UK GHG Inventory Improvement: Carbonation of Concrete Emissions Sink Modelling

BEIS Tender Reference CR21048

Prepared by the Mineral Products Association
for the Department of Energy Security and Net Zero (formerly BEIS)

Department for Energy Security & Net Zero

mpa UK Concrete

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1. List of abbreviation/Glossary

AD	Activity data: the annual amount of an activity that leads to a GHG emissions source or sink (IPCC)
BEIS	Former Government Department for Business, Energy and Industrial Strategy
BRMCA	British Ready-Mixed Concrete Association: part of the Mineral Products Association (MPA) which represents the interests of UK ready-mixed concrete producers
Carbonation front	Boundary between carbonated and non-carbonated volumes in concrete
Carbonation rate *(k)*	Rate at which the carbonation front progresses from the surface of the concrete
C&DW	Construction and demolition waste
CEM	Prefix in defined notation for cements and cement combinations in BS 8500
CEN	European Committee for Standardization: association of the national standardisation bodies of 34 European countries, which provides a platform for the development of European standards and other technical documents in relation to various kinds of products, materials, services and processes
Degree of carbonation (D_c)	Percentage of CO_2 absorbed compared to the theoretical maximum, in carbonated concrete
Depth of carbonation *(d)*	Depth from the surface to which concrete has carbonated, calculated as $d = k\sqrt{t}$, where t is the time in years
EF	Emissions factor: the emission/sink of a GHG per unit activity (IPCC). Within this project refers to the emissions sink factor, that is, the CO_2 uptake by carbonation per unit of concrete
EPD	Environmental product declaration: independently verified life cycle assessment of the environmental performance of a product
Fly ash	A by-product of coal-fired power generation used as a cement SCM: previously known as pulverised fly ash (PFA)
GGBS	Ground granulated blast-furnace slag: a by-product from the blast furnaces used to make iron, used as a cement SCM
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory: see also NIR
GIFA	Gross internal floor area of a building
IPCC	The Intergovernmental Panel on Climate Change: the United Nations body for assessing the science related to climate change

IPCC EFDB	IPCC emission factor database: IPCC database of EFs and parameters that can be used for estimation of national GHG emissions/removals, contains default data from IPCC guidelines and data from other sources (for example peer-reviewed papers) with background information
IPCC TFI	IPCC Task Force on National Greenhouse Gas Inventories: develops an internationally agreed methodology for the reporting of national GHG emissions and removals and encourages its use by IPCC participants and UNFCCC signatories
LCA	Life cycle assessment: analysis, following standardised methodology, of the potential environmental impacts of products or services during their entire life cycle
MPA Precast	Part of the Mineral Products Association (MPA) representing UK precast concrete manufacturers and members of the supply chain
NFDC	National Federation of Demolition Contractors
NIR	National inventory report: national report of annual estimates of all GHG emissions from the baseline year 1990 submitted annually to the UNFCCC
Portland cement	The most common form of cement used for general purposes: Portland cement is manufactured by firing a mixture of limestone or chalk with clay or shale, then grinding the resulting clinker to a fine dust
RCA	Recycled concrete aggregate: crushed concrete deriving from crushing C&DW
SCM	Secondary cementitious material: materials that may be used as part of cements, including fly ash, GGBS, limestone, silica fume, natural pozzolana and natural calcined pozzolana. When added at the concrete mixing plant such SCMs are referred to as 'cementitious additions' as they are added to high clinker CEM I or CEM II/A cements. Fly ash and GGBS are most used in the UK. May also be referred to as supplementary cementitious material
Service life	The [expected or predicted] time period from installation during which a building or infrastructure construction, or its parts, meet or exceed its performance requirements
UNFCCC	United Nations Framework Convention on Climate Change: United Nations entity tasked with supporting the global response to the threat of climate change

2. Executive summary

As the binder in concrete and products such as mortar, Portland cement is one of mankind's most widely used materials. Portland cement clinker is made by heating limestone with clay or shale to very high temperatures. 'Calcination' breaks down the limestone into calcium oxide, the key ingredient of cement, and carbon dioxide, CO_2. The cement clinker is ground with gypsum and other materials to make cement. In 2020 in the UK, direct emissions from cement production were 5.81Mt CO_2; 3.90Mt CO_2 due to the calcination reaction and the remaining 1.91Mt CO_2 from combustion of fuels within the cement kiln.

'Recarbonation', or carbonation, describes how concrete and other cement-containing products naturally reabsorb and permanently store CO_2 during their life, in effect reversing the calcination reaction. Carbonation is scientifically well established and has been recognised by the Intergovernmental Panel on Climate Change (IPCC)[1] (AR6, Chapter 5) as an important carbon emissions sink. Construction industry product standards[2,3] for life cycle assessment (LCA) and environmental product declarations (EPDs) include established methodologies for calculating concrete carbonation. However, there is currently no IPCC method for calculating national estimates of the carbonation sink in greenhouse gas (GHG) national inventory reports (NIR). In 2018, IVL Swedish Environmental Institute[4,5] proposed methodologies at three tiers of increasing complexity – in line with IPCC requirements. Sweden first included a Tier 1 calculation of the carbonation concrete emissions sink – 297 ktonne CO_2 in Sweden in 2018 – in its 2020 NIR submission[6].

In 2021, the Mineral Products Association (MPA), leading a consortium including Ricardo (the UK's GHG inventory agency) and other experts, were commissioned to develop a UK-specific model, at IVL Tier 2 (or above), to calculate the UK emissions sink from carbonation of concrete for consideration by the Department of Energy Security and Net Zero (formerly BEIS) for inclusion in the UK NIR.

MPA commissioned an independent literature review from Dr Phil Renforth of Heriot-Watt University, which concluded that, the IVL Tier 2 methodology, based on the British Standard EN 16757, would provide a robust method for calculating the CO_2 uptake due to carbonation of concrete and mortar during their primary use service life. However, the CO_2 uptake values for end-of-life and secondary use of concrete suggested by IVL are not suitable for a national GHG inventory calculation. A UK-specific end-of-life carbonation model should be developed. The literature review also highlighted the limitations of the EN 16757 carbonation calculation, and the need for further UK-based experimental research, acknowledging that this was beyond the current project scope.

To develop a Tier 2 concrete carbonation model for the UK, annual concrete consumption must be disaggregated into at least five primary use concrete applications covering 65% or more of national cement consumption. Appropriate, publicly available, and reliable annual UK-specific activity data for input into the model must be identified. Construction output data from the Office for National Statistics (ONS) encompasses activity across the construction industry, at the required level of sub-sector disaggregation, and so is used in the model as a proxy for the bottom-up distribution of cement and concrete consumption between primary uses. Further top-down activity data comes from MPA cement and mortar production statistics.

Informed by expert opinion and a targeted market survey, five primary use applications, which reflect the stratification of activity data across specific sub-sectors of the construction industry, and cover 80-90% of the UK cement market, were selected:

- Buildings of steel composite frame construction type, for example, offices and other commercial buildings
- Buildings of concrete-frame construction type, for example, high-rise residential
- Buildings of masonry construction type, for example, low-rise residential
- Infrastructure projects
- Mortar and merchant sales of bagged cement.

For each of these primary use applications, a typical UK-specific building/infrastructure prototype was identified, and a CO_2 emissions sink factor (EF) calculated. Crucially, the model re-adjusts the annual distribution of concrete between applications to ensure consistency between top-down cement production and bottom-up concrete consumption. The adjusted activity data for each application is then multiplied by the EF to calculate the carbon sink.

MPA also developed a UK-specific model for end-of-life and secondary use concrete. Annual activity data is taken from Department for Environment, Food and Rural Affairs (Defra) construction and demolition waste (C&DW) statistics. In the UK, over 90% of C&DW is recovered, and 95% of concrete C&DW crushed and recycled into groundworks. Where carbonation is incomplete, crushing accelerates the process by greatly increasing the exposed surface area of concrete.

