ARUP

Buildings & Infrastructure Priority Actions for Sustainability

Embodied Carbon

Concrete

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This document is a snapshot in time of industry research, opinion, and knowledge. The information is subject to change as industry progresses and new information comes to light. This document is to be periodically reviewed and any comments or suggestions are welcomed via jo.spencer@arup.com and the BIPAS team. BIPAS is a multi-disciplinary group of engineers within Arup, funded via Arup's internal investment programme. We carry out research and create resources relating to sustainability, primarily for use within Arup but shared externally when it is appropriate. Our objective is to address those areas that engineers engage with on a daily basis, to enable them to address sustainability in an informed and effective manner.

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Introduction

Concrete is the most used construction material in the world with approximately 14 billion m^3 used worldwide each year [1]. Up to 90% of the greenhouse gas emissions (GHGs) in the production of concrete are created in the manufacture of Portland cement [2], which is currently accountable for 8% of all global emissions, and this is expected to rise by 25% by 2050 [3]. Per kilogram, concrete has a relatively low embodied carbon and cost compared to steel, whilst also providing high strength and durability, making it an effective and accessible construction material. Due to the vast quantities of concrete used globally, reductions in the carbon factors we use can have a significant global impact [4], but efficient design choices have real potential to be the most effective way of reducing construction's carbon footprint. Note that by reducing the assumed carbon factors of concrete during early design stages, this reduces the incentive to do leaner designs.

The greenhouse gas emissions (referred to in this document as 'carbon') and the carbon factor (the quantity of greenhouse gases emitted per kg of material) for concrete can vary depending on raw material extraction, processing and manufacturing techniques, supplementary cementitious materials, transportation mode and distance, concrete strength, consistence (workability), and use of water and (super)plasticisers.

We need to understand the carbon emissions associated with the different stages of the concrete manufacturing process, and work collaboratively with contractors, clients and suppliers to meet increasingly critical carbon targets to ensure that the impact of our decisions is felt throughout the supply chain.

This document sets out the factors stage by stage that contribute towards the emission of carbon through the whole life cycle of concrete used for buildings and infrastructure. It will also highlight the potential route to decarbonising the production of concrete through identifying the carbon journeys of the principal constituents, which include:

- Portland cement
- Supplementary cementitious materials (additions)
- Aggregates (fine and coarse)
- Admixtures
- Water

Using less material as an industry is **fundamental** to reducing emissions. At present there are no solutions that work at an industry, as opposed to project, scale to significantly reduce the carbon intensity of concrete [5]. This paper aims to provide the reader with information on the status of the industry and best practice, so that they can understand the impact of their design choices and avoid greenwashing.

Lifecycle

The stages referred to in this document align with the life cycle assessment referenced in ISO 14040, whereby Stage A is ‘up-front’, Stage B is ‘in-use’, Stage C is ‘end-of-life’ and Stage D is ‘beyond the lifecycle’. Figure 1 describes the lifecycle of CEM I fits into Stages A-C, and the approximate proportion of carbon associated with each.

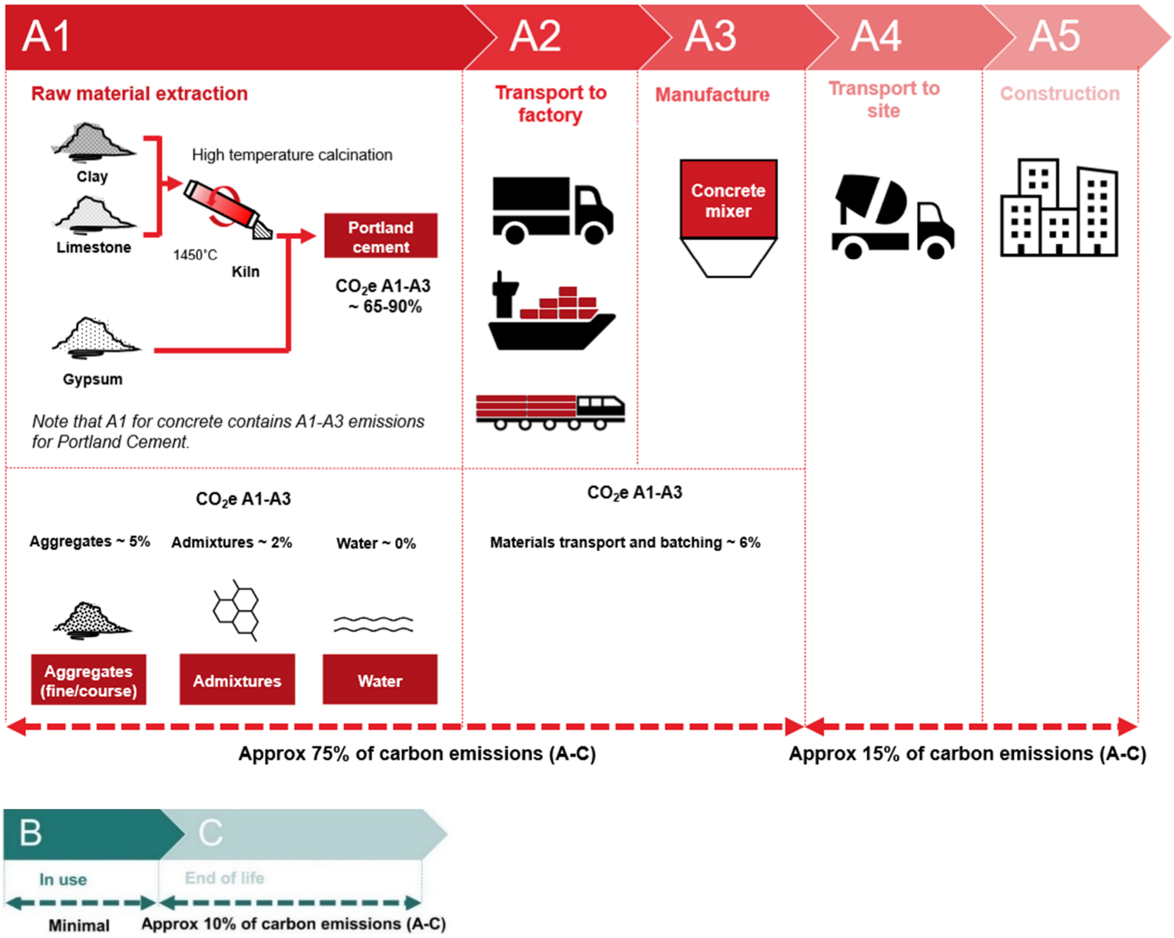

Figure 1
Life cycle stages for Portland cement concrete into corresponding percentages of carbon emissions [5].

