains approximately 400 kg/m^3 of Portland cement, but there are still sprayed concretes being used with 500 kg/m^3 of Portland cement. Often sprayed concretes achieve much higher 28 day strengths than required by the design because the Portland cement content has been increased to improve early age strength. It is possible to reduce the Portland cement content to 300 kg/m^3 for most situations by using a 30-35% replacement with fly ash, silica fume, limestone powder and/or GGBS, while still meeting the project requirements, as is already done in some countries, e.g. Austria and Australia, which would represent a large decrease in CO_2e emissions. Tests have shown that a 25-30% replacement with fly ash does not affect early strength development up to 6 hours (Jones, 2016; Hallam, 2014). It is recognised that lower cement contents may require the supply of more reactive Portland cements, which are not always available. This requires the cooperation of the cement industry.

Many countries, e.g. the USA, routinely use binders with 85-100% Portland cement, when it is possible to easily reduce this to 70% or lower, as is common practice in Europe and Australia. This is a challenge to the cement industry to lead the way in providing easy access to blended cements and to make them the default option. In the UK, benchmarks are being set for the cement and concrete industry in routemaps to net zero by the ICE's Low Carbon Concrete Group (ICE, 2022) and the Mineral Products Association (MPA, 2022 & 2023). This is also being done globally by the Global Cement and Concrete Association (2023).

For **precast concrete segments or cast-in-place concrete**, it is possible to use very high percentages of cement replacement up to 50 to 70% or more (e.g. Edvardsen et al., 2018), which could reduce the CO_2e emissions by 50% or more. Reducing the Portland cement content will reduce heat of hydration and problems of early age thermal cracking or delayed ettringite formation, reduce shrinkage, and often improve durability and resistance to sulphate attack.

Annulus grout is often overlooked but can represent a large proportion of the overall carbon footprint of a tunnel (Aldrian et al., 2022). It is common practice on many projects to use two-component grouts with over 250 kg/m^3 of Portland cement, activated by sodium silicate. However, in many cases this is unnecessary. It is possible to use grouts with very low or even zero Portland cement, for example the Groene Hart Tunnel (c.2001) and parts of the Westerscheldetunnel (c.2006) in the Netherlands used fly ash only.

On some projects we are already doing some or all these things, but we do still need to push for even less carbon if we are to achieve net zero by 2050. For example, by replacing more Portland cement with supplementary cementitious materials, or using AACMs or geopolymers – leading so others can follow.

The inflexibility of client specifications is often cited as a barrier to innovation and this needs to be addressed. However, much can be done while working within existing standards and specifications and without requiring any additional testing or special design or construction practices. Clients should focus on leadership, and on incentivising carbon reduction in their procurement strategy. There are some good examples of this, e.g. Anglian Water in the UK incentivise carbon reduction through their procurement and management of contracts, with the aim of achieving net zero emissions by 2030 (ICE, 2023).

There is a strong interaction between the materials, the design and the construction, so designers should work closely with their client and with contractors and suppliers to deliver low carbon solutions. For example, reducing tolerances may result in less wastage of concrete, but only if the contractor can achieve the tolerances using their labour, plant and equipment.

In order for designers to innovate, they need to be given the opportunity to collaborate with contractors and suppliers to work through the practicalities and deliver a system that works. Replacing conventional steel bar reinforcement with either steel or macro synthetic fibres can reduce carbon, because the volume of steel can be reduced significantly and steel has a high carbon intensity. It is important to remember, however, that the performance of each reinforcement type is different and a straight swap is not possible without considering buildability, structural performance and durability.

With clear incentives and leadership from governments and clients to reduce carbon emissions, we can all make significant reductions now without doing anything special.

3 >> Reducing Carbon Through Contracts & Procurement

Procurement of the design and construction of tunnelling projects should incentivise the reduction of CO_2e emissions within a sustainability framework that balances environmental, social and economic factors. For this to be effective, a sustainability indexing tool should be used that allows benchmarking and quantification of any reductions.

The impacts at the network and system level should be assessed, not just one product or material or structure in isolation.

Contract specifications should be performance-based rather than prescriptive. Early involvement of the contractor in the design phase should be considered to allow collaboration between client, designer and contractor to drive innovation. A good example can be found in Kundan et al. (2023).

4 >> Carbon Accounting

Carbon accounting is the process of estimating the embodied carbon in an activity and/or object. In the context of a tunnelling project, the output of this is often referred to as the 'carbon footprint' of the tunnel. This measure of the footprint should be updated and monitored during the project, and this provides a vital tool for tracking the reduction of that footprint.

There are two types of carbon accounting that we do as tunnel engineers. One is in the optioneering stage, very early during the project definition when we are deciding what to build. The other is during detailed design and construction, when we are measuring the actual embodied carbon in a detailed and specific way. The underlying carbon calculation uses the same methodology in both, but what we are trying to achieve is different.

4.1 OPTIONEERING

Optioneering could be deciding whether to construct a bridge or a tunnel, or choosing between an immersed tube or bored tunnel. Or it could involve deciding whether to build a piece of infrastructure or not building it.

Here it is important to be pragmatic. We are not able to precisely define the materials or the exact dimensions of the structures. Therefore, we must look at the most important factors, usually the volumes of concrete and steel, generic values of carbon intensity (the amount of CO_2e per unit volume), and estimate the dimensions of the structures. This can give a very rough estimate of the likely carbon footprint of different options. Sensitivity analysis, i.e., varying the factors between realistic minima and maxima and gauging the effect, is essential to get a feel for the possible range of outcomes.

4.2 DETAILED CARBON ACCOUNTING

The two main carbon accounting approaches for projects are the scope-based approach, which is focused on organisational boundaries, and the module-based approach, which is oriented around chronological boundaries. The module-based approach is the most useful for a construction project and is shown in Figure 3. It is the basis of 'Life Cycle Assessment' (LCA), which is described in EN ISO 14040:2006+A1:2020.

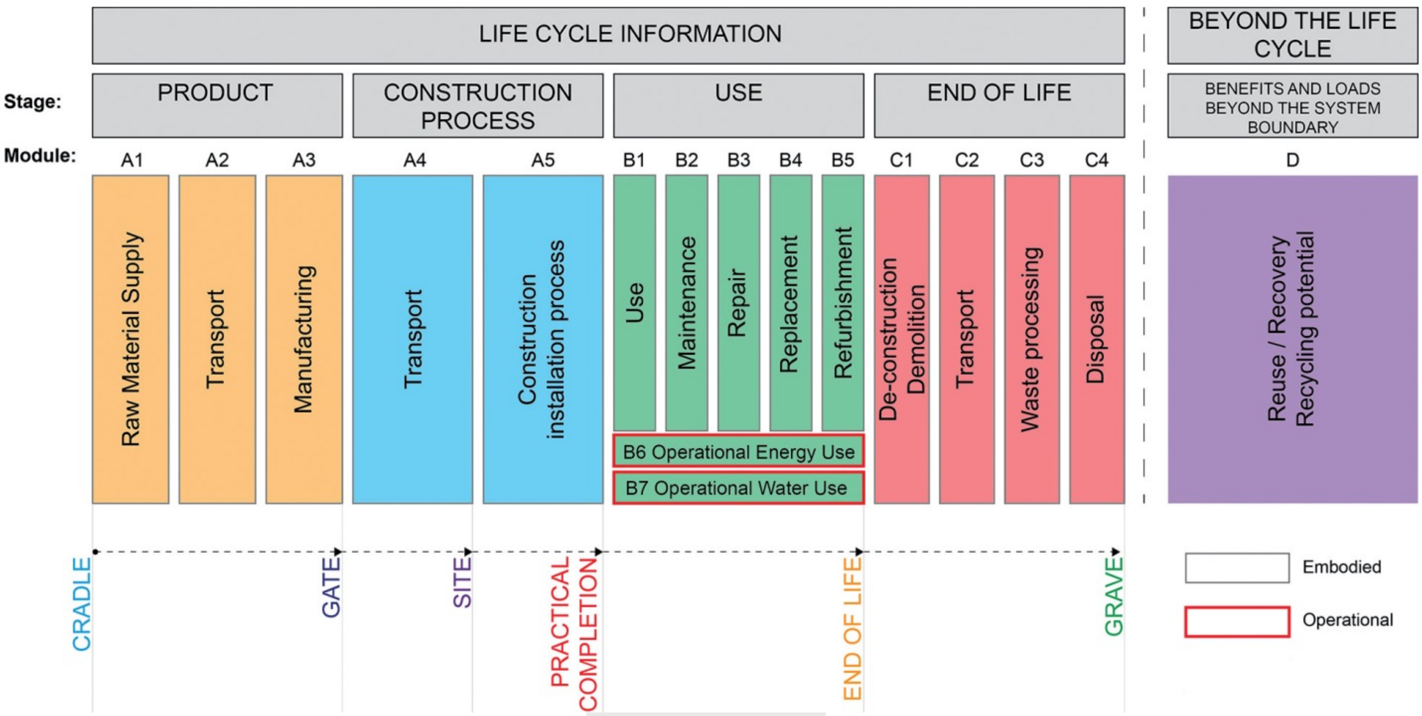

Figure 3: Module-based approach as per EN 15978:2011 (figure from IStructE, 2022).