In line with IPCC guidance, MPA and Ricardo analysed the model uncertainty, taking into account the very significant uncertainties associated with the model outputs due to:

- the limited scientific evidence base for the rate and completeness of carbonation in concrete, notably the degree of carbonation behind the carbonation front
- scarce activity data specific to primary use applications for concrete as well as for recovered concrete in the UK; hence numerous assumptions are applied within the model, for example, the use of ONS economic data as a proxy for concrete consumption
- the primary use EFs are calculated from typical UK case studies. However, construction methods and concrete mixes have evolved over time and will vary within each application.

For concrete carbonation in the UK in 2020, the estimated total emissions sink, and overall uncertainty is 1.548 Mt CO_2 ±34% or 0.4% of the UK's total GHG emissions. Concrete in primary use absorbed 0.862Mt CO_2; end-of-life and secondary use concrete 0.686Mt CO_2.

For 1990-2020, the estimated CO_2 sink from concrete in primary use varies between 14% and 20% of the annual UK cement calcination emissions (on a consumption basis). This is consistent with IVL's Tier 1 estimate, that the annual primary use sink equals 20% of calcination emissions. For end-of-life and secondary use concrete, the sink varies between 9% and 16% of calcination emissions (on a consumption basis) - higher than the IVL Tier 1 value of 3%, but lower than the maximum 110kg CO_2/m^3 concrete suggested by IVL. The end-of-life/secondary use CO_2 sink is consistent with the range of values in the studies reviewed by IVL, and higher recovery and recycling rates in the UK. The greatest contribution to the model uncertainty also comes from the end-of-life/secondary use.

A UK-specific, Tier 2 model of the concrete carbonation CO_2 emissions sink has been developed for the first time, based on the IVL methodology and using the best available UK data combined with the expert knowledge of the project team. The model design is deliberately flexible, to facilitate future improvement, for example, the primary use applications can easily be further disaggregated to create a Tier 3 model. High priorities to reduce the uncertainty in the model include:

- Improvement of the quality of the bottom-up activity data, with a view to further disaggregation – especially for the diverse infrastructure sector
- More experimental data on the rate and degree of carbonation within higher strength (>50MPa) concretes, being specified for large bespoke infrastructure applications such as the HS2 rail link and the new nuclear power station at Hinkley Point C
- More experimental data on the rate and degree of carbonation within UK concretes for end-of-life and secondary use concrete.

Wider implications for consideration include:

- Incorporation of the carbonation sink within the next UK NIR, and into other UK GHG evidence and reporting systems, such as carbon budgets
- International collaboration/knowledge exchange to help other countries develop similar models, for example, with the IPCC TFI Technical Support Unit and emission factors database (IPCC EFDB) panel
- Maximising the permanent carbon sink potential of concrete by encouraging and incentivising optimal practices in concrete demolition, end-of-life, and reuse, and by R&D and scaling up of industrial enhanced carbonation technologies, for example, CO_2 curing of concrete products.

3. Introduction

3.1. Aims and objectives

The science of recarbonation, or carbonation, the natural reversal of the calcination reaction in the cement production process, is well established. Carbonation of concrete is recognised by the IPCC in its Sixth Assessment Report[1] (AR6 WG1, The Physical Science Basis, Chapter 5) as an important carbon emissions sink and included in analysis such as the Global Carbon Budget[7] for the first time in 2020.

There is currently no IPCC method for the calculation of national estimates of the carbon sink from carbonation of concrete. The 2006 IPCC guidelines for national CO_2 inventories[2] (Section 2.2.1.4 in the report) from cement production suggest that carbonation *"may become relevant for consideration in the future"* and that *"This is an area for future work before inclusion into national inventories"*. Carbonation was considered in the screening phase of the 2019 Refinement (IPPU Volume[9]) but not taken forward.

However, across the construction industry, methodologies for calculating the carbonation of concrete products have already been developed and included in the product standard, EN 16757[3], for life cycle assessment and environmental product declarations. The European Committee for Standardization, CEN, has also prepared a more detailed technical report, PD CEN/TR 17310:2019[4], on carbonation and CO_2 uptake in concrete.

Methodologies to calculate carbonation for inclusion in national GHG inventories have now also been developed by IVL Swedish Environmental Institute[4,5,10]. Sweden first included a Tier 1 calculation of the concrete carbonation emissions sink as a memo item in its 2020 NIR submission[6] to the UNFCCC. The carbonation emissions sink was calculated as 297 ktonne CO_2 in Sweden in 2018.

The MPA, in association with Ricardo and other subcontractors, has developed a UK-specific Tier 2 model to calculate the carbonation of concrete emissions sink for consideration by the Department of Energy Security and Net Zero (formerly BEIS) for future inclusion in the UK NIR.

3.2. Portland cement*

Portland cement is one of mankind's most widely used materials, as the binder in concrete and other products such as mortar. Portland cement is made by heating a mixture of limestone or chalk, blended with clay or shale, to temperatures of about 1450°C in a rotary kiln in order to produce cement clinker. The calcium carbonate ($CaCO_3$) in the limestone or chalk decomposes into free lime and carbon dioxide, in a reaction known as 'calcination'. The cement clinker is ground, with up to 5% gypsum and up to 4% minor additional constituents (MAC), to create Portland cement, or CEM I. CEM I may be further mixed with secondary cementitious materials (SCMs), such as limestone, fly ash or ground granulated blast-furnace slag (GGBS), either at the cement factory or at the concrete plant.

There are two main sources of CO_2 emissions from cement manufacture: first, the combustion of fossil-based fuels in the kiln, and second, the calcination or process emissions from the chemical decomposition of calcium carbonate into free lime and CO_2. In national GHG inventories, these are reported in the respective categories:

- 1A2f Stationary combustion in manufacturing industries and construction: Non-metallic minerals – GHG emissions from fuel combustion in cement kiln
- 2A1 Cement production – GHG emissions from calcination of non-fuel feedstocks.

Fuel combustion accounts for 33% of the total CO_2 emissions; calcination for the remaining 67%.

* The current project is restricted to Portland cement and excludes other more specialist cement types, such as calcium aluminate cements.

3.3. Recarbonation

Concrete, and other products containing Portland cement such as mortar, naturally absorbs CO_2 from the atmosphere to form carbonates. This process is known as recarbonation, or simply 'carbonation'. While the underlying chemistry is complex (Appendix A7.4), conceptually carbonation can be understood as the reversal of the calcination reaction. The reabsorbed CO_2 is permanently stored within the mineralised concrete. The carbonation of concrete therefore acts as an emissions sink.

Carbonation starts at the concrete surface and progresses inwards. The speed at which carbonation progresses depends on both the physical characteristics – strength, porosity, composition – and the environmental exposure of the concrete. Mortar and precast concrete products carbonate rapidly – for example, mortar or render is likely to fully carbonate within the first year of its life. However, reinforced concrete structures carbonate extremely slowly by design, to avoid corrosion of the steel rebar.

The depth of the carbonation front can be measured by applying a phenolphthalein indicator to a freshly cut surface of the concrete (Figure 1). The dye will become colourless at lower pH, showing that the concrete has already carbonated. Concrete that has not yet carbonated will remain pink. The border between the pink and colourless areas therefore indicates the location of the carbonation front. Testing concrete samples of different ages shows that the depth of carbonation increases with the square root of time.

Figure 1 Phenolphthalein indicator test – CEM III/A concrete (31.9MPa 28-day strength) tested at 17 years

Although the phenolphthalein indicator test shows the depth of the carbonation front, it does not show how much CO_2 has been absorbed in the carbonated volume (colourless area). The 'degree of carbonation' – that is, the percentage of CO_2 absorbed compared to the theoretical maximum – varies considerably with the exposure conditions. In EN 16757, the degree of carbonation is assumed to be much lower (40%) for indoor surfaces than for outdoor or buried surfaces (75-85%).

If concrete is crushed at the end of its life, the surface area increases. Assuming it has not already fully carbonated, fresh uncarbonated surfaces are exposed and carbonation therefore increases.

See literature review Appendix 7 and references therein, e.g. [11], for a detailed discussion.

3.3.1. Accelerated carbonation

Innovative industrial technologies, such as CO_2 curing of concrete, can accelerate and enhance carbonation, but still need further development to remove GHGs at large scale. Examples include the 2021 winners of the Carbon XPrize[12]:

- Carbon Built[13], which uses CO_2-rich industrial flue gases directly to cure precast products, and

- CarbonCure[14], which injects CO_2 into concrete during mixing, where it mineralises.