Figure 2 shows an example C30/37 concrete mix broken down into the principal constituents per m^3, and compares mass and embodied carbon (A1-A5) to show the materials with the most significant environmental impacts. Note that the reinforcement contribution will be dependent on the recycled content of the steel.

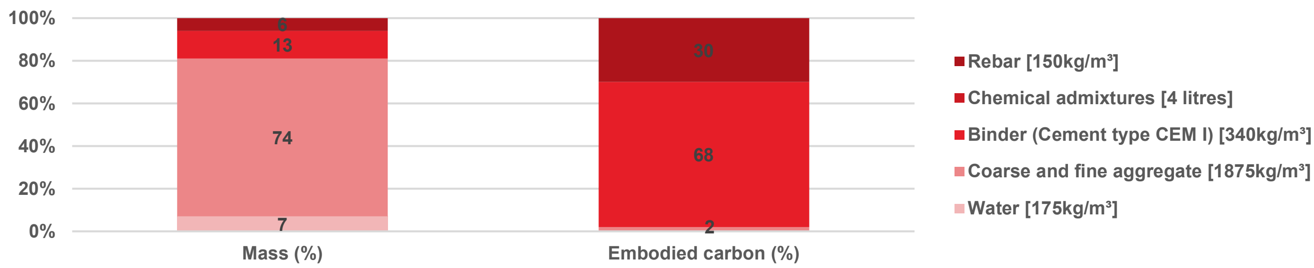

Figure 2
C30/37 concrete example mix including only CEM I with no replacements, by mass and embodied carbon, not including mineral additives [2].

Stage A

A1 – Raw material extraction

Module A1 includes the carbon emissions associated with extracting and manufacturing each constituent material of concrete, which includes four main components: cement or cementitious materials, fine aggregates, coarse aggregates, and water. The A1 emissions for concrete includes the A1-A3 emissions of extracting and producing each material. Figure 3 shows the breakdown of A1-A5 emissions. A1-A3 for concrete typically accounts for 75% of the A1-A5 carbon emissions concrete production.