Inputs to a carbon footprint calculation come from 'Environmental Product Declarations' (EPDs), which provide certified environmental information for construction products, services, and processes. The core rules for EPDs are set out in EN 15804:2012+A2:2019 and EN ISO 14025:2010.

An EPD will provide the CO_2e emissions for the product or material, based on a life cycle assessment. These may be specific to a particular plant or factory, but sometimes are generic, e.g., for the whole cement industry in one country. Therefore, they may not be accurate. It is also important to check the life cycle phases that the EPD covers, and whether this is correct for your analysis. An example carbon footprint calculation can be found in Jarast et al. (2023a) and Bakhshi & Nasri (2023).

Consistency and traceability of the sources of data is essential, especially where the assessment will form a live document which will be updated as the project evolves. Building Information Modelling (BIM) offers a powerful tool for gathering data on carbon as the design develops but the process for carbon accounting must be aligned with the BIM tool to make this as smooth and simple as possible Following the principles of BIM, there should be a "single source of truth" on the project, rather than multiple, unconnected, and inconsistent pots of data. A sensible approach is to adopt the same methodology as for the cost estimate, i.e., the same Work Breakdown Structure for identifying elements, which should be mirrored in the BIM model.

4.2.1 Project carbon baseline

If carbon reduction performance is to be measured and incentivised, then a baseline needs to be established. This is the amount of CO_2e emissions that would be expected "in the absence of planned measures aiming to reduce emissions" (PAS 2080:2023). This should be based on current best practice, for example, using the benchmarks in the ICE Low Carbon Concrete Routemap (ICE, 2022).

The baseline carbon cost should be established as early as possible in the project life cycle. The carbon cost estimate then becomes a live document that is updated throughout the life of the project, in a similar manner to the cost estimate or the programme. Many aspects of a project may not be well-defined in an early design stage so allowances will have to be made for the uncertainties. The baseline can be compared to other similar projects to check that it is reasonable.

4.2.2 Targets for carbon reduction

Having established a baseline, the project should set the target for carbon reduction relative to that baseline. It may be expressed as a percentage reduction across the whole project, or there may be several targets set for different project elements.

For these targets to be effective they must be contractually binding with an incentivisation mechanism that will encourage the client, designer and contractor to collaborate to remove obstacles. Targets and incentives for carbon reduction should be incorporated into design contracts as well as construction contracts.

The greatest potential for carbon savings can be found in the design stage and this is also where savings can be made most easily (Figure 4). Often carbon savings in this stage are accompanied by cost savings.

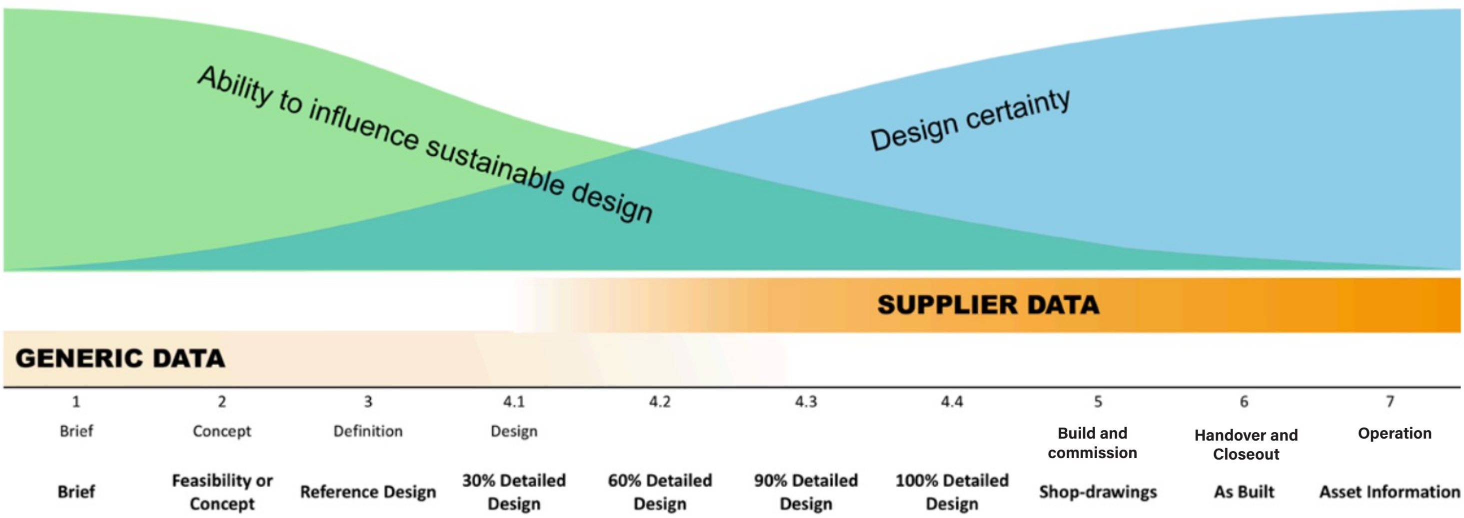

Figure 4: Decisions taken early in a project have more influence on sustainable design (from Aldrian, 2021).

The choice of materials will have a big impact on carbon. However, we need to take a holistic approach, considering performance specification, design and construction.

Low carbon concretes need to be developed in partnership with the designer and constructor to ensure they meet the design requirements and can be used efficiently in construction.

The material's structural efficiency should be considered by the designer. For example, there is no point reducing the Portland cement content by 20% if the thickness of the structure needs to increase by 30%.

Resilience and durability are also important factors. If the material will need to be repaired or replaced during the design life this needs to be factored into the carbon calculation along with the impacts of closures of the tunnel. Generally speaking, clients require low carbon concretes to meet the same performance requirements in the specification as conventional concretes and will expect them to have the same design life and inspection and maintenance regime during operation (see Section 9 'Operation and maintenance of tunnels with low carbon concrete linings').

5.1 LOW CARBON CONCRETE

It would be desirable to specify concrete by its embodied carbon as well as its compressive strength, rheology and durability characteristics. The Institution of Civil Engineers' Low Carbon Concrete Routemap (ICE, 2022) includes a rating system for ready mix and precast concrete similar in form to Environmental Performance Certificates for houses and apartments (Figure 5).

This is based on a series of benchmark performance curves relating carbon footprint to strength class, as shown in Figure 6. The curves are based on a survey of concretes produced in the UK, hence they show what can be achieved today for standard applications. These benchmarked ratings will change every year, so a static ratings scheme has been developed by Arup (2023).

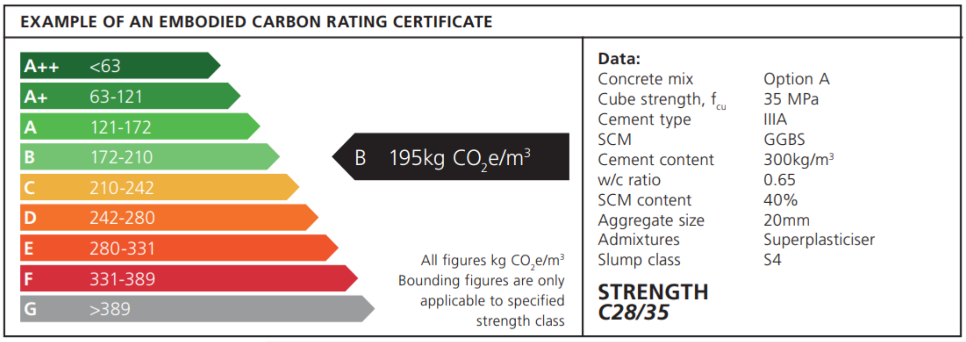

Figure 5: Example embodied carbon rating system for concrete (ICE, 2022).