Other industrial carbonation technologies in development include:

- Carbon8 Systems'[15] Accelerated Carbonation Technology (ACT), which processes industrial waste products into construction aggregates
- O.C.O. Technology[16] also uses ACT to turn industrial waste products into Manufactured LimeStone (M-LS), a construction aggregate
- FastCarb[17], which accelerates the carbonation of recycled concrete aggregate
- Solidia[18] cement, which is made in a conventional kiln but uses less energy. Solidia cement is the binder in Solidia concrete, which is factory-cured with CO_2 to make precast concrete products.

4. Research scope and methods

4.1. Literature review summary

An independent literature review (Appendix 7) has been carried out by Dr Phil Renforth, associate professor at Heriot-Watt University, including an assessment of the outline methodology developed by the Swedish Environmental Research Institute (IVL).

This review concluded that:

- ✓ The Tier 2 methodology proposed by IVL, based on the British Standard EN 16757, appears to provide a robust method for calculating the CO_2 uptake due to carbonation of concrete and mortar during their service life. There appears little merit in the application of Tier 1, and Tier 3 speculates at the creation of more robust model frameworks, without specifying detail.
- ✗ However, the IVL proposal for an arbitrary CO_2 uptake value at end-of-life and during the secondary life of concrete is insufficiently robust to have meaningful use in a national GHG inventory calculation.
- ✓ Instead, a UK-specific model of end-of-life carbonation should be developed.

The review highlighted that not all of the material within the carbonation front fully carbonates (that is, the complete conversion of calcium silicates/oxides to calcium carbonate). A fundamental weakness of the EN 16757 approach is that the proportion of the total carbonation potential (or the 'degree of carbonation') needs to be assumed. Previously, research has assumed ~70-80%, but empirical evidence suggests substantial variability. There is no predictive model for calculating the degree of carbonation. The review therefore proposed that sensitivity of the model outcomes to the possible variations in the degree of carbonation, across the range of 40-90%, be analysed.

4.2. IVL methodologies

To align with the IPCC requirements for GHG reporting, the IVL methodology proposes three tiers of increasing complexity, where higher tier calculations require more detailed knowledge of actual concrete use.

4.2.1. IVL Tier 1 methodology

The IVL Tier 1 methodology is based on annual CO_2 emissions due to cement calcination and is recommended for use where concrete production statistics are limited or not available. The estimate, based on an international literature review, is that each year 23% of the raw material calcination CO_2 emitted during cement production is reabsorbed: 20% by concrete in its primary use (based on current construction levels) and 3% by demolished and recycled concrete (based on much lower historic construction levels, typical global demolition practices and low recycling rates). The calcination CO_2 emissions should be calculated on a <u>consumption basis</u> – that is, from the annual national cement consumption, including both domestic cement production and cement imports but excluding cement exports. This may differ from the CO_2 emissions reported in the national GHG inventory category 2A1 (see Section 3.2), which are calculated on the basis of annual domestic cement production.

Although the uncertainty in calcination emissions is very low, the uncertainty in the Tier 1 calculation is relatively high, due to the assumptions made in the methodology. Note that historic construction rates, as well as recovery and recycling rates, are higher in the UK than the typical practices assumed by IVL.

4.2.2. IVL Tier 2 methodology

Concrete in primary use

For a Tier 2 model, IVL recommends that, to be representative of national circumstances, data in the primary use stage should cover at least one year, five or more cement or concrete use applications – such as bridges, residential buildings, office buildings or mortar – and at least 65% of national cement consumption. The remaining 35% of cement consumption is either distributed across the top five or more primary use applications or assigned to specific applications.

For each primary use application, annual data on concrete volumes (or cement consumption) is required, as is data on typical cement/clinker content in the concrete mix, and the concrete quality, exposure and surface area. Typical prototypes of each application are used to calculate EFs using the EN 16757 methodology.

The total carbon emissions sink for concrete in the primary use stage is calculated by multiplying the concrete volume for each primary use application by its CO_2 uptake EF, then summing over all the applications. As a final check, the bottom-up concrete consumption, calculated from the primary use applications, should be reconciled with top-down cement consumption data.

For Tier 2, the methodology assumes that the national annual CO_2 uptake for all concrete in primary use in the built environment can be estimated from new-build construction during the reporting year. Instead of calculating the annual increment in CO_2 uptake for all existing concrete, the method calculates the CO_2 uptake of new-build concrete over its whole service life and treats this as an instantaneous carbon sink. Although this will introduce some uncertainty into the model, it is a reasonable approximation in countries with a mature market, where concrete production and construction has been relatively constant in recent decades. Sections 7.1 and 12.3.3 show that it is appropriate for the UK.

Concrete at end-of-life and in secondary use

For carbonation in the end-of-life and secondary use stages, IVL proposes fixed CO_2 uptake values of 10kg CO_2/m^3 of concrete, or 20kg CO_2/m^3 with improved end-of-life handling procedures. Alternatively, a country-specific model can be developed.

4.2.3. IVL Tier 3 methodology

For a Tier 3 model, IVL proposes advanced user-developed software models to include at least 50 years of cement consumption data and detailed concrete use data covering at least three different years. Furthermore, the CO_2 uptake calculation should not be based solely on the cement clinker (or CEM I) content, but incorporate carbonation of SCMs, such as fly ash and GGBS. Ideally, a Tier 3 model should also include historic CO_2 emissions data for cement calcination and SCMs.

4.3. Developing a UK-specific Tier 2 carbonation model

The IVL team have illustrated in previous research[19] how the Tier 2 methodology could be applied to Sweden. However, there are many aspects in which concrete consumption and construction practice may differ in the UK. Hence a UK-specific model is needed.

4.3.1. Required elements of a UK-specific Tier 2 model

The following elements are required for development of the UK-specific Tier 2 model:

- Identification of appropriate annual activity data (AD) to input into the model for primary, end-of-life and secondary use of concrete (Sections 5.4, 10.3)
- Identification of an appropriate choice of primary use concrete applications to satisfy the IVL Tier 2 model criteria (Section 6)
- EF calculated for each of the primary use concrete applications identified (Section 8)
- EF calculated for concrete in the end-of-life and secondary life stages (Section 10.4).

MPA has examined data available from government, such as ONS construction output, and industry, such as NHBC quarterly reports and Barbour ABI commercial contract data, which can be used to fulfil these requirements (Section 5). IPCC good practice techniques (such as extrapolation, interpolation and use of proxy data) and statistical analysis of the survey data, together with expert opinion from across MPA's team of structural engineers and material scientists, has been used to address data gaps and inconsistencies that arise from the top-down cement/concrete production data and bottom-up government and industry statistics.

5. Primary use applications – review of data sources

Available data sources for concrete and other cement-containing products within the UK built environment fall into two broad categories:

- Top-down data for production and supply of cement and concrete at a national level
- Bottom-up data on different types of construction where concrete is used. Bottom-up data may be cross-sectoral, covering the whole construction market in the UK, or specific to an individual sector, such as housing or infrastructure.

Data sources in each of these categories are described in Sections 5.1, and Sections 5.2 and 5.3 respectively. Figure 2 gives a schematic overview of the data sources reviewed.