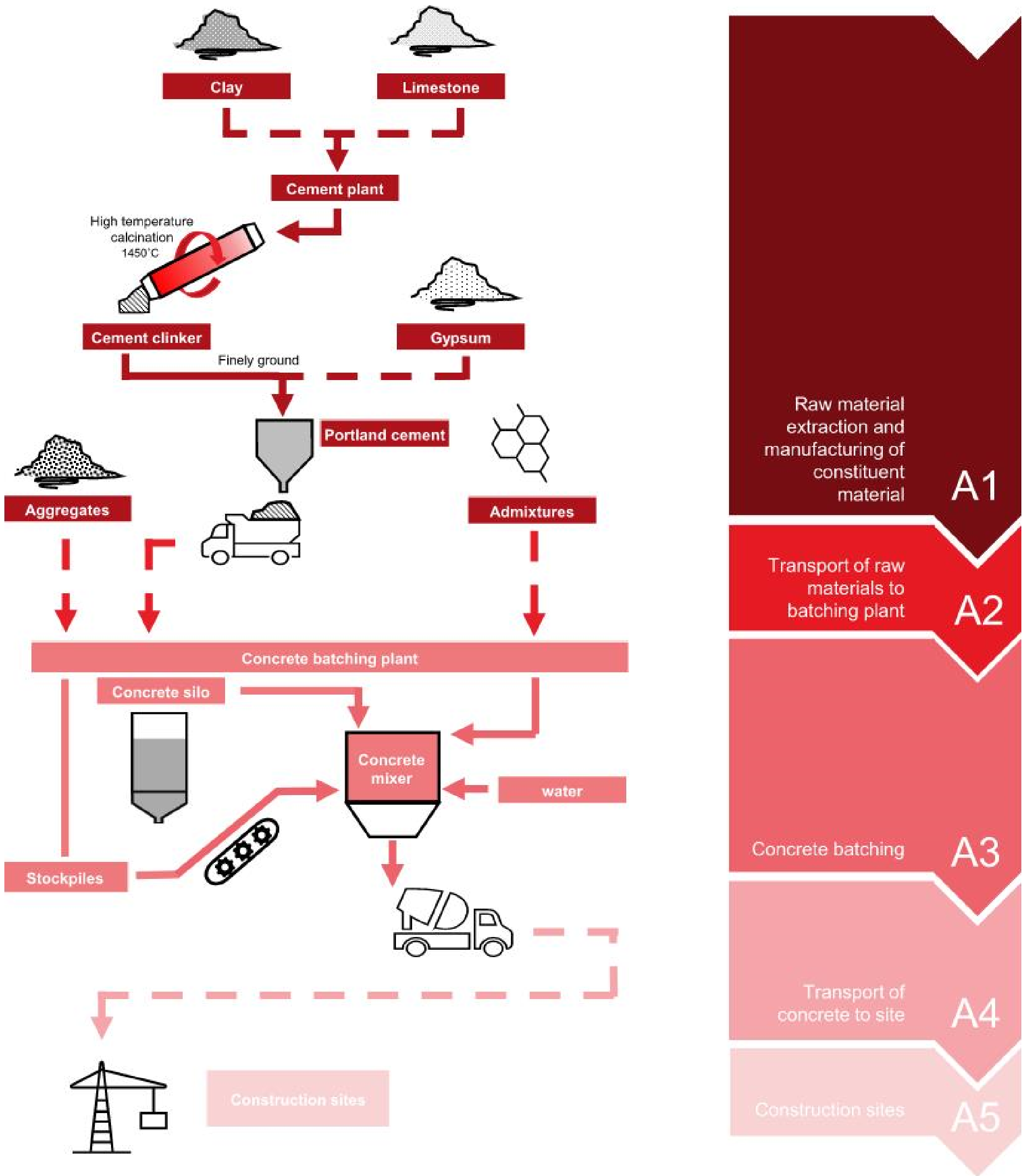

Figure 3
A1-A5 emissions process.

Aggregates

Aggregates can make up to 70% of the concrete volume, only account for 1-5% of A1-A3 emissions [6]. However, there are wider impacts associated with constrained resource use. They are naturally occurring materials which require minimal processing, and are often acquired locally [2]. Formation of aggregate is extremely slow in comparison to the existing demand; this threatens the long-term availability of aggregates in the future.

Aggregates are sourced as virgin/primary, recycled, or secondary materials:

Virgin/primary aggregates: Naturally occurring aggregates quarried from the land or dredged from the seabed.

Recycled concrete aggregates: Aggregate resulting from the reprocessing of inorganic material previously used in construction, such as crushed concrete. Note that CO_2e values for recycled aggregates may be higher than for virgin materials if delivery distances are greater than 15km.

Secondary aggregates: Industrial by-products, such as slag, slate and recycled glass, which are often sourced locally.

Manufactured carbon sequestering aggregates: Relatively novel technologies utilising industrial wastes and captured CO_2 for manufacturing carbon neutral/negative lightweight aggregates (such as those from O.C.O Technology [7] or Low Carbon Materials [8]).

Water

Clean, uncontaminated water should be used for mixing and curing concrete. EN 1008:2002 specifies the requirements for water that are suitable for making concrete. The emissions associated with water in the A1 stage are less than 1% and so are negligible.

Admixtures

Admixtures can be added to the concrete mix during the manufacturing process (A3). By adding certain admixtures, this can increase the consistence (workability) of a concrete and reduce the amount of water required in the mix, hence reducing the permeability of the concrete, and increasing the overall strength without increasing the cement ratio which is carbon intensive [9]. However, by using a plasticising admixture, not to increase consistence, but to use less water for the required consistence, the cement content of the concrete can be reduced to maintain an equal water/cement ratio. The concrete will therefore have a lower embodied carbon but with equal strength and durability. They can also be added to facilitate environmentally optimised mixes and are generally only added in small amounts.

Environmental Product Declarations (EPDs) for admixtures are provided per kg of admixture, and this may not reflect differences in the functional performance of each admixture; For example shrinkage-reducing admixtures include both liquid and powder-based products. Table 1 shows average values of carbon emissions per kg of various admixture types. Note that admixtures are typically a small contribution to overall CO_2 emissions, but there are other environmental impacts attributed to manufacture and safe storage.

Table 1

$kgCO_2e/kg$ of admixture types [8].

Carbon Emissions $kgCO_2e/kg$	Air entrainer	Hardening accelerator	Plasticiser and superplasticiser	Retarder	Set accelerator	Shrinkage reducing admixture	Water resisting admixtures
Mean value	0.5	2.1	1.8	1.4	1.3	3.0	2.8

Manufacture of Portland cement

The manufacturing stage of Portland cement is the most carbon intensive part of the production of concrete, with 4-5% of all global GHG emissions coming from cement kilns alone [10]. As seen in Figure 2, for a typical concrete mix, Portland cement generally consists of 10%-20% of the mass, but can account for 75-90% of the embodied carbon impact of concrete [2]. The embodied carbon of concrete is therefore significantly affected by the amount of PC within the mix.

Material quarrying and transport to cement plant

The manufacture of cement starts at a mine or quarry where the raw materials are extracted. Calcium rich materials such as limestone, chalk, and silica, and alumina rich materials such as clay and shale, are extracted from rock quarries [7]. The widespread abundance of limestone and chalk makes it a suitable local material to be used in the production of concrete [8]. The raw material is then transported via truck to the cement factory. Due to the vast amounts of these materials necessary for cement production globally (1.6t of limestone is needed to produce 1t of clinker), it is common for cement manufacturers to locate their factories near to the quarries [8]. Mining, quarrying and transport of the raw materials often accounts for less than 5% of cement related emissions and could be reduced or eliminated through electrification of mining operations [9].

Drying and grinding

The individual materials arrive at the cement factory separately, where they are dried and ground further to create a fine powder called "meal". These materials are individually stored into silos for use later when each material can be added in the required amounts for different cement mixes [7]. Electricity used for grinding and moving materials around the cement plant account for 8-13% of indirect emissions of cement production [9].

Kiln

Fossil fuels are often used to heat the kiln to over 1400ºC [2]. CO_2 is indirectly emitted in this process which can account for 30-40% of CO_2 emissions of cement production [2] [9]. The combined raw materials are heated and ground to form a lumpy substance called clinker. During the production of clinker, calcium carbonate ($CaCO_3$) is converted to lime (CaO) which is the primary element of cement. These carbon dioxide emissions are unavoidable when producing limestone-based cement [9].

Cement milling and dispatch

Portland cement is then produced by grinding 95% clinker with 5% gypsum to produce a fine powder [8] [10]. The cement can then be packaged and dispatched in bags or in bulk quantities.