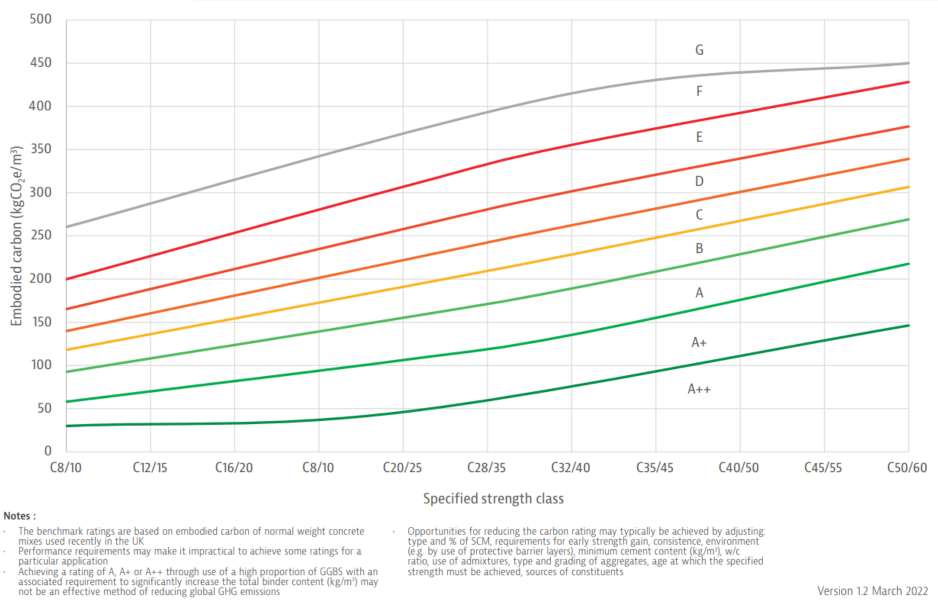

Figure 6: Green Construction Board/Low Carbon Concrete Group benchmark ratings for embodied carbon, normal weight concrete, LCA stages A1-A3 (ready-mix: cradle to batching plant gate; precast: cradle to mould) (ICE, 2022).

Such carbon ratings are a powerful concept, and perhaps in the near future the tunnelling industry could consider developing similar ratings specifically for sprayed concrete, precast segments, cast-in-place concrete and annulus grout, perhaps initially within a country or region.

As energy production is decarbonised, and steel production becomes more circular, GGBS and fly ash are becoming scarcer. Figure 7 shows that current global production of GGBS is 10% of global cement production and fly ash is less than 20% (ICE, 2022). Currently not all the available GGBS and fly ash are used in concrete, but in future other sources of supplementary cementitious materials will need to be developed and used.

The use of ternary (three component) cements, containing Portland cement and either GGBS or fly ash, but with some of the Portland cement, GGBS or fly ash replaced by up to 15% limestone fines is one way to make the GGBS and fly ash go further, without affecting the performance of the concrete (Scrivener et al., 2018; McCague, 2022), as shown in Figure 8. These are included in European Standard EN 197-5:2021 and will be recognised as general purpose cements in British Standard BS 8500:2023. So-called 'Portland limestone cements' are also being increasingly used in the USA.

In the future, calcined clays and limestone, both of which are abundant close to the Earth's surface across the world, will become important binder components for concrete. This type of concrete is called 'limestone – calcined clay concrete', or 'LC^3' and is being researched worldwide by the LC^3 project (LC^3, 2023). In addition, carbon capture and storage and carbon sequestration in binder materials to produce carbon-negative cements may be developed to reach net zero or beyond.

Calcined clays are produced from waste bricks, or by heating natural clays to 700-850°C to unlock their pozzolanic properties (McCague, 2022). Metakaolin produced from the clay mineral kaolinite is the most reactive type and is more reactive than fly ash. However, kaolinite clays are not abundant everywhere in the world. Lower grade calcined clays, made from clays with low kaolinite content, vary widely in their reactivity, but still may be used as part of a multi-component cement.

The paste content of a concrete mix may be reduced by optimising the grading of the aggregates and fine materials and this can enable a CO_2e emissions reduction of up to 14% according to Jarast et al. (2023b). Reducing the paste content will not only reduce the carbon footprint, but also will reduce cost, improve durability and improve strength.

5.2 FIBRE-REINFORCED CONCRETE

The use of fibre-reinforced concrete (FRC) allows the reduction or elimination of conventional bar or mesh reinforcement in concrete tunnel linings. The volume of fibres is usually significantly less than the volume of bars replaced and therefore there is a reduction in the carbon footprint of the reinforcement.

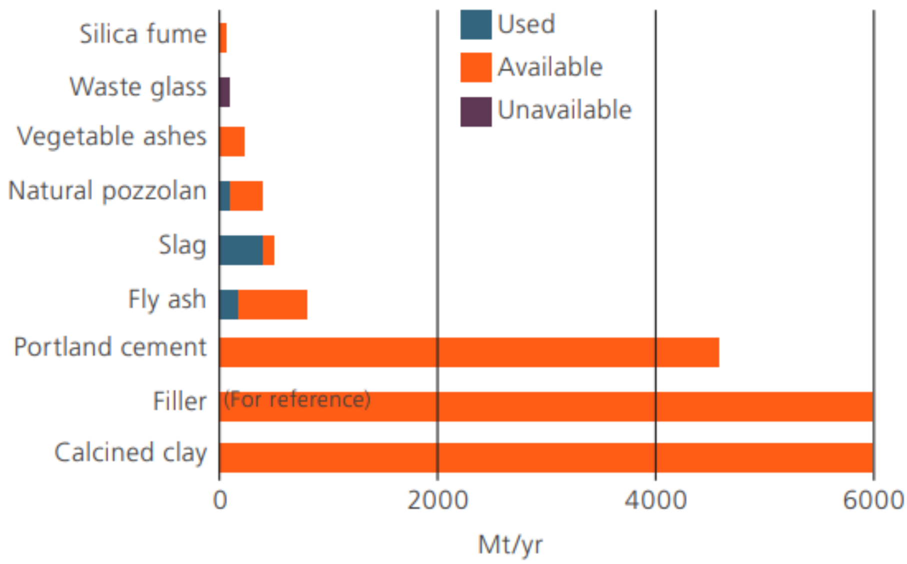

Figure 7: Estimated global availability and use of Portland cement and supplementary cementitious materials (figure from ICE, 2022, with graphic based on data from Scrivener et al., 2018).

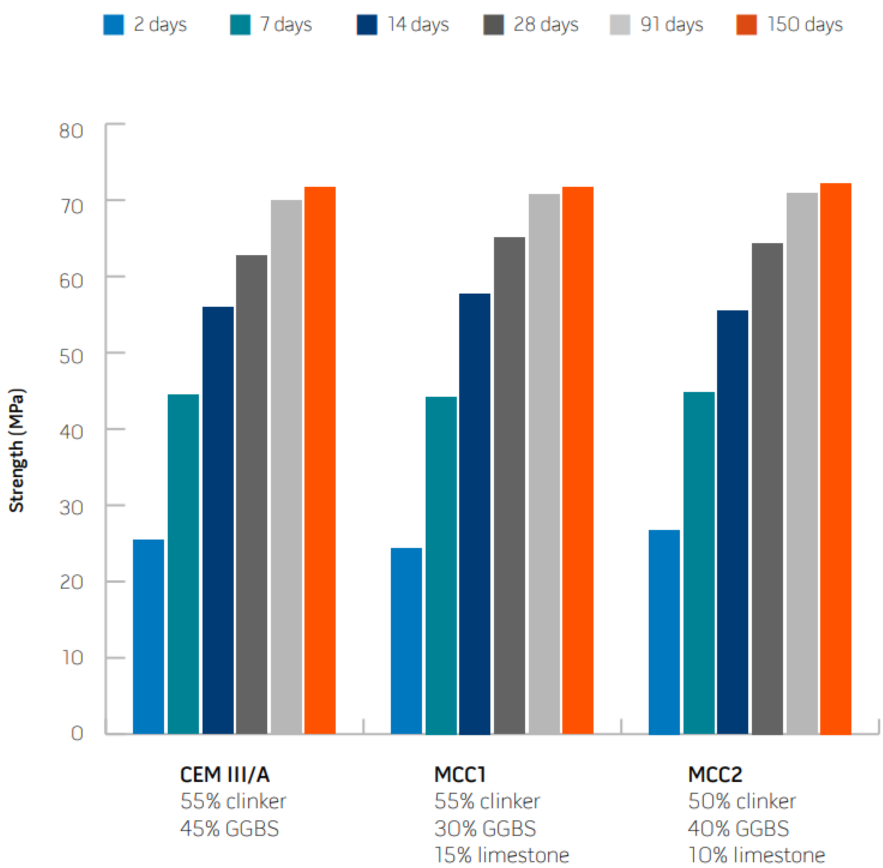

Figure 8: Strength gain of multi-component cement concretes incorporating limestone fines compared to a CEM III/A (McCague, 2022).