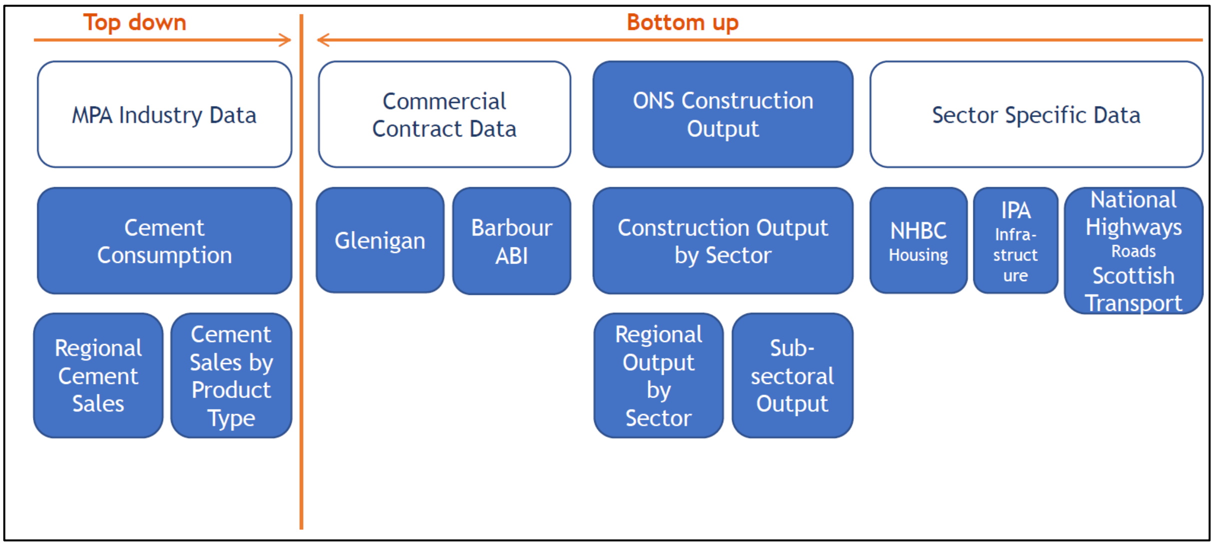


Figure 2 Schematic of data sources reviewed for primary use concrete applications

5.1. Cement and concrete production data

5.1.1. MPA industry data

MPA is already a key supplier of activity data to the UK Greenhouse Gas Inventory (GHGI), providing cement clinker production data and fuel use data for all UK cement producers. This data is used to calculate GHG emissions from cement production, which are reported in the IPCC NIR categories 1A2f and 2A1 (see Section 3.2).

MPA publishes aggregated industry data[†], including:

- Annual cementitious statistics
    - Cement sales from UK production (all UK cement production is by MPA members)
    - Cement imports by MPA members
    - Estimated sales of cement imported by non-MPA members (about 15% of UK cement sales in 2019)
- Cement channel of sale
  Domestic cement sales by MPA members (that is, cement sales from UK production plus cement imports by MPA members) are also published, divided into the following 'channels of sale'
    - Ready-mix – cement sold in bulk to be used in ready-mix concrete production
    - Merchant – cement bagged at the cement plant and sold on via builders' merchants and DIY stores
    - Products – cement that goes into factory-made products including ready-mix mortar and precast concrete products
    - Other – cement that goes into soil stabilisation, special grout formulation, diaphragm wall grouts and other specialist applications
- Mortar – factory-made mortar sales by MPA members.

Data on precast concrete production (such as concrete blocks, drainage products and pipes) is collected from MPA members. MPA only covers part of the precast market, and this data is not published. MPA also collates members' expert opinion on the end uses of concrete but formally collected data is not publicly available.

5.2. Construction data – cross-sectoral

The currently available top-down data is not sufficiently disaggregated into concrete end use for a Tier 2 model. Bottom-up construction data is needed to understand the distribution of concrete between primary use applications and to calculate the CO_2 sink.

5.2.1. Government statistics – ONS construction output

ONS publishes annual construction output data[20] broken down by sector and sub-sector. (Note that the value covers construction work carried out by each contractor surveyed. Output does not include payments made to architects or consultants from other firms – this would cover engineers and surveyors. Output would, however, include wages paid to such people if they were directly employed by the business[21].)

Table 1 shows the ONS construction output[20,22] by type of work. For this analysis, the output for each type has also been calculated as a percentage of the total.

[†] Unlike in Sweden, there are multiple cement producers in the UK. Due to competition law requirements, volumes for production of cement clinker and cement, and for cement sales, are collected via a third party and received by MPA in aggregated form.

Table 1 ONS construction output by type of work (Table 1.3 in 2020 edition; Table 2.4c in 2019 and previous editions)

ONS Table number 1.3 (2.4c prior to 2020)	**Value of construction output by type of work New work for public and private sectors, Great Britain, current prices**			
2019			(£million)	% of total
New housing			47,588	40%
Infrastructure		Water	819	1%
		Sewerage	970	1%
		Electricity	6,550	6%
		Gas, communications and air	883	1%
		Railways	7,662	6%
		Harbours	1,440	1%
		Roads	4,930	4%
Other non-housing excluding infrastructure	**Industrial buildings**	Factories	2,489	2%
		Warehouses	3,550	3%
		Oil, steel & coal	63	0%
	Non-residential buildings	Schools, colleges and universities	10,806	9%
		Health	2,993	3%
		Offices	10,479	9%
		Entertainment	9,912	8%
		Garages, shops	5,184	4%
		Agriculture, miscellaneous	2,660	2%
All New Work			**118,977**	**100%**

5.2.2. Commercial contract data

Information about specific construction contracts is provided on a commercial basis by two companies:

- Glenigan
- Barbour ABI

MPA has access to Barbour ABI data. Barbour ABI data is also used in the calculation of the ONS construction statistics.

Glenigan data was purchased to find and select contacts for the targeted market survey carried out by Leading Edge (Section 6.1, Appendix 3).

5.3. Construction data - sector-specific

5.3.1. Housing

NHBC housing market reports

NHBC housing market reports[23] include quarterly data for new homes covered by an NHBC warranty (approximately 75% of the market). They include:

- Percentage of homes by the following types
    - detached houses
    - detached bungalows

  - semi-detached houses
  - terraced houses
  - attached bungalows
  - flats and apartments
- Timber-frame market share by property type.

The NHBC housing market reports also include a comparison of NHBC registered new home numbers with government data on new housing supply published by DLUHC.

The NHBC housing market reports do not distinguish between low-rise and high-rise flats. NHBC can provide more detailed data, including a full breakdown of construction types, on a consultancy basis.

Department of Levelling Up, Housing and Communities (DLUHC)
DLUHC publishes live tables on new housing supply[24]. Table 254 in the DLUHC dataset gives percentages of new homes by dwelling types (house or flat, and number of bedrooms). The DLUHC data covers all completions, not just those registered by NHBC. It does not distinguish between low-rise and high-rise flats.

English Housing Survey (EHS)[25]
This is a long-running national survey of people's housing circumstances and the condition and energy efficiency of housing in England.

The EHS gives a stock profile by dwelling type – including the split between low-rise and high-rise flats. However, the survey covers all housing stock in current occupation, regardless of build date, whereas the methodology adopted in this project is based on annual new construction.

5.3.2. Infrastructure

There are several government publications covering planned infrastructure construction projects.

National Infrastructure and Construction Pipeline[26]
Published by the Infrastructure and Projects Authority, this brings together planned procurements across infrastructure and construction.

Other data sets provide information on planned transport projects in Scotland and planned road projects in England.

- **Transport Scotland Projects[27]**
- **Department for Transport Road Investment Strategy 2:2020-2025[28]**
- **National Highways' pipeline of possible future schemes[29]** (for England)

5.4. Activity data sources for UK Tier 2 model

A key objective of the current project is to identify reliable sources of data that will provide appropriate annual activity data for the carbonation emissions sink model. MPA has identified the following data sources, which provide reliable annual activity data to input into the model:

- ONS annual construction output
- MPA annual cement and mortar production statistics
- Defra annual statistics on volumes of C&DW recovered

For primary uses of concrete, ONS construction output data encompasses activity across all sub-sectors of the construction industry, at the required level of disaggregation for a Tier 2 model. This is used in conjunction with MPA cement and mortar production statistics, to achieve consistency between top-down cement production data and bottom-up consumption data within the model.

Defra annual statistics on volumes of C&DW recovered, with expert opinion on the concrete content, are used as activity data for end-of-life and secondary use concrete.

These data sources are reliable, consistent and readily accessible. The risk that these data sources will be discontinued, severely impacting implementation of the model in subsequent years, is considered very low.

Other data sources reviewed, such as commercial contract data and sector-specific construction data, are less readily accessible and are at greater risk of becoming unavailable. They could be considered for use as annual activity data in future model development – for example, the extension of the current model to a UK Tier 3 model. Nonetheless, these other data sources have informed the model development, such as with the model parameter to split new housing construction into concrete-frame (high-rise) and masonry applications (Section 9.1.2).