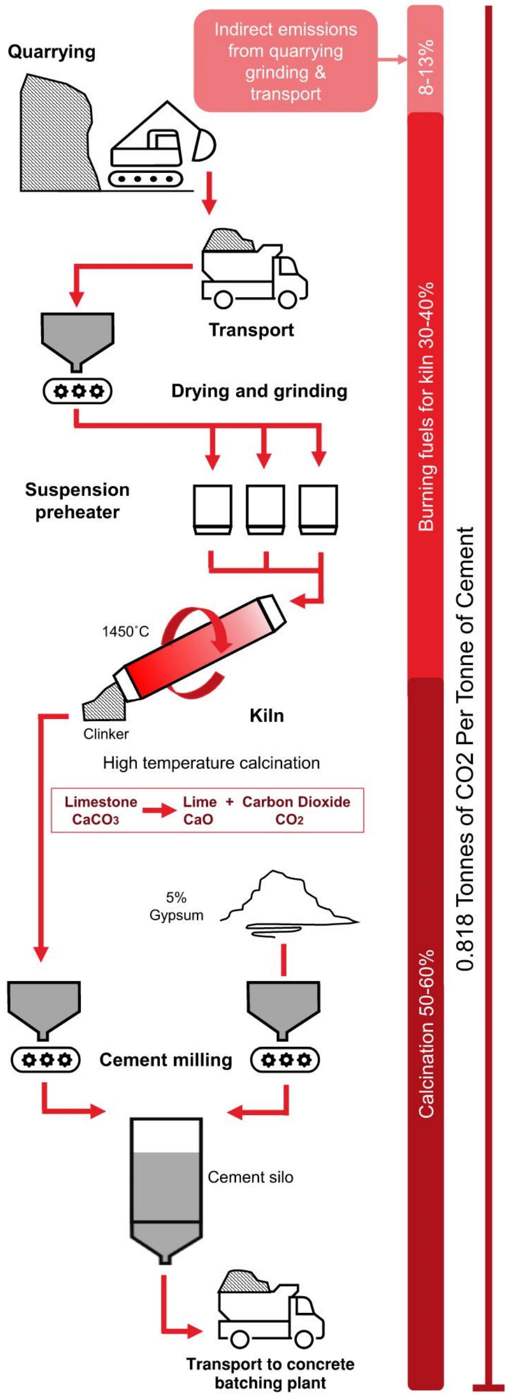

Figure 4
Carbon emissions produced in the manufacture of cement.

Supplementary cementitious materials

Supplementary cementitious materials (SCMs) are often the by-products of other industries, replacing the high carbon Portland cement clinker. Alternatively, they can be used directly in the clinker manufacturing process to reduce the need for virgin materials, and can contribute to large CO_2 reductions in the production of cement and concrete [11] [12].

Some common SCMs include Ground Granulated Blast Furnace Slag (GGBS - a by-product of the iron making industry), Pulverised Fuel Ash (PFA or 'fly ash', a by-product of the combustion of coal) and silica fume (by-product from silicon alloy production) [13]. Structural concrete can maintain acceptable design performance whilst substituting over 50% of Portland cement for SCMs. However, global supplies are currently limited to 10-15% of cement usage today. Due to the finite supplies, if SCMs are locally specified above and beyond the global availability, this will limit the overall supply worldwide [12]. Additions have an optimal proportion before there is a significant effect on concrete strength. For GGBS, this is 50-55% and so increasing the proportion much beyond this will result in a much higher total binder content (lower w/c ratio) for equal strength. This negates some of the carbon saving that was intended by increasing the proportion of GGBS.

The industry is searching for new sources of SCMs [11]. Figure 5 shows supply and demand of commonly used SCMs.

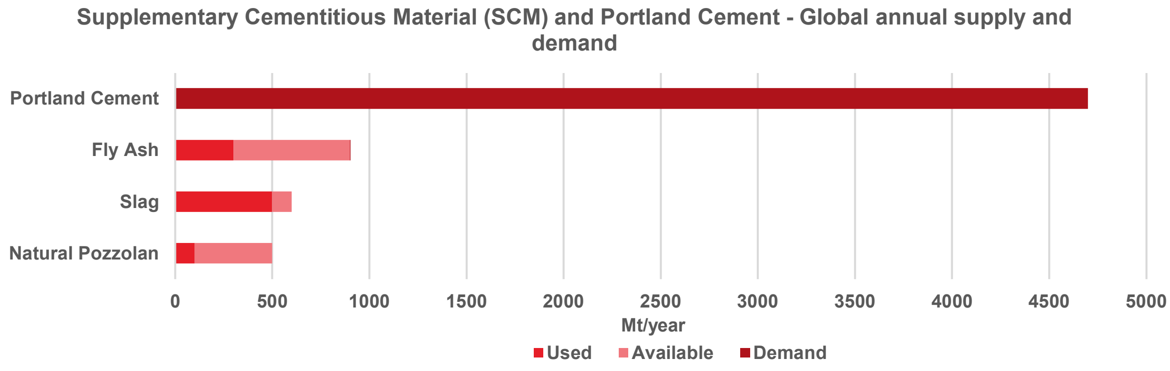

Figure 5
Supply and demand of commonly used supplementary cementitious materials and Portland cement [10].

Understanding the data for SCMs is an important step towards reducing the embodied carbon content of concrete. Table 2 lists the A1-A3 embodied carbon emissions of cement and other cementitious materials alongside relevant information on non-standard technologies, such as alkali-activated materials and carbon sequestering technologies, for comparative purposes. However, it is noted that these technologies are not currently commonly used in construction but may become increasingly popular in the next decade.

Table 2
A1-A3 embodied carbon emissions of cement and cementitious materials [2] [14].