5 >> Selection Of Low Carbon Concrete Materials

Over the last 30 years, the use of FRC in tunnel linings has increased in segmental linings, sprayed concrete and cast-in-place concrete (ITAtech, 2016; ITA, 2020). This growth is due to the development of codes of practice and design guidance, improvements in fibre and concrete technology, as well as increasing confidence and acceptance of the use of FRC through accumulated industry experience.

The use of FRC has clear benefits for all types of tunnel lining, which include (ITAtech, 2016; Jones, 2022):

- FRC can have improved post-crack behaviour, with narrower crack widths than conventional reinforced concrete, and hence better durability and watertightness.
- There is no need to fix reinforcement bars or mesh in sprayed concrete or cast-in-place linings, and no need to fabricate cages and install them into moulds for precast concrete segments.
- In the particular case of precast segments, the presence of steel fibres close to the segment faces can better resist bursting and spalling stresses caused by the application of TBM jacks and radial joint stresses (de Waal, 2000; Schnütgen, 2003), or accidental impacts during transportation and handling (ITAtech, 2016; fib Bulletin 83, 2017).
- For reinforcement of sprayed concrete in hard rock tunnels, steel mesh requires more sprayed concrete than fibres because the mesh cannot easily follow the contours of the excavated rock profile.

Fibres can be used in conjunction with bars in areas of high stresses, which adds a further option to the designer and may be more efficient than providing a higher dosage of fibres or a thicker lining to deal with localised stresses.

For all types of tunnel linings and methods of application, the total mass of steel required for steel fibre reinforced concrete is usually far less than for conventional reinforced concrete, resulting in a saving in the overall carbon footprint. Note that embodied CO_2e for steel varies greatly depending on the region, type of furnace and the source of energy, and can typically vary between 0.26 and 2.0 $kgCO_2e/kg$ for steel fibres, 0.4 to 3.5 $kgCO_2e/kg$ for conventional steel bars and 1.8 to 2.2 $kgCO_2e/kg$ for macro synthetic fibres.

It is important to remember that conventional steel reinforcement bars, steel fibres and macro synthetic fibres all provide a different performance and are not necessarily interchangeable. It will depend on the specification and design requirements for a particular project, as well as the construction and logistics constraints.

In this section, it will be very difficult to cover all the standards and model specifications used across the world. Most of the time, European standards and specifications will be used as an example, but that example will often be valid for other standards and specifications used elsewhere in the world. The inflexibility of client specifications is often cited as a barrier to innovation. However, most specifications allow for non-compliance with the client's agreement. Designers and constructors should therefore feel confident to challenge specifications and request changes or exceptions. Contractual incentives to reduce carbon will provide motivation for all parties to work together.

If specifications prevent the use of low carbon concrete, for instance by specifying a minimum cement content, then they should be rewritten to be performance-based rather than prescriptive. 'Performance-based' means the specification should specify the performance required and what testing methods will be considered acceptable as proof of that performance, rather than rigidly specifying the ingredients of the concrete.

6.1 ALLOWING THE USE OF LOW CARBON CONCRETES IN SPECIFICATIONS

If European standards are being used, the range of cement replacement material types and proportions that are covered by EN 206:2013+A2:2021 (the European standard for concrete) and EN 197-1:2011 (the European standard for cement) is quite large. For example, up to 95% replacement with GGBS (CEM III/C) or up to 55% replacement with fly ash (CEM IV/B) are considered part of the 'family of common cements'. It is therefore possible to achieve substantial reductions in CO_2e while using current standards.

The ASTM C-1157 Standard Performance Specification for Hydraulic Cement specifies the performance requirements for finished cement without limitations to the ingredients. Thus, based on it, producers can use innovation as a competitive advantage, designing and producing a mix that meets or exceeds the needed strength and quality requirements, and at the same time minimise cost and the environmental footprint.

Some low carbon concretes or alkali-activated cementitious materials (AACMs) fall outside of the range of application of EN 206 and EN 197-1 because they have less than the minimum cement content. Therefore, specifications should be written to explicitly allow them to be used, as long as they meet the performance requirements via a 'design assisted by testing' approach.

'Design assisted by testing' is described in EN 1990 (Annex D of EN 1990:2002+A1:2005). It is used for determining the characteristic flexural tensile strength parameters of fibre-reinforced concretes (e.g. Jones, 2022: pp.252-258) and so will be an approach familiar to many tunnel engineers. It is a statistical approach to testing and the determination of characteristic values of design parameters, which is covered in more detail in Section 7 'Design' of this report.

BRE Information Paper IP4/16 (2016) provides advice on how to obtain approval for alkali-activated binders. One method is to specify that alkali-activated cementitious materials (including geopolymers) should follow the PAS 8820:2016 specification.

The British Standards Institution's PAS 8820:2016 is a publicly available specification for alkali-activated cementitious materials and concretes (AACMs), usually containing no Portland cement but can include up to 5% Portland cement in the binder. The 5% limit is so that its requirements do not clash with EN 197-1. Although AACMs may be assessed using the same tests and requirements as Portland cement-based concretes, some details are different and these differences are explained in PAS 8820. For example, the requirements for fly ash and pozzolanic materials for inclusion in an AACM are different compared to when they are SCMs in a traditional Portland cement concrete complying with EN 197-1.

In Australia, a technical specification SA TS 199:2023 'Design of geopolymer and alkali-activated binder concrete structures' was published in May 2023 to accompany the Australian Standard for Concrete Structures AS3600. It contains requirements and guidance for specification and design using such materials.

6.2 DURABILITY AND DESIGN LIFE

If a client's specification is performance-based, then the designer and constructor are given an expected design life for the structure and minimum performance in terms of watertightness, aesthetic considerations and the need for maintenance. It is then up to the designer to determine the exposure class and hence the design chemical class of the concrete, the limits on crack widths, and the waterproofing system design. The designer will optimise the structural design and determine the concrete strength class required. The constructor will then need to either make or procure concrete that meets these requirements. This offers much more freedom to choose a low carbon alternative than the traditional 'prescriptive' type of specification which dictates specific materials (e.g. setting minimum Portland cement contents in concrete).

6.3 PRE-CONSTRUCTION TRIALS AND LABORATORY TESTING

If a low carbon concrete is outside of the 'family of common cements' of EN 197-1 and is to be approved using a design assisted by testing approach, then pre-construction trials may be necessary.

Pre-construction trials are common practice for sprayed concrete where the placement method has such an important influence on the properties of the material. This is often stipulated in the specification, for example in the British Tunnelling Society/Institution of Civil Engineers 'Specification for Tunnelling' (BTS, 2023).

PAS 8820:2016 recommends full-scale plant trials prior to production for AACM concretes, since there are significant differences compared to the production and use of traditional concrete in terms of handling of the constituent materials (some of which may be highly caustic), mixing, rheology, placement and curing. An example of the trialling and use of geopolymer concrete on a tunnelling project can be found in Day et al. (2023).

Optioneering at an early stage of planning and design can result in the largest reductions in CO_2e emissions. Since at this stage, details of the exact materials and construction methods to be used are not available, it is important to be pragmatic. The largest contributors to CO_2e emissions will be concrete and its reinforcement. Simple calculations of CO_2e emissions based on estimates of volumes of reinforced concrete, estimates of wastage rates, allowances for unknown items and generic values of CO_2e intensity for various materials can provide the designer and client with an approximate aid to decision making.

The importance of leadership by the client, and incentivisation of CO_2e emissions reductions through the contract, cannot be understated. There should be binding targets for designers to reduce the carbon footprint during each design stage.

The means by which carbon may be reduced in design require a close collaboration between the owner, designer, contractor and concrete suppliers. For example, reduction of construction tolerances for reinforcement placement and thickness of the lining, reduction of variability of concrete quality, timings or durations of load cases, or acceptance of a slower strength gain at early age or at later ages, all require the agreement and cooperation of the contractor and their suppliers. In conventional tunnelling, designing the primary sprayed concrete lining to be permanent may require enhanced quality control by the contractor and supervision by the designer but will result in a significant carbon reduction.

7.1 REDUCING CARBON THROUGH EFFICIENT STRUCTURAL DESIGN

The design of low carbon concrete linings needs to deliver the same reliability as required for any other designs, as defined in the applicable local structural design standards (e.g. the Eurocodes).
For any tunnel lining the CO_2e is embedded in:

- The lining concrete, including any annulus grout and wastage.
- The reinforcement.
- The volume of excavated material to be removed, which requires excavation, handling, processing and transportation for disposal or reuse.
- The installation process for the lining.
- Maintenance.