6. Selection of UK primary use applications

From the ONS construction output, approximately 80% of new construction value is in buildings. However, buildings use very different types of concrete. Concrete masonry is the most common form of construction for houses. Masonry construction uses low-strength concrete blocks which will carbonate to a greater depth than the higher strength structural concrete used for non-residential and higher rise residential framed buildings. For framed buildings, the concrete mix is designed to limit the depth of carbonation and therefore protect steel reinforcement from corrosion (Appendix 4 and [2]).

The primary use applications should therefore differentiate between these different building types. MPA has reviewed all the appropriate data identified above and combined this with in-house knowledge and expert opinion to select appropriate primary use applications for buildings.

Infrastructure comprises about 20% of the total value of UK construction. Different high-value sub-sectors – railways, electricity, roads – have been investigated.

6.1. Targeted market survey

In order to fill data gaps between the top-down cement production data and bottom-up ONS construction output, and to verify assumptions made in the selection of primary use applications, MPA carried out a targeted market survey of concrete use across key sectors and applications. The results were used to:

1. verify expert opinion on typical frames for differing building types and use categories and therefore assign different ONS sub-sectors to the most appropriate primary use application in the model (Section 6.6, 9.1.1), and to
2. create proxies to relate cement and concrete consumption to economic values for ONS construction output in each sector or sub-sector (Section 9.2.1).

Appendix 3 contains further details of the market survey results and analysis.

6.1.1. Buildings survey methodology

The survey aimed to establish the distribution of frame types in the building sectors, and concrete usage and exposure within each frame type. Projects, with a start date in 2020-21, were sourced from Glenigan data. Survey questions for buildings covered:

- construction value
- construction type (frame, masonry)
- Volumes of concrete consumed for different building elements: foundations, superstructure etc.
- Detailed building geometry: GIFA, number of storeys, storey height, depth of concrete in the floor slabs, floor coverings, roof and façade make-up etc.

Sampling of buildings focused on the ONS construction sectors with highest output value and greatest homogeneity. The expected homogeneity of construction types within each sub-sector was based on the ONS sub-sector definitions and expert opinion. For non-residential buildings, offices are expected to be the most homogeneous sub-sector, mostly steel composite frame. The education, health, retail and warehouse sub-sectors were also surveyed, albeit with smaller sample numbers. The entertainment sub-sector was not included in the survey, as construction types within this sub-sector vary considerably. Therefore, a small sample size would not be representative.

Surveying of new housing focused on low-rise masonry construction (both houses and flats) and high-rise concrete-framed flats, which were targeted separately.

Regional sampling within each sub-sector was informed by ONS construction output by region and, for housing, by NHBC housing market reports.

Although all responses included the project value, collecting complete data was challenging – data on GIFA or concrete volumes, for example, was missing from some responses. MPA carried out data cleansing and gap filling (Appendix A3.2), using assumptions that aligned with standard industry practice. The resulting completed responses were also checked to ensure that they were consistent with the complete survey responses received without any gaps.

6.2. Framed buildings

Expert opinion, from MPA's team of structural engineers, is that all multi-storey framed buildings are structurally similar regardless of end use and fall into three common sub-types (illustrated in Figure 3):

- Steel composite frame – steel frame with metal deck and in-situ concrete floor slabs
- Steel plus hollowcore – frame with hollowcore floors
- Concrete frame, mostly with flat slabs.

The market survey confirmed that most of the buildings included in the ONS construction non-housing sub-sectors – such as education, offices, entertainment, retail and health – are framed buildings, although some smaller projects, such as primary schools, primary care and local shops, are masonry construction.

Steel composite frame is the predominant frame type by value, for offices, education and retail. A smaller proportion (20% or less in the survey) in these sub-sectors is of steel plus hollowcore construction.

Health buildings are a mixture of frame types, although large hospitals are usually concrete-framed. The market survey found that 53% of the health sector total value is in concrete-frame types.

The ONS housing sector will include high-rise residential buildings (that is, with five or more storeys). The market survey confirmed that high-rise residential buildings are predominantly concrete-framed (87% by value) to satisfy acoustic and fire separation requirements.

The warehouse sector is dominated by a fourth frame type – portal frame. Retail construction also contains some portal frame buildings. Portal frame is effectively a steel-framed shed, although there may be some blockwork office structures inside the main building. Most of the concrete is in the foundations/base and therefore determined by the building's footprint. In this analysis, portal frame construction is assumed for all ONS industrial building types, and the ONS non-residential building types: garages, agriculture, miscellaneous.

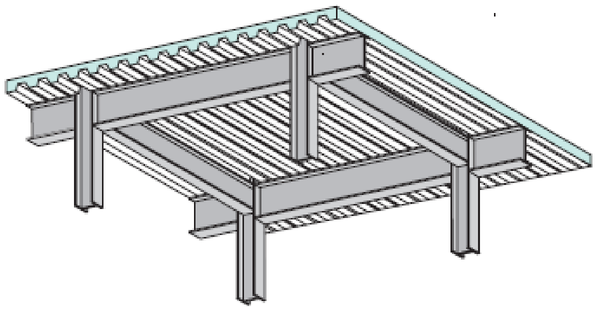
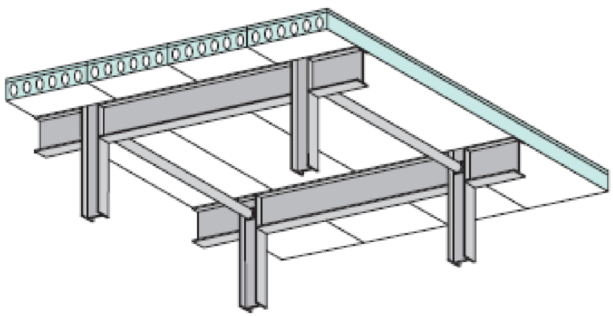
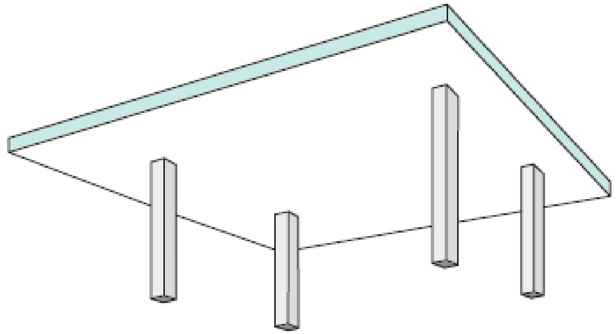
Steel composite frame	Steel plus hollowcore	Concrete frame – flat slab
		
Steel beams and metal decking, both acting compositely with in-situ concrete floor slabs Steel columns	Steel beams acting compositely with precast concrete hollowcore floor slabs Steel columns	Reinforced in-situ concrete flat slab and columns

Figure 3 Framed building types

6.3. Masonry buildings

Masonry buildings predominate for low-rise (four storeys or less) new housing construction. There will also be some masonry construction for smaller building projects within the non-housing sector, such as primary schools, primary healthcare and local retail.

Analysis of NHBC data[30,31] gives a breakdown of home types by timber-framed and non-timber-framed construction (Table 2). Note that there is significant regional variation in the market share of timber frame, which is much higher in Scotland (92%) than England (9%). However, most new construction is in England (83% of completions), followed by Scotland (11%), Wales (3%) and Northern Ireland (3%).

Table 2 UK home completions in 2019 by home type and construction

UK totals by home type and construction			Government completions (000's)					
Construction	Period		Detached houses	Detached bungalows	Semi-detached houses	Terraced houses	Attached bungalows	Flats and apartments
Timber frame	2019	Year	13.24	0.44	13.37	7.10	0.66	3.86
Non-timber frame	2019	Year	48.88	1.78	46.09	22.37	1.55	57.00
			Government completions (%)					
Timber frame	2019	Year	6%	0%	6%	3%	0%	2%
Non-timber frame	2019	Year	23%	1%	21%	10%	1%	26%

DLUHC produces live housing supply data[32]. Table 254 gives the number of bedrooms across different home types.