Material / constituent	Remarks	Carbon factor [kgCO_2e/tonne]	Availability
CEM I	Typical Portland cement used in concrete production	818 - 860 [14]	Wide
GGBS	Widely used in concrete; up to 70-75% replacement. Up to 90% in certain applications	42-70 [14] This does not include economic allocation.*	Short-term. Note that this is subject to change once economic allocation is incorporated throughout industry so could be up to 200 kgCO_2e/tonne.
Fly ash	Widely used in concrete; up to 35% replacement. Up to 55% in certain applications	4 [2] This does not include economic allocation.*	Very limited in the UK. Note that this is subject to change once economic allocation is incorporated throughout industry so could be up to 200 kgCO_2e/tonne.
Silica fume	Used in special applications; mainly in high strength and sprayed concrete applications. Up to 10-15% replacement.	28 [14]	Limited
Metakaolin	Rarely used in concrete; mainly in high strength concrete applications where available. Up to 15-20%.	150-470 [14]	Very limited to none in the UK
Natural Pozzolans (e.g., volcanic ashes, trass)	Used in other countries; up to 35% replacement. Up to 55% replacement in special cases.	Exact value unknown but normally low (<50) [14]	Very limited in the UK. Exploration required

Calcined Natural Pozzolans (e.g., calcined clay, LC3)	Not generally used; up to 35% replacement. Up to 55% replacement in special cases.	Approx. 300 - 500 depending on raw material and production methods [14]	Not currently produced in the UK or Europe but used in large scale UK infrastructure projects.
Limestone fines	Widely used as filler and has the potential to be regarded as SCM in the UK; up to 25% replacement.	75 [2]	Widely used. Not so much in the UK as SCMs but industry is changing.
Alkali activated materials / "Geopolymers"	Portland cement free materials which utilise GGBS and fly ash together with chemical activators to produce concrete. Currently not included in standards but covered by PAS 8820.	50-400 [14]	Somewhat in the UK; short-term. Inconsistent material behaviour.
Carbon sequestering technologies	Cementitious materials manufactured with sequestered CO_2	Highly variable – from carbon negative, to 700	Under development in the UK (Concrete4Change, Seratech) Note that carbon negativity is a controversial issue as it depends on the source of CO_2 used. It difficult to claim carbon negativity when using commercial CO_2 from methane reforming. If CO_2 from a cement plant is used, then there is a high risk of double counting if both the cement plant and the downstream user of the CO_2 claim the benefit of CO_2 capture and sequestration.

* economic allocation refers to the levels of responsibility at economy or firm level.

GGBS and fly ash are by-products created from other industries; When assessing the embodied carbon of structures, it is important that this carbon is calculated correctly. It is often tempting to take the highest possible GGBS content (up to 70%) to lower embodied carbon in our design calculations – however, due to the finite supplies of this material globally, increasing this content on one project *may* reduce the potential for another building to do the same.

The carbon associated with internationally traded recovered resources currently stands behind a 'double-blind' system of accounting: emissions do not register in the conventional territorial accounts of the importing country and could be hidden from its consumption-based accounts too. The impacts of such trade and related carbon accounting conventions are unclear, and we emphasise the need for further investigation.

A2 – Transport

Module A2 includes the carbon emissions attributed to the transport of concrete constituent materials from their source or factories to the concrete batching plants. Globally, the raw materials used to make concrete are typically abundant and locally supplied, making the transportation emissions of concrete minimal [15]. The type of transport mode used to move the different constituents of concrete will depend on the location of the mines and quarries, processing facilities, and batching plants, but they are usually transported via road or rail.

Portland cement

Portland cement is transported from the cement factories, often located near the quarries where the raw materials are extracted, to various batching plants which are situated near towns or cities with the need for concrete manufacture. It is worth noting that the UK currently imports around 20% of required cement.

Cement is also being traded globally and transported around the world. Vietnam and Türkiye are the biggest cement exporters, with 13% and 10% respectively of shares in world exports of cement in 2021. The United States and China are the biggest cement importing countries, accounting for 12% and 10% of global cement import in 2021 respectively [16]. Table 3 shows the largest importing and exporting countries of cement and cement clinkers.

Table 3
Export and import of cement, including cement clinkers [16].

Exporting country	Share in world exports (2021)
Vietnam, Türkiye	10-20%
USA, Canada, Mexico, Algeria, Spain, China	1-5%
Russia, Australia, UK, Brazil, India	0-1%

Importing country	Share in world imports (2021)
USA, China	10-20%
Australia, Canada Peru, France, Germany	1-5%
Russia, UK, Brazil, Türkiye, Mexico, Algeria, Spain, India	0-1%

Supplementary cementitious materials

SCMs are often transported from the point of manufacture (from the steel or coal industry) directly to the concrete batching plants. This is beneficial, especially for GGBS where the range of substitution may vary significantly, so the materials can be transported directly to the concrete batching plant without having to go to a cement plant first [17]. The extent of opportunities to use lower-carbon concrete mixes can often be dictated by the materials available to local batching plants. It may be carbon effective to import cement substitutes from further afield depending on their impact on the concrete when the A2 emissions have been taken into consideration [10].

Aggregates (fine and coarse)

Both coarse and fine aggregates are traded globally, but with relatively shorter transportation distances compared to cement products. Aggregates are usually locally or regionally sourced and therefore low transport emissions are expected. By identifying specific aggregates, this may impact sourcing and therefore increase the embodied carbon [18]. Table 4 shows comparative CO_2e for virgin and recycled aggregates travelling different distances.

Table 4
Comparative CO_2e for virgin and recycled aggregates [18].