Of these, by far the most important is the concrete and grout, followed by the reinforcement. Reductions in the volume of excavated material should not normally be prioritised over reducing the concrete or reinforcement volume.

The design must meet the client's performance requirements, comply with the applicable codes and specifications, be resilient and durable for the whole design life with minimal maintenance, and must be buildable in a safe and efficient manner. Optimisations must not compromise these elementary requirements.

Efficient structural design therefore means reducing the volume of excavated material, of the lining, and of the reinforcement. Where a tunnel requires a lining, the ideal tunnel lining would be of a geometry resulting in minimal bending moments, built with very low tolerances and sized to accommodate exactly the local peak loading.

Design codes often penalise the absence of ductility in a material, therefore it is usually not beneficial to remove the reinforcement completely, even if the lining can be shown to be everywhere in compression. It is in linings such as these that fibre-reinforced concrete (FRC) is competitive, as it can provide the minimum ductility required with much less reinforcement volume compared to conventional steel bars or mesh.

If the tolerances on excavation or lining can be reduced, or if the lining can be designed to be thinner, then that will reduce the volume of excavated material.

For sprayed concrete linings, the shape can be non-circular and therefore can be optimised to fit around the required space envelope and reduce the overall volume of excavation compared to a circular tunnel. However, particularly for soft ground tunnels, non-circular shapes are usually less structurally efficient and large bending moments can be induced, perhaps requiring a stronger, thicker or more reinforced lining. Therefore, there is a balance to be struck between reducing volume of excavation and minimising the embodied CO_2e in the concrete and reinforcement volumes. The most sustainable design will be to make the shape non-circular to reduce excavation volume, but only up to the point where the minimum reinforcement required for ductility is sufficient for the bending moments and axial forces induced. As soon as increased reinforcement or lining thickness is needed then the saving in excavation volume will probably not be worthwhile.

Similarly, there is a balance to be struck between the strength of the material and the thickness of the tunnel lining. Generally speaking, higher strength concretes require a higher cement content and therefore have higher CO_2e emissions. Likewise, more reinforcement will give higher bending capacity but will increase CO_2e emissions. However, a stronger lining could be thinner and this reduction in volume would reduce CO_2e emissions.

Damineli et al. (2010) showed that higher strength classes of concrete have less binder per MPa of compressive strength than lower strength classes (Figure 9). In other words, increasing the strength class from a characteristic compressive strength of 20 MPa to 40 MPa will require much less than double the CO_2e emissions. Whether this can result in lower overall CO_2e emissions will depend on the interaction between thickness and structural capacity of the lining, which is not a linear relationship.

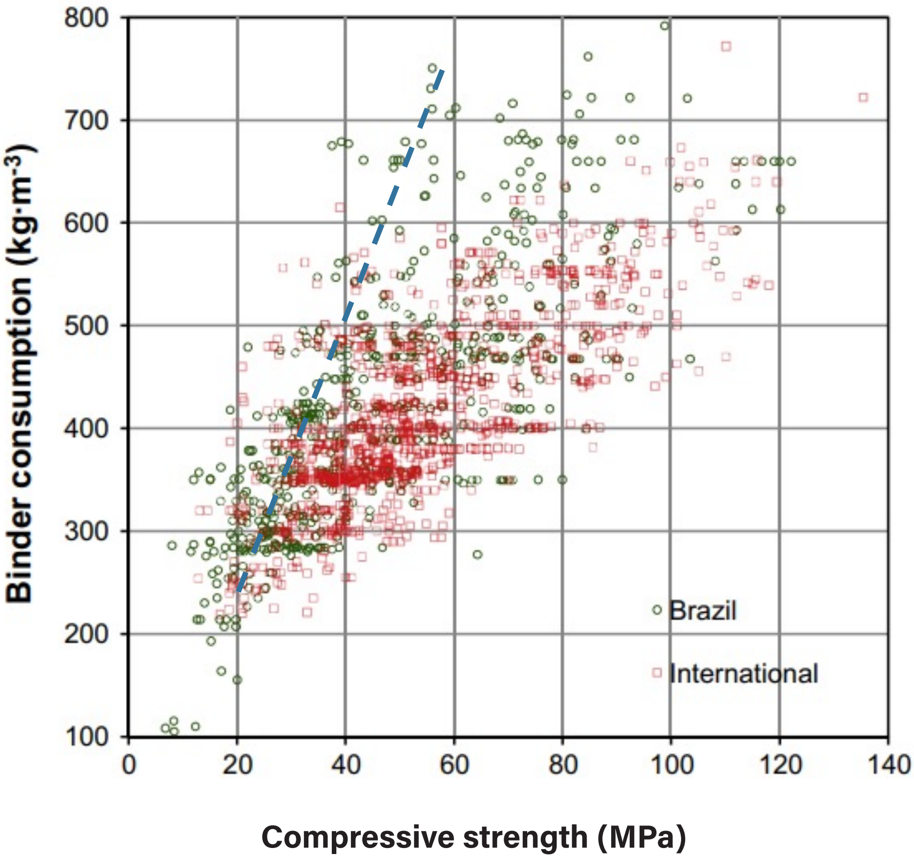

Figure 9: A meta-analysis of the relationship between binder consumption and compressive strength of concretes in Brazil and internationally (Damineli et al., 2010). The dashed blue line shows the trend if the strength were proportional to the binder content.

7.2 DESIGN ASSISTED BY TESTING

Design using materials such as AACM is currently only partially covered by codes and standard specifications. Similarly, specific aspects of tunnel design such as partially loaded surfaces are addressed in a relatively conservative manner in the relevant design codes. Therefore, testing can provide the characteristic and mean parameters needed for design, or evidence that concentrated loads at joints will not damage segments, at the confidence level required by the design standards.

Annex D of EN 1990 contains comprehensive information on setting up and interpreting tests to provide parameters for further use in a design based on partial factors or LRFD (Load and Resistance Factor Design).

Additional information is presented in the fib Model Code 2010 (2013) section 7.11. A detailed explanation of design assisted by testing for FRC is given in Jones (2022: pp.252-258) with examples.

7.3 CHARACTERISTIC STRENGTH

Concrete linings are often designed according to their characteristic compressive strength at 28 days. If a tunnel lining does not need its full strength until later than 28 days, then the characteristic compressive strength at a later age, e.g. 56 or 90 days, could be used to calculate the design resistance of the structure (Bamforth & Allen, 2015). The Crossrail project in London, UK, specified a concrete cylinder strength of 28 MPa at 28 days and 32 MPa at 90 days for the permanent primary and secondary sprayed concrete linings (Su & Thomas, 2014). This would either provide a stronger material for the designer, thus reducing the thickness of the lining, or would mean a lower strength class at 28 days could be used for the construction with potentially a lower carbon footprint.

7.4 SECONDARY LININGS

The choice of a secondary lining depends on two key design decisions: firstly, the waterproofing concept and secondly the durability of the primary lining.

There are a range of options for the waterproofing concept, particularly for sprayed concrete lined tunnels (Thomas 2019b, Jones 2022). This is a very broad subject which cannot be covered in detail here. Studies have shown that there can be significant reductions in the carbon footprint for tunnel linings by adopting different designs, based on current technology. For example, in a hard rock tunnel the reduction could be 33 to 50% (Thomas 2019a) and in a weak ground case up to 25% (Thomas 2020).

If the primary lining is designed to be durable for the whole design life, this can result in large savings in overall concrete volume. Either the secondary lining can be deleted as it is no longer needed, or its thickness and/or reinforcement volume can be reduced as the primary lining is sharing the load.

Although single lining construction is common for segmental linings, it is not common for sprayed concrete linings. This is because sprayed concrete linings are rarely watertight on their own.

With adequate consideration in design and quality control during construction, a sprayed concrete primary lining can be considered permanent in most cases. However, in some situations, such as deep tunnels with high stresses, or tunnels with high water inflows, a sprayed concrete primary lining may be damaged by overstressing or of insufficient quality to be considered a permanent structure. The ITA Working Group No.12/ITAtech Report on ‘Permanent Sprayed Concrete Linings’ provides more guidance (ITA, 2020).

7.5 SUSTAINABILITY LIMIT STATE / CLIMATE LIMIT STATE

There have been attempts to define a sustainability limit state (Geiker et al., 2019) or climate limit state (Haist et al., 2022). These are intended to be analogous to the ultimate limit state or serviceability limit state and hence the aim is to force the designer to quantify how the structure contributes to reducing CO_2e emissions to within the targets set by climate scientists. The climate limit state gives the designer a target CO_2e emissions value for a structural member based on the year of construction and a requirement to reduce CO_2e emissions from a 2020 benchmark reference value (defined by the designer) to net zero by 2050.