Table 3 DLUHC live housing table 254, all tenures (2019-20)

	Percentage of dwellings		
	Houses	**Flats**	**Houses and flats**
One bedroom	1%	6%	7%
Two bedrooms	15%	13%	28%
Three bedrooms	34%	1%	35%
Four or more bedrooms	29%	0%	29%
All	80%	20%	100%

Expert opinion is that all timber-framed flats and apartments are low- or medium-rise (four storeys or less). All non-timber-framed house and bungalow types are low-rise masonry construction. Non-timber-framed flats and apartments will be a mixture of low- or medium-rise masonry construction and high-rise concrete frame.

New housing can therefore be divided into four sub-types:

1) Timber-framed houses and flats. These will contain some concrete in the foundations. There may also be concrete in any cladding and concrete tiles in the roof
2) Masonry houses (detached, semi-detached, terraced, bungalows). There will be concrete in the external and party walls, ground floor and foundations. Concrete tiles are often used on the roof

3) Low-rise (four storeys or less) masonry flats and apartments. There will be concrete in the external and party walls, ground and upper floors and foundations. There may also be concrete tiles in the roof
4) High-rise (five storeys or more) flats and apartments. These are typically concrete-framed and are therefore included in framed buildings, rather than masonry.

Bespoke data provided by NHBC for the period 2006-present was used to analyse the split between these sub-types in more detail (Section 9.1.2, Table 5)

6.4. Infrastructure

Infrastructure accounts for 20% of total construction output value. Most output is in the railways, electricity and roads sub-sectors (Table 4, extract from Table 1).

Table 4 ONS construction output infrastructure

2019	Construction output	As % of total construction output
ONS sub-sector	**£ million**	**%**
Railways	7,662	6%
Electricity	6,550	6%
Roads	4,930	4%
Harbours	1,440	1%
Sewerage	970	1%
Gas, communications and air	883	1%
Water	819	1%

Barbour ABI commercial contract data for rail, electricity and road projects beginning during 2018-2020 was analysed in order to drill down into the distribution of projects.

6.4.1. Infrastructure survey methodology

Six road projects were included in the market survey. The sample included projects of varying size, from large motorway projects to small new residential developments.

Survey questions for roads covered:

- Construction value
- Details of road make-up
- Volumes of concrete in different road elements: pavement build-up, drainage and access chambers, barriers, bridges etc.

Stakeholder interviews were also conducted with contractors to HS2 for the rail sector, and concrete suppliers to Hinkley Point C for the energy sector.

6.4.2. Rail

Barbour ABI data shows that construction spend is dominated by long-term high-value rail projects, such as HS2 and the Transpennine Route Upgrade. Industry expert opinion is that HS2 is expected to consume large volumes of concrete over the next decade.

6.4.3. Electricity

Barbour ABI data shows that construction spend is dominated by long-term high-value projects, mainly offshore wind and new nuclear developments.

Industry expert opinion is that current offshore wind development in the UK uses steel monopile foundations. Within the energy sector, concrete usage is predominantly in new nuclear. This could change with future trends in energy generation – for example, if floating concrete bases, which are already widely used in continental offshore wind projects, were adopted for UK wind generation. The Swansea tidal barrage is also expected to consume large volumes of concrete, if approved.

6.4.4. Road

Barbour ABI data shows that construction spend is distributed across many projects, ranging from higher value major motorway or A-road improvement schemes to more local road construction for new housing estates.

Industry expert opinion is that most new roads have an asphalt pavement build-up. Concrete is used in numerous other road elements, such as bridges, safety barriers and parapets, kerbs, and drainage and access chambers.

6.5. Merchant cement sales and mortar

MPA collects reliable top-down production data for sales of bagged cement via builders' merchants and other outlets, and of factory-made mortar. As these account for approximately 25% of the cement market, this is an appropriate primary use application for a UK Tier 2 model.

6.6. Model primary use application

Following the analysis described above, and in line with the IVL Tier 2 methodology, the following five primary use applications were chosen for use in the UK Tier 2 model.

Model primary use application			
		Construction type	*Includes:*
1.	**Buildings**	**steel composite frame**	offices other commercial buildings
2.	**Building**	**concrete frame**	high-rise residential buildings hospitals
3.	**Buildings**	**masonry**	houses low-rise apartment blocks
4.	**Infrastructure**		rail electricity road
5.	**Merchants and mortar**		bagged cement sold through builders' merchants factory-made mortar

7. Historic data analysis

The Concrete Society has analysed patterns in historic concrete construction and buildings currently undergoing demolition (Appendix 2 provides more comprehensive statistics and information). This shows that construction levels have been relatively constant in recent decades – an important assumption in the IVL Tier methodology (Sections 4.2.2, 12.3.3). The information was also used to inform the assumptions underlying the calculation of an emissions sink factor for end-of-life and secondary use concrete (Section 10.4, A4.2.6).

7.1. Historic use of concrete in construction

The building boom of the 1920s and 30s was particularly strong, with increasing use of concrete as an architectural material and the rapid growth of precast concrete, particularly blocks. A lot of the growth was in the housing sector, much of which remains in use today. Following the Second World War, concrete was central to the reconstruction effort, in part due to its continued availability compared with steel (which was in short supply) and its increasing desirability as a medium of modern architecture.

Figure 5 shows the volumes of ready-mix concrete supplied between 1950 and 2020, with production peaking in the early 1970s and late 80s[33]. The 1960s, up to 1973 (Figure 4, Figure 5), was a period of maximum growth for the use of concrete/cement, characterised by ongoing urban development, the erection of tower blocks, continued house building, the expansion of the higher education sector and the building of the motorway network. Concrete played a major role in all these sectors: including the development of panel systems for industrialised buildings, proprietary methods such as 'no fines' concrete for housing and a wide range of flooring components.

The vogue for industrialised building in the 1960s was short-lived and precast reinforced concrete (PRC) housing finally came to an end by the mid-1970s. The water supply industry reached its peak in the 1960s, ceasing to enjoy such high levels of investment after the mid-1980s. Much the same could be said of agricultural building in the 1970s; the concrete portal frames so widely used in this sector are now no longer available. The motorways programme came to an end, and major road building was largely suspended in 1997. However, the residential sector saw the development of beam-and-block flooring and a steady increase in hard landscaping. The recent concentration on apartment building has opened a new market for in-situ concrete. Considerable demand for concrete has also been created by such headline projects as the London, Severn and Humber bridges in the 1970s, the Channel Tunnel and Canary Wharf in the late 1980s and 90s, and facilities for the 2012 Olympic Games[34].

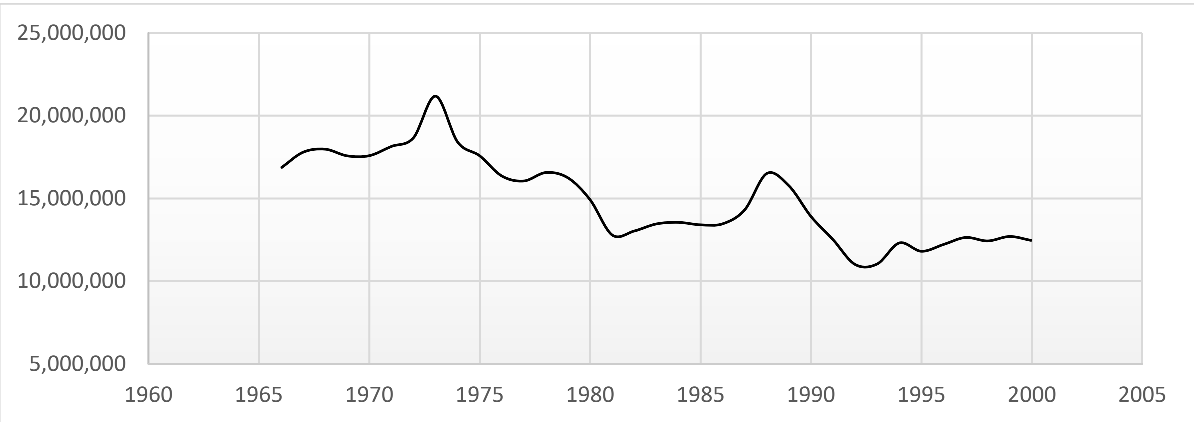


Figure 4 Cement production (tonnes) 1966 – 2000 (see A2.5, Table 13 for data).