Material and delivery distance	Cradle to gate kg CO_2/tonne	Transport kg CO_2/tonne	Total kg CO_2/tonne	+/- % CO_2
		Virgin aggregates		
+58.5 km (delivery and return distance by road)	6.6	2.7	9.3	-
		Recycled C&D* aggregates compared to the use of virgin aggregates		
Used on-site, 0 km transport	2 - 7.9	0.0	7.9	- 15 %
+ 5 km (delivery and return distance by road)	2 -7.9	0.5	8.4	- 10 %
+ 10 km (delivery and return distance by road)	2 - 7.9	0.9	8.8	- 5 %
+ 15 km (delivery and return distance by road)	2 - 7.9	1.4	9.3	0 %
+ 20 km (delivery and return distance by road)	2 - 7.9	1.8	9.7	5 %
+58.5 km (delivery and return distance by road)	2 - 7.9	2.7	10.6	14 %

In the UK, the average journey of raw materials to a concrete batching plant is around 54km [2]. This may vary in locations around the world where there is a higher demand than local availability. In large cities or hard to reach areas, materials are brought in via rail or ships and vehicles will be used to transport aggregates and cement to site for the last few miles [2].

At early design stages, the concrete specifications may not have been decided; However, depending on the project location, there should be sufficient information to understand if concrete can be supplied locally. The distance from the quarries and factories to the concrete batching plants are most likely to be local or national. Table 5 shows the carbon emissions produced for local, national, regional and global concrete ingredients.

Table 5
Transportation CO_2e values.

Location of Mill compared to the site	Carbon Emissions $kgCO_2e/kg$	Assumption
Local <50km	0.005	Transported 50km by road
National <300km	0.032	Transported 300km by road
Regional <1500km	0.161	Transported 1500km by road
Global >1500km	0.183	Transported mostly (10,000 km) by sea and then 200km by road

The embodied carbon that is typically released through burning fossil fuels for transport varies from country to country. The transport industry is aiming to decarbonise with the electrification of railways and development of hydrogen powered heavy goods vehicles (HGVs).

A3 – Manufacturing

Module A3 includes the carbon emissions of the manufacture of concrete which is also described as the "batching" of concrete. The individual components of concrete are stored at the batching plant in bins and silos. They are weighed and then mixed in either a plant mixer or truck mixer, then transported to site. This process is mainly fuelled by electricity or diesel depending on the batching facility and this is the main contributor to CO_2 emissions during this stage [4]. Admixtures are added at this stage. Table 6 shows carbon emissions produced in the A3 stages to batch concrete per kg in-situ and precast.

Table 6
A3 manufacturing process – batching plants [ICE database].

Item	Carbon Emissions $kgCO_2e$ at A3
Concrete batching energy, per kg concrete	0.0007
Concrete precast, per kg precast	0.0142

A4 – Transport

The batching of concrete is done in many locations positioned around cities and towns to ensure minimal transport times. The A4 emissions associated with transporting the concrete from the batching plant to the final site contribute relatively small amounts of CO_2 to the total A1-A5 emissions [4].

In-situ concrete is most commonly transported to site in a concrete mixer. This allows for concrete to be batched and pre-mixed ready for use on site immediately. Due to the restricted setting times of concrete, this limits how far away the batching plants can be from the site; Hence, they are usually relatively close to the site. For example, in-situ concrete in the UK travels on average 16km from batching plant to site. Batched concrete is transported to site in wagons fuelled by diesel.

Alternative methods of transport can vary due to project requirements. A volumetric mixer is a mobile batching plant which transports the ingredients of concrete to site, mixing it on the way, or once the vehicle has arrived on site. This is a useful transportation method on projects where different types of concrete are needed in small volumes.

A5 – Site construction

Module A5 includes carbon emissions of construction related activities associated with placing concrete on site. This includes the emissions from the equipment used for installation, and the emissions associated with the waste material. A5 typically accounts for approximately 14% of the A1-A5 carbon emissions of in-situ concrete, however this value can vary [6].

Placing concrete activity

Placing concrete on site requires the use of fuel for activities such as pumping or skipping concrete to its destination, and vibration for compacting and finishing. The emissions factors for onsite placement activities can be assumed as $0.0090tCO_2e/m^3$ [4].

Formwork

Timber formwork (generally 18mm plywood) is a flexible solution which is commonly used to shutter concrete on site. The embodied carbon is significantly affected by the reuse rate and End of Life (EoL) scenario, aspects which can be difficult to determine in the earlier stages of a project. Due to the short service life of timber formwork, it would be inappropriate to include the benefit of sequestration within embodied carbon calculations as the carbon is only stored in the short term.

RICS guidance assumes that, in the absence of project specific information, plywood formwork is re-used three times before being incinerated [19]. Information from contractors suggests that this may not reflect the reality, with a lot of plywood formwork being used just once. Plain and special finish concrete can result in a single use ply, as remnants remaining on the sheet make it unsuitable for further pours. Ordinary finish concrete makes allowances for small defects, hence timber plywood can often be reused multiple times.

Plywood formwork may get reused on site in a different role, such as for fencing, but this can vary project to project and will still result in new formwork being required for further pours. How the ply is recycled/reused is down to the supply chain.

It is important that engineers engage early with architects and contractors to discuss the benefits of specifying a lower grade finish, changing formwork reuse rates, and alternative formwork types.

Waste

The volume of site waste and the associated carbon emissions, varies depending on the processes used by the contractor. Global waste values are typically 1-6%, but can sometimes reach as much as 13% due to overordering of concrete as a precaution. Additional elements to enable the concrete pour should also be taken into consideration such as concrete blinding, temporary works including timber formwork and falsework [20]. Table 7 shows the associated waste ratios and waste factors for several concrete products [20].

Table 7
Waste ratios and factors for in-situ/precast concrete and formwork.