This approach is similar to the concept of most routemaps or roadmaps to net zero produced by institutions or associations of cement/concrete producers (e.g. MPA, 2020; ICE, 2022; GCCA 2023), where a linear or exponential trend from a current benchmark down to zero by 2050 is provided as a target for the industry. The main difference incorporated in the climate limit state of Haist et al. (2022) is that the CO_2e emissions are divided by the service life of the structure, and so are amortised over its lifetime. Therefore, the climate limit state can be met by either reducing the CO_2e emissions or increasing the service life, or both.

In order to achieve significant reductions in CO_2e emissions, constructors need to work closely with the design team and the client. It is important that the client shows leadership in carbon reduction and ensures the constructor and designer are supported and incentivised to reduce CO_2e emissions. It is also important that the constructor feels able to challenge the client's specification if it is preventing CO_2e emissions reductions.

The main objective should be to reduce the amount of Portland cement used in the construction process. This can be achieved by:

- Reducing the concrete and/or grout volume
- Reducing the clinker content of the concrete or grout

8.1 PRECAST CONCRETE SEGMENTAL LININGS

In this case the volume is fixed by the designer, but by working together with the segment manufacturer the production process can be optimised to reduce CO_2e emissions. The concrete strength required for demoulding is a key parameter that can sometimes prevent the use of low carbon concretes that are slower to develop early age strength (e.g. Jarast et al., 2023b). The most sustainable solution can be found by all parties working collaboratively with transparency about the costs, programme impacts and CO_2e emissions of different options. For example, it is relatively common for the segment manufacturer to adopt higher 28-day strengths than those specified in the design to achieve early demoulding and handling strength. A feedback loop, such that the higher strength can be used in the design, may allow for thickness reduction and, consequently, carbon saving in these cases. A lighter segment will also have lower handling loads.

Admixtures can help to reduce the CO_2e emissions. Superplasticisers can allow a reduction of water/cement ratio, increasing the strength without changing the cement content. They can also change the timing and magnitude of strength development, as can hardening accelerators that catalyse the formation of CSH (CSH is calcium silicate hydrate, the main contributor to strength development of the C_2S and C_3S clinker hydration).

Reducing the paste content of concrete, and hence the CO_2e emissions from cement per unit volume, can be achieved by paying attention to the grading of the materials in the concrete (Jarast et al., 2023b).

Fibre reinforcement is a good way to reduce the carbon footprint. The ITAtech report no.7 (2016) provides guidance on how to use this in precast segments, including case studies for inspiration. There are also case studies separately published by this Activity Group on the ITA-AITES website.

Thermal monitoring of segments during curing, when coupled with a properly set up and calibrated maturity method, can also help optimise the curing temperature and demoulding times.

8.2 ANNULUS GROUT

As part of the tunnelling method using a TBM, the grouting of the gap between the segmental rings and the excavated substrate can be considered part of the whole lining system. The annulus grout can in some cases have almost as high CO_2e emissions as the segmental lining itself (Aldrian et al., 2022).

There are different approaches to fill the annulus gap and the objective should be to reduce the CO_2e emissions of the binder used as much as possible.

The carbon intensity of annulus grout varies enormously on different projects, from below 50 $kgCO_2e/m^3$ up to more than 300 $kgCO_2e/m^3$ (Aldrian et al., 2022). There is therefore huge scope for carbon reductions in the design of the grout mix.

The designer should define the required compressive strength of the annulus grout at early age and in the long term, as well as other requirements such as durability and permeability (BTS, 2023). This should be based on what is needed to provide stable and durable support to the tunnel lining during construction and in the long-term. Then the type of grout (e.g. single component, bi-component) and its injection method will need to be determined based on the project requirements and construction logistics, with due consideration of the CO_2e emissions.

During pre-construction trials it is recommended to define a proper early strength development assessment method, able to reproduce the fluid dynamics of the accelerator mixing process on site and consequently optimise the mix needed to meet the design requirements.

8.3 SPRAYED CONCRETE

Sprayed concrete is often required to have a fast early strength development so it does not fall down during application and to support the ground as the tunnel advances. The precise requirements should be thought through carefully by the designer and constructor, because a specification requiring high early strengths is likely to require a higher Portland cement content.

It is possible to produce sprayed concrete with less than 330 kg/m^3 of Portland cement that can meet typical requirements of a 'J2' (EN 14487-1:2005) early strength development and a 28 day characteristic compressive strength of 40 MPa. However, many projects still use sprayed concrete mixes with up to 500 kg/m^3 of Portland cement. Refer to Section 2 for more details.

Compressive strength depends on many factors, including the competence of the nozzle operator and the capability of the pumping and spraying equipment to produce a dense and well-compacted concrete without laminations or zones of trapped rebound. It also depends not only on the type of binder and the binder content, but also on the concrete temperature (Jones et al., 2017), the water/cement ratio and the type and grading of the aggregates. Long-term strength and durability can be improved by replacing some of the Portland cement with other pozzolanic materials.

For these reasons, there is no need to use a high Portland cement content in sprayed concrete to achieve strength or durability.

The wastage rate of sprayed concrete is defined as the total sprayed concrete volume produced for the works divided by the theoretical volume in the design drawings. With good practice this can be around 1.4-1.5, but can be much higher if not controlled. Wastage occurs due to:

- Filling overbreak
- Rebound
- Batching more sprayed concrete than is needed
- Sprayed concrete rejected because of nonconformity (e.g. a whole batch is rejected because an error was made in the batching or because it fails the slump or flow test)
- Sprayed concrete used for training, trials and testing
- Cleaning out of pump and pipelines

Rebound can be reduced through good mix design and the competence of the nozzle operator. There are tests available to measure it and rebound should be minimised as much as possible. Rebound should be less than 10% and ideally less than 7%.

Overbreak is a major cause of sprayed concrete wastage in soft ground, as it needs to be filled to ensure the lining has a stable shape. For a given geology it is the skill of the excavator driver and the precision with which the excavator can be operated that determines the overbreak. Overbreak due to ground instability may be reduced by employing mitigation measures such as face division, pocket excavation or spiles, though from a carbon point of view these will have a cost.

For drill and blast tunnelling, overbreak can be reduced by employing digitalisation and automation to improve the accuracy of drilling and design of the blast. A well-designed, charged and detonated round yields a better quality tunnel profile, blasting pull-out factor and face shape at round bottom. A good quality profile lessens the required look-out angle of the contour holes for rounds to come, leading to a smaller blasted volume. Reaching the target profile in one go (correcting underbreak leads easily to overbreak) is essential to keep the excavation 'rhythm'; to control the cycle and minimise the use of sprayed concrete and therefore its CO_2e emissions.

Measuring the excavation profile and the sprayed concrete lining thickness using laser scanning can give feedback to the excavation or blasting process and the spraying process, enabling improvements to be made to reduce consumption of sprayed concrete and hence CO_2e emissions. This requires careful specification of minimum and maximum sprayed concrete thickness and what local asperities are allowed. Depending on what the sprayed concrete lining is there to do (for example, is it there only to prevent weathering of the rock, to prevent block falls, or is it there as an arch support in compression?), it may be appropriate to specify an average thickness, with nowhere less than 50% of the average (NB7, 2011).

8.4 CAST-IN-PLACE CONCRETE LININGS

For cast-in-place concrete linings, it has always been important to optimise the cycle time to reduce the programme time and hence also the cost. The aim is usually to achieve a full cycle of setting up the shutter, casting the concrete and then striking, cleaning and repositioning the shutter in 24 hours. This means that the concrete must be self-supporting within 6-12 hours.

Comments on admixtures and reducing the paste content in Section 8.1 'Precast concrete segmental linings' also apply to cast-in-place concrete linings.

Again, where minimum or light reinforcement is required by the design, fibre reinforcement may be a good way to reduce the carbon footprint. Combining high-performance structural fibres with higher-strength concrete may allow some savings in thickness.

The use of thermal sensors and the implementation of the concrete maturity concept may help to optimise the mix design needed and the time required to achieve the early strength to strike the shutter.

9 >> Operation & Maintenance Of Tunnels With Low Carbon Concrete Linings

A workshop including several tunnel owners (London Underground, HS2 and the Nuclear Decommissioning Authority from the UK, Trafikverket from Sweden and CETU from France) was held on 13th April 2023. The consensus was that the approach to utilising low carbon concrete does not deviate from the existing requirements or standards that are in place for normal concrete, which cover both materials and the design. Tunnel owners want to maximise availability of the tunnel asset, so they expect zero maintenance of concrete tunnel linings over the design life. They do not expect low carbon concrete linings to require extra monitoring or inspection.