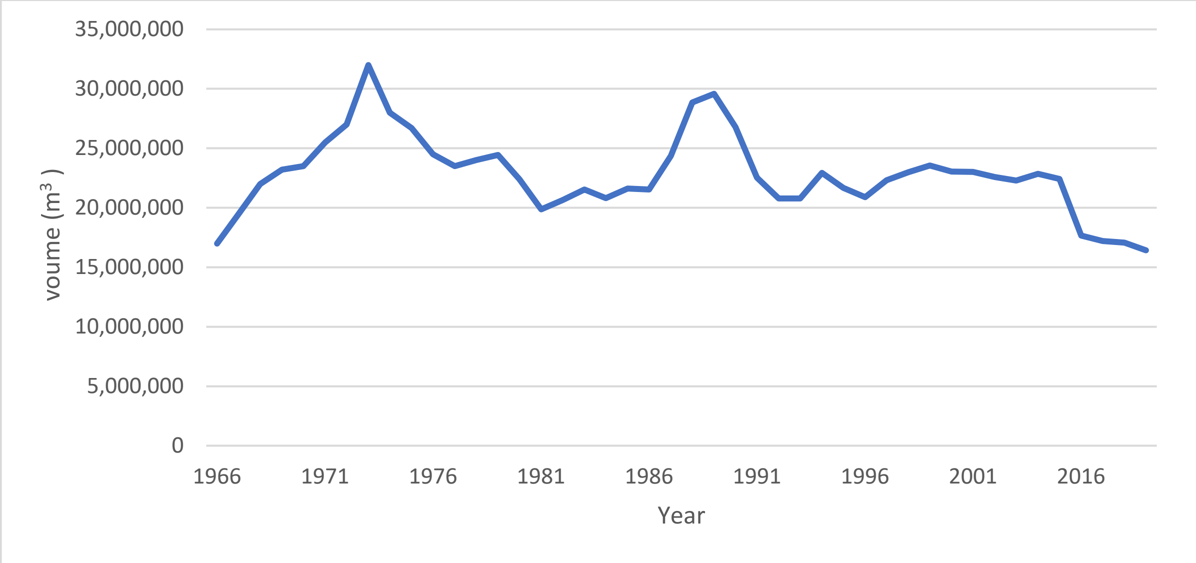


Figure 5 Volume of ready-mixed concrete, 1966-2020 (see A2.5, Table 14 for data)

Commercial construction between 1960 and 1980 was predominantly concrete-frame. Between 1980 and 2000 there was a shift towards use of steel frames in the non-residential markets[35] (Figure 6).

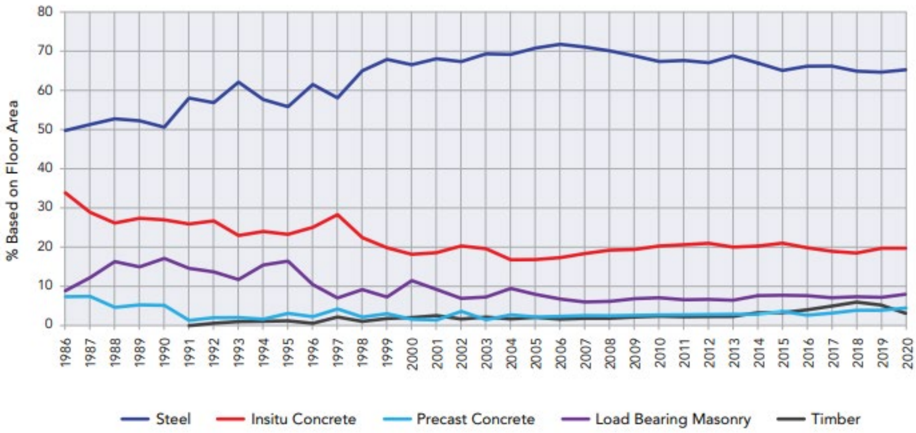


Figure 6 Share of UK multi-storey non-residential market by construction type[35]

7.2.Historic trends in concrete strength and cement intensity

The strength of concrete test cubes was monitored by BRE on a consistent basis from 1934 to the 1980s, and the results reveal an increase in cement strengths over this time. “Modern Portland cements (1983) produce significantly greater compressive strengths in mortars and concretes than did the cements of the 1950s and earlier. The observed strength increases allow significant reductions in cement content and increases in water/cement ratio while still achieving specified strengths. Such reductions are sufficient to produce adverse effects on durability.” [P.J. Nixon, BRE, Sept 1983].

A review of changes in the UK cement intensity (MMD for BCA, April 1997) states that:

“The demand for cementitious materials in the UK is no higher now than it was 30 years ago, but construction output has increased by around 30%. This decline has, on average, subtracted around 1% from cementitious demand each year since the early 1960s.”

This is due to the increasing sophistication of buildings and competition from other materials. While cement strength has increased significantly since the mid-1970s, the amount of cement used in a cubic metre of ready-mixed concrete has increased rather than declined.

7.3. Service life

Conventional expectations for service life were set out in 1950 as CP3: Life expectancy & Durability of buildings. In 1991 this document was updated[36], as indicated:

Temporary:	up to 10 years	Site buildings, exhibition structures
Short life:	min 10 years	Classrooms
Medium life:	min 30 years	Industrial buildings, house refurbishment
Normal life:	min 60 years	Public sector building
Long life:	min 120 years	Civic and high prestige buildings

7.4. Demolition

For service life in practice, the characteristic age of classes of building at the time of demolition could be considered. However, this is difficult to document with any comprehensiveness (even impossible to trace systematically). However, some trends seem apparent under a broad historical review, including the observation that demolition since the 1990s probably has an increasing proportion of concrete structures from the heyday of concrete construction in the 1960s and 70s.

8. UK-specific carbonation of concrete emissions sink factors – primary use

8.1. Calculation of CO_2 uptake

UK-specific EFs have been developed for each of the primary use applications using typical structural prototypes (Appendix A4.2) and concrete mixes (Appendix A1.3). For each application, the speed and degree of carbonation depends on both the characteristics of the concrete – strength, porosity, composition – and the environmental exposure. Mortar and precast concrete products carbonate rapidly – for example, mortar or render is likely to carbonate fully within the first year of its life. However, reinforced concrete structures carbonate extremely slowly by design, to avoid corrosion of the steel rebar.

As recommended in the IVL methodology, the calculation of CO_2 uptake in the primary use phase follows EN 16757[2]. The rate of carbonation depends on the concrete strength and exposure, such as whether it is outdoors, indoors, covered or buried. The carbonation front progresses inwards from the concrete surface. The depth of the front increases with the square root of time, and therefore depends upon the concrete primary service life, whereas the degree of carbonation depends on the concrete exposure.

Since 1980, increasing amounts of SCMs, such as fly ash and GGBS, have been used in concrete mix designs for buildings (Appendix A1.2, Figure 14). Fly ash and GGBS were also used as SCMs in concrete prior to 1980 in major infrastructure projects. The clinker content of mixes which include SCMs is lower than for a concrete mix containing only CEM I.

EN 16757 recommends that, as a conservative approach, the maximum theoretical CO_2 uptake, U_{tcc}, should be based on cement clinker content only, excluding any SCMs in the concrete mix. However, the presence of SCMs in the mix does increase the rate of progression of the carbonation front. For each of the primary use applications, the typical concrete mix determines the CEM I content (kg CEM I/m^3 concrete). Following EN 16757, the EF calculations use CEM I content as a proxy for clinker content (assuming 95% clinker content, see Appendix A4.1 Equation (1)). The CEM I content is also used in the model to reconcile the bottom-up cement consumption in each concrete application with top-down MPA cement consumption and production data.

Full details of the methodology and prototypes used in the EF calculations are contained in Appendix 4. Concrete mixes are discussed in Appendix 1.