Material/product	Waste ratio (WR)	Waste factor (WF)
Concrete in situ	5%	0.053
Concrete precast (beams and frames)	5%	0.053
Timber formwork	10%	0.111

Stage B

B1 Use - Carbonation and CO_2 sequestration

Concrete and mortar containing cementitious materials absorb CO_2 if their surface is exposed to air. This natural process is called carbonation. Carbonation can have positive effects on the strength of concrete; however, it significantly lowers the alkalinity, and thus may have adverse effects such as corrosion of embedded steel. Reinforcement cover and mix design are designed to limit this [19] [21]. The amount of carbonation during the life of a structure is estimated to be up to 2.5% reabsorption of the CO_2e emitted in stages A1-A3 (so comparatively, a small value). [13]

B2 & B3 maintenance and repair

There can be high emissions related to maintenance and repair of concrete structures during their lifetime, but this will vary on a case-by-case basis; Therefore, there is currently little information available to advise on carbon factors for maintenance and repair for concrete due to these variations.

Stage C

Stage C includes the emissions associated with demolishing and removing concrete components from a building.

Global figures on the waste and disposal of concrete are not readily available and are expected to be highly variable from country to country as well as from region to region. Many different factors contribute to these variations such as local laws and regulations for landfilling of demolition waste and the access to virgin aggregates. Often there are incentives or penalties and therefore there may be increased interest in recycling concrete as aggregate, rather than letting the material go to landfill. High recycling rates are reported in the Netherlands, UK and Japan [22]. Concrete waste can also be used as an Alternative Raw Material (ARM) or Mineral Component (MIC) in the manufacture of new cement, but this is still under development.

Stage D

Circular economy

For concrete this could be re-using concrete by crushing for aggregate, cutting it up into smaller blocks, or more effectively, re-using structural elements, allowing for maximum use before being recycled or replaced [23]. Carbon could be saved by extending a concrete frame's life; however, this is project-specific and needs to be calculated on a case-by-case basis. Designing for deconstruction with concrete is difficult, so the future use of buildings needs to be considered at the outset of a project. [23].

Recycled aggregate

Recovered concrete can be recycled as aggregate in new concrete, but the quantities may be limited by local regulations and physical properties, especially for structural concrete applications. Regardless, in some situations crushed and reused concrete can often be better than virgin aggregates [24]. It is important to only specify recycled aggregates when there is a local source available, otherwise transportation emissions may outweigh the intended carbon benefits [18]. Additionally, depending on the type of recycled or secondary aggregates, there may be increased water demand and a need to increase the cement content of the concrete to achieve the specified characteristic strength, with a consequential increase in eCO_2.

The potential for CO_2 uptake during the demolition, crushing and waste handling stages is relatively larger than the B1 stage due to the increased surface area of concrete, however it is still only a small percentage of the overall carbon impact [19] [21]. It has been claimed that if a concrete element is crushed and left on site for 26 weeks before being moved, it can reabsorb up to 5% of the original A1-A3 emissions carbon produced [13].

Route to Net Zero

There is no global solution to eliminate the embodied carbon of cement and concrete, but there are several different approaches for reducing these emissions on our projects. As designers we have a huge impact, and it is our responsibility to recognise and support parts of the supply chain that are looking to make technological advancements to improve the emissions of the cement and concrete industries. Figure 6 shows the projected pathway to net-zero for the cement and concrete industry and all the component contributions required to achieve net zero. For more information on the route to net zero for concrete, refer to the "GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete" [25]. Published routes for the decarbonisation of concrete heavily rely on the use of carbon capture and storage. Without the investment and rapid development of these technologies, the routes to net zero for concrete may never be realised.

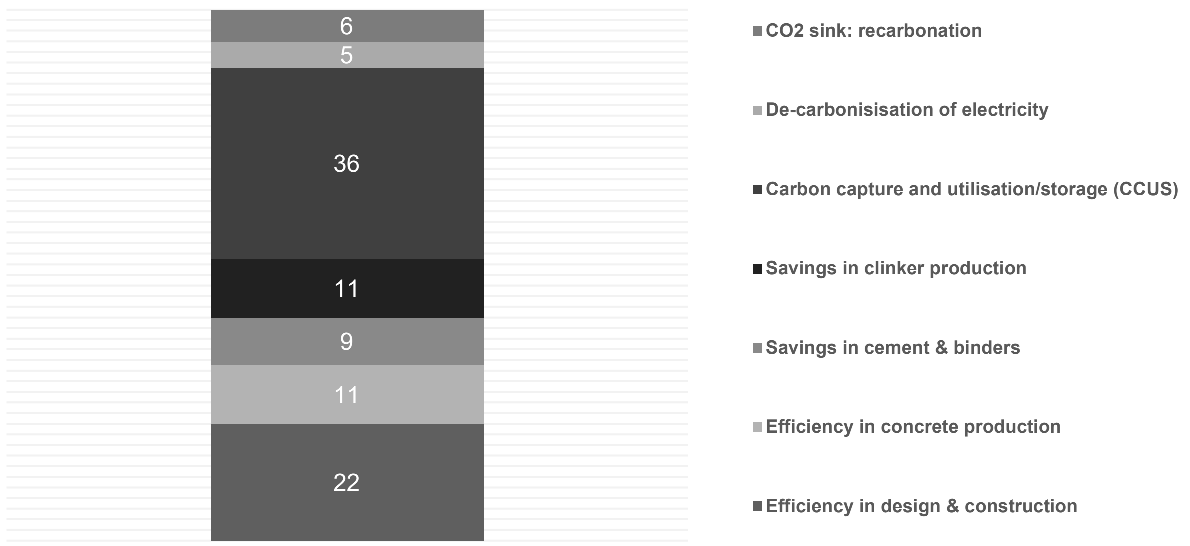

Figure 6
Projected pathway to net-zero for the cement and concrete industry and the different contributors to achieve net-zero before 2050 [25].

Efficiency in design

According to the GCCA 2050 Cement and Concrete Industry Roadmap for Net-Zero Concrete, 'Efficiency in design and construction' is the second largest area that will impact achieving net-zero carbon emissions by 2050. As designers, we can lower our carbon impact by:

Using less: Design with the minimal amount of concrete required by revising assumptions which are often conservative; Aiming to have maximum utilisation can also be beneficial [26]. Using less can have the biggest cost and carbon savings on a project!