The Sellafield nuclear site in the UK has been using high replacements of GGBS and fly ash in its concrete mixes since the 1970's and has the lowest embodied carbon value of any major infrastructure asset in the UK to date. Whilst this use of low carbon concrete is not a tunnelling example it does demonstrate that it has been consistently and safely used over the last 50 years in a high safety and high regulatory setting.

10 >> Conclusions

An urgent response to the climate crisis is needed now. We need to dramatically reduce emissions of carbon dioxide and other greenhouse gases (CO_2e emissions). As tunnel engineers we have a professional responsibility to reduce the CO_2e emissions caused by tunnelling.

Sustainability must be used as the decision-making framework, where social, environmental and economic factors are all considered. As part of this framework, climate change must be a criterion in all decision-making.

All parties - clients, designers, constructors and suppliers - must work together to reduce CO_2e emissions and we must do it urgently. Leadership by the client, and incentivisation of CO_2e emissions reductions through the design and construction contracts, is essential to achieving this collaboration.

The biggest reductions in CO_2e emissions can be achieved during the planning and design stages. It is important, therefore, to try to quantify the CO_2e emissions related to different options in a pragmatic way as early as possible to aid decision-making.

For tunnelling projects, by far the largest contribution to CO_2e emissions is the Portland cement in concrete tunnel linings and annulus grout.

We should use every lever available to reduce CO_2e emissions, but we should focus first on the areas we can make the biggest difference. In most cases this will be to reduce the volume of concrete in tunnel linings, and to reduce the Portland cement content of that concrete.

The second biggest source of CO_2e emissions in the lining is the reinforcement. Replacing conventional steel bar reinforcement with fibre reinforcement can reduce this footprint in many cases.

Procurement of the design and construction of tunnelling projects should incentivise the reduction of CO_2e emissions within a sustainability framework that balances environmental, social and economic factors.

For this to be effective, a sustainability indexing tool should be used that allows benchmarking and quantification of any reductions.

Carbon accounting is a well-developed methodology for quantifying CO_2e emissions. It is important to set a baseline for the project as early as possible so that targets for reducing CO_2e emissions can be set relative to it.

Materials, design methods and construction methods exist today that can be used to significantly reduce the CO_2e emissions of tunnelling projects by 50% or more, without the need to make changes to standards or specifications.

To reach net zero emissions may require the development of very low carbon materials such as AACMs, geopolymers and LC^3 cements, some of which are already available in some regions.

For conventional tunnelling, if the sprayed concrete primary lining is designed to be permanent, i.e. durable for the whole design life, this can result in large savings in overall concrete volume. Either the secondary lining can be deleted as it is no longer needed, or its thickness and/or reinforcement volume can be reduced as the primary lining is sharing the load.

There are many examples in Sections 7 and 8 where designers, constructors and suppliers must work together to achieve reductions of CO_2e emissions in design and construction, and this collaboration must be incentivised by the client. One example is early strength development of concrete (whether sprayed, precast or cast-in-place), where the production or construction method affects the loads and hence the required strength, so there is a feedback loop that can be exploited if there is good collaboration.

Finally, it is up to us as tunnel engineers to rise to this challenge and to save our planet.

11 >> Recommendations For Further Work

Annexes to this report will be produced in the near future to provide more detail on the following subjects:

- Carbon accounting
- Design
- Construction

In addition, case studies of good practice are being collected and published on the ITA-AITES website.

Member Nations of ITA-AITES should be encouraged to publish the carbon footprints of recently completed tunnels and provide national/regional targets for carbon reduction as part of a routemap to net zero.

Aldrian, W. (2021). Reducing the carbon footprint of segmental linings. Tunnelling Journal, April/May issue, 16-21.

Aldrian, W. & Bantle, A. (2021). Sprayed concrete for tunnel construction - ways to reduce carbon. Proc. 13th International Tunnelling and Underground Structures Conference, Ljubljana, Slovenia, 17-19 November 2021, pp.38-46. Ljubljana, Slovenia: Slovenian Society for Underground Structures.

Aldrian, W., Bantle, A., Green, D. & Jacobs, A. (2022). Greenhouse gas reduction in tunnel construction: Chances and Possibilities. Proc. ITA-AITES World Tunnel Congress WTC2022, Copenhagen, Denmark, 22-28 April 2022.

Aldrian, W., Traldi, D. & Fataei, S. (2023). CO2 reduction in tunnel construction – focus on materials. Proc. Let's Talk Underground!, ITA Slovenija, 15th – 17th November 2023, Ljubljana, Slovenija.

Arup (2023). Embodied carbon classification scheme for concrete. Ove Arup & Partners Ltd for UKRI (UK Research & Innovation) / Innovate UK. Available at: https://www.arup.com/perspectives/publications/research/section/embodied-carbon-classification-scheme-for-concrete [last accessed 30/10/2023].

AS 3600:2018. Concrete Structures, Incorporating Amendment Nos 1 and 2. Sydney, Australia: Standards Australia.

ASTM C1157-08a. Standard Performance Specification for Hydraulic Cement. West Conshocken, PA, USA: ASTM International.
Bakhshi, M. & Nasri, V. (2023). Fiber-Enabled Carbon Footprint Reduction in Design and Construction of FRC Tunnel Segments in North America. FRC2023: Fiber Reinforced Concrete: from Design to Structural Applications, Joint ACI-fib-RILEM International Workshop, pp.1-13.

Bamforth, P. B., Allen, C., Denton, S., Jonasson, J. -E. & Isgren, C. (2015). Reducing the embodied energy of concrete structures through more reliable prediction of in-situ properties and the use of appropriate material safety factors. ICE Research Project 1004 06/2022.

Bergmeister, K. (2019). The Brenner Base Tunnel – geological, construction and logistical challenges and innovations at half time. Geomechanics & Tunnelling 12, No.5, 555-563.

BRE Information Paper IP4/16 (2016). Alkali-activated binders for precast and ready-mixed concrete products – A route map to standardisation, certification and guidance. Bracknell, UK: BRE Press. ISBN 978-1-84806-456-0.

BREEAM (2023). https://bregroup.com/products/breeam/ [last accessed 30/10/2023].

BTS (2023). Specification for Tunnelling, 4th Edition, British Tunnelling Society and the Institution of Civil Engineers. London: ICE Publishing/Emerald Publishing.

Day, J., Allen, C. & Sutherden, R. (2023). Geopolymer concrete in tunnelling. Tunnels & Tunnelling International, July issue, 16-23.

de Waal, R. G. A. (2000). Steel Fibre Reinforced Tunnel Segments for the Application in Shield Driven Tunnel Linings. PhD Thesis. Technische Universiteit Delft.

EN 197-1:2011. Cement. Part 1: Composition, specifications and conformity criteria for common cements, Incorporating corrigenda November 2011, October 2015 and February 2019. Brussels: European Committee for Standardization.

EN 197-5:2021. Cement – Portland-composite cement CEM II/C-M and Composite cement CEM VI. Brussels: European Committee for Standardization.

EN 206:2013+A2:2021. Concrete. Specification, performance, production and conformity. Brussels: European Committee for Standardization.

EN 1990:2002+A1:2005. Eurocode – Basis of structural design, incorporating corrigenda December 2008 and April 2010. Brussels: European Committee for Standardization.

EN 14487-1:2005. Sprayed concrete – Part 1: Definitions, specifications and conformity. Brussels: European Committee for Standardization.

EN 15804:2012+A2:2019. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. Brussels: European Committee for Standardization.

EN 15978:2011. Sustainability of construction works. Assessment of environmental performance of buildings. Calculation method. Brussels: European Committee for Standardization.

EN ISO 14025:2010. Environmental labels and declarations. Type III environmental declarations. Principles and procedures. Brussels: European Committee for Standardization.

EN ISO 14040:2006+A1:2020. Environmental management. Life cycle assessment. Principles and framework. Brussels: European Committee for Standardization.

ENVISION (2015). ENVISION rating system for sustainable infrastructure, manual. Washington DC, USA: Institute for Sustainable Infrastructure. Available at: https://research.gsd.harvard.edu/zofnass/files/2015/06/Envision-Manual_2015_red.pdf [last accessed 30/10/2023].

fib Bulletin 83 (2017). Precast Tunnel Segments in Fibre-Reinforced Concrete, State-of-the-art Report, fib WP 1.4.1, October 2017. Lausanne: Fédération internationale du béton (fib).

Geiker, M. R., Michel, A., Stang, H. & Lepech, M. D. (2019). Limit states for sustainable reinforced concrete structures. Cement and Concrete Research 122, 189-195.