Specifying concrete more effectively: Reduce the use of CEM I/Portland cement where possible, specify appropriate concrete grade, allow the use of alternative aggregates and admixtures within concrete [27]. This includes precast elements.

Benchmarking concrete: Establishing carbon benchmarks for concrete is important to classify concrete by embodied carbon. There is ongoing work around this; However, this will require cross-industry support to standardise the measuring, reporting and benchmarking of emissions produced by different concrete mixes [10].

Design for the future**:** If future changes are anticipated, trying to delay the need for any replacement/major refurbishment can have significant long term carbon reduction [26]. Also, circular economy principles should be incorporated into the design and detail for easy disassembly and re-use at end of life. We should also be designing to make maintenance and repair easier.

Reusing and refurbishing: Where possible, reusing concrete structures in-situ can have huge cost, programme and carbon benefits. Where concrete structures cannot be reused, circular economy principles can be implemented to maximise carbon benefits [26].

Offsite prefabrication: By exploring alternative methods such as off-site manufacture, this may have multiple benefits including a potential decrease in carbon emissions (due to less wastage).

Generally, the concrete strength used for precast concrete is higher than for ready-mix concrete. Additionally, the use of supplementary cementitious materials is traditionally limited, because replacing CEM I slows down the curing process. The commercial principle in the precast factory often relies on a quick re-use of moulds, so the precast elements need to cure quickly; Supplementary cementitious materials are more widely used for in-situ concrete. Precast and prefabrication components are standardized for manufacture and can have more mass (and emissions) that in-situ to accommodate production efficiencies against material costs. Precast concrete elements may use more carbon intensive mixes and therefore a carbon comparison in the context of the market and suppliers will be necessary for holistic understanding.

References

[1] Global Cement and Concrete Association, “Cement and concrete around the world,” [Online]. Available: https://gccassociation.org/concretefuture/cement-concrete-around-the-world/. [Accessed 06 June 2023].

[2] The Concrete Center, “Whole-Life Carbon and Buildings,” MPA The Concrete Centre 2016, 2016.

[3] E. Sentucq and M. Clayton, “Beyond Portland cement: Low-carbon alternatives,” The Institution of Structural Engineers.

[4] A. Nazari and J. G. Sanjayan, “Handbook of Low Carbon Concrete,” 2017.

[5] Fragkoulis Kanavaris (Arup), Karen Scrivener (EPFL), “The confused world of low-carbon concrete,” *Concrete Magazine,* vol. 57, no. 3, pp. 36-39, 2023.

[6] P. Astle, “How can we reduce the embodied carbon of structural concrete?,” The Institute of Structural Engineers, 2021.

[7] OCO Technology, “Sustainable Construction Products,” 2023. [Online]. Available: https://oco.co.uk/sustainable-construction-products/. [Accessed June 2023].

[8] Low Carbon Materials, “OSTO - Carbon negative lightweight aggregate for carbon zero blockwork,” 2022. [Online]. Available: https://www.lowcarbonmaterials.com/products. [Accessed June 2023].

[9] “Sustainable concrete: Admixtures,” The Concrete Centre, [Online]. Available: https://www.sustainableconcrete.org.uk/Sustainable-Concrete/What-is-Concrete/Admixtures.aspx.

[10] ICE, “Low Carbon Concrete Routemap,” 2022.

[11] K. Scrivener, F. Martirena, S. Bishnoi and S. Maity, “Calcined clay limestone cements,” in *Cement and Concrete Research*, 2018.

[12] World Business Council for Sustainable Development, “Net-zero buildings: Halving construction emissions today,” 2023.

[13] The Institution of Structural Engineers, “How to Calculate Embodied Carbon,” 2020.

[14] Arup, “Low Carbon Concrete: Practical guidance for Arup engineers,” 2019.

[15] Global Cement and Concrete Association, “Availability: Abundant, Local and Cost-effective,” [Online]. Available: https://gccassociation.org/sustainability-benefits-of-concrete/availability/.

[16] International Trade Centre, “Trade Map,” International Trade Centre, [Online]. Available: https://www.trademap.org/Index.aspx. [Accessed Jan 2023].

[17] Concrete Society Working Party, “Cementitious materials,” The Concrete Society, 2011.

[18] The Concrete Centre, “Specifying Sustainable Concrete - Understanding the role of constituent materials,” www.concretecentre.com/publications, 2021.

[19] The Institute of Chartered Surveyors, “Whole life carbon assessment for the built environment,” 2017.

[20] The Institute of Structural Engineers , “How to Calculate Embodied Carbon,” 2020.

[21] O'Donoghue, “Carbonation,” The Concrete Society, 2019.

[22] Global Cement and Concrete Association, “Circular Economy,” 2023. [Online]. Available: https://gccassociation.org/sustainability-benefits-of-concrete/circular-economy/.

[23] The Concrete Centre, “Concrete futures: How concrete is evolving for a net-zero built environment”.

[24] The Cement Sustainibility Initiative (CSI), “Recycling Concrete,” 2009.

[25] Global Cement and Concrete Assosiation, “Concrete future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete,” October 2021. [Online].

[26] M. Moynihan, “Steel, concrete and climate change,” The Institution of Structural Engineers, 2019.

[27] J. Burridge, “How to specify lower carbon concrete,” The Institution of Structural Engineers, 2020.

[28] Esri, “Ecosystem Science for Global Restoration,” in *2018 Esri User Conference Plenary*, 2018.

[29] Price & Myers, “Avoiding false accounting - why correct carbon factors matter,” 2021.

[30] Z. P. V. I. B. Millward-Hopkins, “Resource recovery and low carbon transitions: The hidden impacts of substituting cement with imported ‘waste’ materials from coal and steel production,” Elsevier/Global Environmental Change, 2018.

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