Global Cement and Concrete Association (2023). Concrete Future – Action and Progress: 2050 Net Zero Roadmap – One

Year On. Available at: https://gccassociation.org/wp-content/uploads/2023/01/GCCA-Roadmap-One-Year-On-Action-and-Progress.pdf [last accessed 17/10/2023]. London: GCCA.

Haist, M., Bergmeister, K., Kurbach. M., Deiters, M. V., Forman, P., Gaganelis, G., Gerlach, J., Mark, P., Moffatt, J., Müller, C., Müller, H. S., Reiners, J., Schack, T., Scope, C., Tietze, M. & Voit, K. (2022). Climate Limit State (CLS) for building structures - a possible companion of ULS, SLS and durability limit states. Proc. 6th fib Congress, June 2022, Oslo, Norway, pp. 143–152.

Hallam, H. C. (2014). The effect of accelerating admixtures on blended Portland cement/fly ash mortars. MEng research dissertation, University of Warwick.

ICE (2022). Low carbon concrete routemap. Low Carbon Concrete Group, The Green Construction Board. London: Institution of Civil Engineers. Available at: https://www.ice.org.uk/media/q12jkljj/low-carbon-concrete-routemap.pdf [last accessed 19/10/23].

ICE (2023). Guidance document for PAS 2080, April 2023. Sponsored by the Institution of Civil Engineers, the Construction Leadership Council and The Green Construction Board.

Informationszentrum Beton GmbH (2018). Umwelt-Produktdeklaration für „Beton der Druckfestigkeitsklasse C30/37“. Institut Bauen und Umwelt e. V. (Hrsg.)

IPCC (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001.

IS Ratings (2023). Infrastructure Sustainability Council website. Available at: https://www.iscouncil.org/is-ratings/ [last accessed 30/10/2023].

IStructE (2022). How to calculate embodied carbon, 2nd edition, version 1.1. Institution of Structural Engineers, May 2022. London: Institution of Structural Engineers International.

ITA (2020). Permanent Sprayed Concrete Linings. ITA Report No.24, Working Group No.12 & ITAtech, October 2020. Lausanne: ITA-AITES.

ITAtech (2016). Design Guidance for Precast Fibre Reinforced Concrete Segments – Vol.1: Design Aspects, ITAtech Report No.7. Lausanne: ITA-AITES.

Jarast, P., Bakhshi, M. & Nasri, V. (2023a). Carbon Footprint Reduction in Montreal Blue Line Extension. Proc. RETC 2023, 11th-14th June, Boston, MA, pp.581-588. Englewood, CO, USA: Society for Mining, Metallurgy & Exploration Inc.

Jarast, P., Bakhshi, M. & Nasri, V. (2023b). Carbon footprint emissions of different tunneling construction methods. Proc. ITA-AITES World Tunnel Congress 2023 – Expanding Underground. Knowledge and Passion to Make a Positive Impact on the World (eds Anagnostou, G., Bernardos, A. & Marinos, V. P.), 12th – 18th May 2023, Athens, Greece. Abingdon, UK: CRC Press.

Jones, B. D. (2016). Carbon reduction in tunnelling. Tunnelling Journal, February/March issue, 27-28.

Jones, B. D. (2022). Soft Ground Tunnel Design. London: Taylor & Francis Group.

Jones, B. D., Runtemund, K. & Ahuja, V. (2017). Études de cas européennes de l'imagerie thermique pour la surveillance de la résistance du béton projeté. Proceedings of the AFTES International Congress, Paris, 13-15 November 2017.

Kundan, R., Daniele, S. & Martin, S. (2023). Challenges of delivering 32.5km of major tunnelling infrastructure in South London (UK), and the influences of an innovative “Enterprise” project delivery model. Tunnelling – Smart Solutions, Future Growth, Tunnelling Association of Canada 2023 Conference, 24th – 26th September, Toronto, Ontario, Canada.

LC^3 (2023). LC^3 project website. Available at: https://lc3.ch/ [last accessed 19/10/2023].

McCague, C. (2022). Multi-component mixes for low carbon cements. Concrete Quarterly, Spring 2022, Issue 278, 28-35.

MPA (2020). UK Concrete and Cement Roadmap to Beyond Net Zero. Mineral Products Association. Available at: https://www.sustainableconcrete.org.uk/MPA-ACP/media/SustainableCon-Media-Library/Pdfs%20-%20freely%20downloadable/MPA-UKC-Roadmap-to-Beyond-Net-Zero_October-2020.pdf [last accessed 19/10/2023].

MPA (2023). Embodied carbon of concrete – Market Benchmark. Mineral Products Association / The Concrete Centre / Low Carbon Concrete Group. Available at: https://www.concretecentre.com/Resources/Publications/Embodied-carbon-of-concrete-%e2%80%93-Market-Benchmark.aspx [last accessed 19/10/2023].

NB7 (2011). Sprayed Concrete for Rock Support, Norwegian Concrete Association Publication no.7. Oslo, Norway: Norwegian Concrete Association/Tekna.

Our World In Data (2023). Global CO_2 emissions from fossils fuels and land use change. Available at: https://ourworldindata.org/co$_2$-emissions#global-co$_2$-emissions-from-fossil-fuels-and-land-use-change [last accessed 19/10/2023].

PAS 2080:2023. Carbon management in buildings and infrastructure. London: British Standards Institution.

PAS 8820:2016. Construction materials – Alkali-activated cementitious material and concrete – Specification. London: British Standards Institution.

PBL (2016). Trends in global CO_2 emissions

– 2016 Report. Publication no. 2315, PBL The Netherlands Environmental Assessment Agency. The Hague, The Netherlands: PBL Publishers. Available at: https://www.pbl.nl/sites/default/files/downloads/pbl-2016-trends-in-global-co2-emisions-2016-report-2315_4.pdf [last accessed 19/10/2023].

SA TS 199:2023. Design of geopolymer and alkali-activated binder concrete structures. Standards Australia.

Sauer, J. (2016). Ökologische Betrachtungen zur Nachhaltigkeit von Tunnelbauwerken der Verkehrsinfrastruktur. Dissertation am Lehrstuhl für Massivbau der Technischen Universität München. Available at: https://mediatum.ub.tum.de/doc/1295092/document.pdf [last accessed 06/2022].

Schnütgen, B. (2003). Design of precast steel fibre reinforced tunnel elements. International RILEM Workshop on Test and Design Methods for Steelfibre Reinforced Concrete (eds Schnütgen, B. & Vandewalle, L.), Bochum, Germany, pp. 145–152. Paris, France: RILEM Publications SARL.

Scrivener, K., Martirena, F., Bishnoi, S. & Maity, S. (2018). Calcined clay limestone cements (LC3). Cement and Concrete Research 114, 49-56. https://doi.org/10.1016/j.cemconres.2017.08.017.

Spyridis, P. (2014). Adjustment of tunnel lining service life through appropriate safety factors. Tunnelling & Underground Space Technology 40, 324-332.

UN Environment, Scrivener, K. L., John, V. M. & Gartner, E. M. (2018). Eco-efficient cements: Potential economically viable solutions for a low-CO2 cement-based materials industry. Cement & Concrete Research 114, December 2018, 2-26. https://doi.org/10.1016/j.cemconres.2018.03.015.

Su, J. & Thomas, A. H. (2014). Design of sprayed concrete linings in soft ground – a Crossrail perspective. https://learninglegacy.crossrail.co.uk/documents/design-sprayed-concrete-linings-soft-ground%E2%94%80-crossrail-perspective/

Thomas, A.H. (2019a) Achieving sustainability in underground construction through innovation. Proceedings of the Institution of Civil Engineers – Civil Engineering. https://doi.org/10.1680/jcien.19.00018

Thomas, A.H. (2019b). Sprayed concrete lined tunnels, 2nd edition. Boca Raton: CRC Press.

Thomas, A. H. (2020). Achieving sustainability in tunnelling through innovation. Proc. 10th Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground IS-Cambridge (eds Elshafie, M. Z. E. B., Viggiani, G. M. B. & Mair, R. J.), Churchill College, Cambridge, 27th–29th June. Boca Raton: CRC Press.

Wittke, W., Wittke-Schmidt, B., Wittke, M., Wittke-Gattermann, P. & Druffel, R. (2022). Saving Energy and Resources and Reducing the Carbon Footprint by Innovations in Tunnel Construction. Tunnel, issue 03/2022. Available at: Saving Energy and Resources and Reducing the Carbon Footprint by Innovations in Tunnel Construction - tunnel (tunnel-online.info) [last accessed 06/2022].

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