8.2. Emission factor prototypes

8.2.1. Buildings – steel composite frame EF

The prototype used for the calculation of the emissions sink factor is a 16,500m^2, six-storey city-centre commercial building based upon typical current design practice (similar to Building B in [37,38]). The GIFA and number of storeys are consistent with the market survey results. Figure 7 shows the cross-section.

The building has a composite steel frame with piled foundations. EFs have been calculated for 1990-2000 and 2010-2020, to represent evolution in concrete standards and mixes (see Appendix A1.3). The EF calculation considers carbonation of concrete in the foundations, ground slab, upper floors and roof, and the concrete cores. See Appendix A4.2.1 for full details.

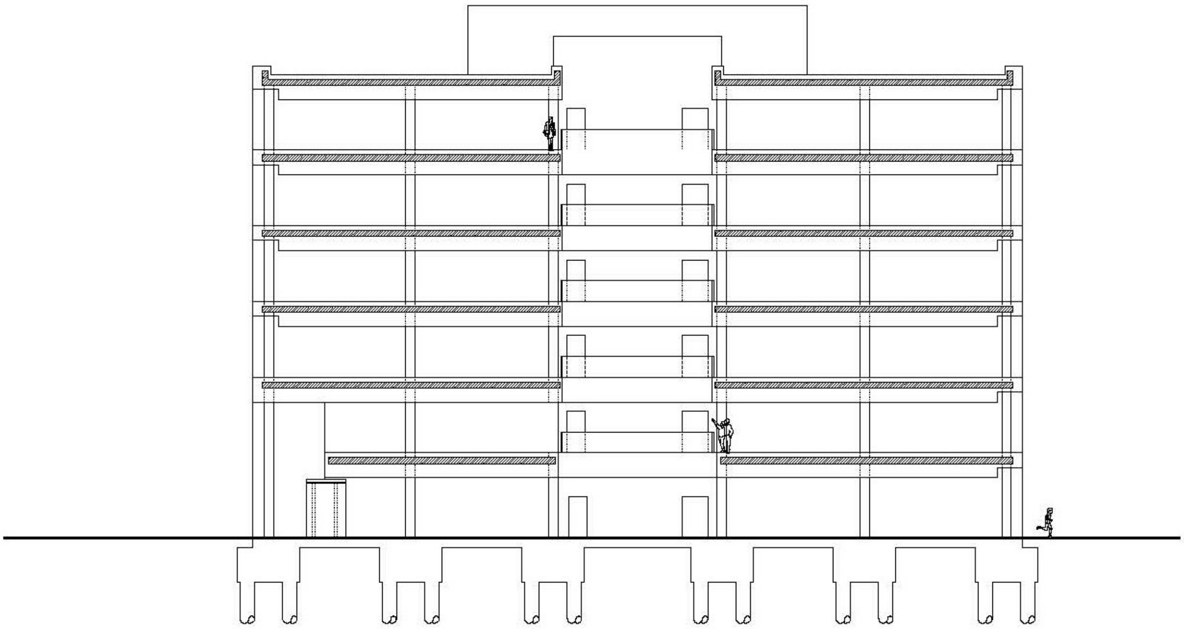


Figure 7 Cross-section of steel composite frame office building

8.2.2. Buildings – concrete frame EF

The prototype used for the EF calculation is a 2,500m^2, six-storey apartment block containing 22 flats based upon typical current design practice (similar to the concrete-frame building in [39]). The GIFA and number of storeys are consistent with the market survey results. Figure 8 shows the layout of one of the upper storeys.

The building is of concrete-frame construction with piled foundations. EFs have been calculated for 1990-2000 and 2010-2020, to represent evolution in concrete standards and mixes (see Appendix A1.3). The EF calculation considers carbonation of concrete in the foundations, ground slab, upper floors and roof, concrete cores and the external walls (which are of lightweight aggregate block and brick masonry construction). See Appendix A4.2.2 for full details.

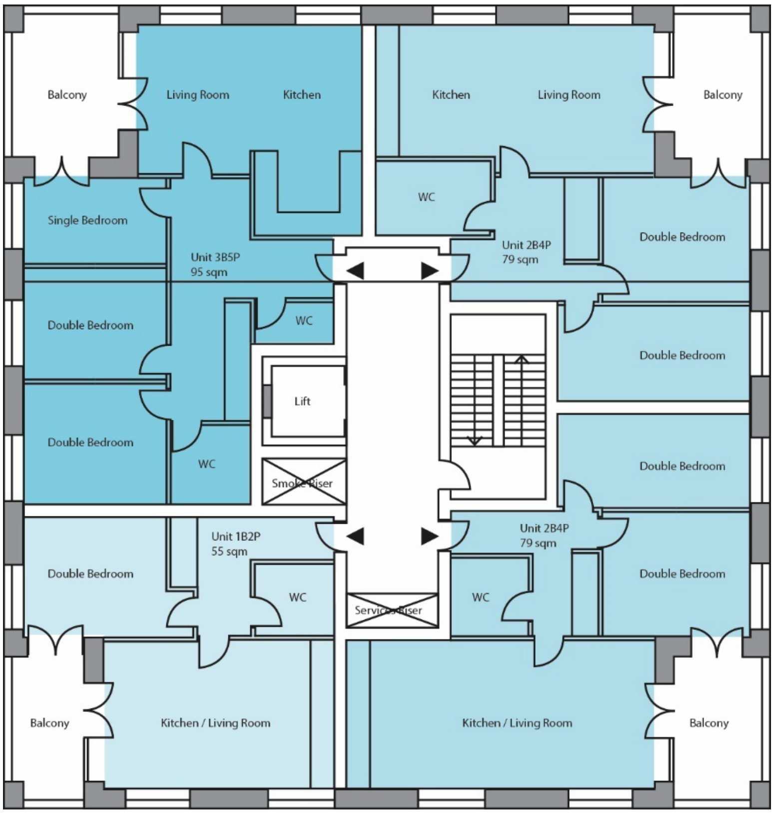


Figure 8 Layout of concrete-frame residential apartment block

8.2.3. Buildings – masonry EF

House

The prototype used for the masonry EF calculation is a typical 80m^2, two-bed, two-storey mid-terrace house with masonry construction, pitched roof and concrete roof tiles (Figure 9). The house has strip foundations, beam-and-block ground floor, block party walls, block-cavity-brick external walls and a pitched roof with concrete roof tiles.

The EF calculation considers carbonation of concrete in the strip foundations and foundation blocks, ground-floor beam, party walls, external walls, and the roof tiles. For the lightweight aggregate blocks in the external and party walls, and the concrete roof tiles, the carbonation front will have progressed through the full depth of the blocks or tiles by the end of the building service life. See Appendix A4.2.3 for full details of the calculation.

The mortar used in masonry construction will also carbonate but comes under the 'merchants and mortar' use application.

Figure 9 https://www.mpamasonry.org/MMA/Case-Studies/Calder-View-Forterra.aspx

8.2.4.Infrastructure EF

Concrete slipform road barrier

The infrastructure EF calculation is based on a typical concrete slipform road barrier. This is regarded as an appropriate prototype as most infrastructure construction will be outdoor and exposed to rain, whereas a tunnel (such as for HS2) is an atypical construction. Choice of this prototype is also consistent with the use of road data to calculate the proxy relationship between ONS construction output and concrete volumes for infrastructure. Details of the calculation are given in Appendix A4.2.4.

8.2.5.Merchants and mortar EF

The merchants and mortar EF calculation is based on the mortar use within the masonry house construction prototype used for calculation of the masonry EF. Mortar is used in the following building elements:

- Party walls (concrete block construction)
- External cavity walls – block and brick leafs.

The carbonation calculation shows that the carbonation front will have progressed through the full depth of the mortar in these walls by the end of the building service life.

A small amount of mortar will also be used between the foundation blocks but, in order to simplify the calculation; this has not been included. See Appendix A4.2.4 for full details of the calculation.

9. UK model development: primary use

Table 6 shows the structure of the model: activity data (AD) inputs together with emissions sink factors (EF) and other key model parameters.

9.1. UK Tier 2 model activity data – primary use

The ONS annual construction output for all years (1990-present) is adjusted to a common baseline (2019) using the ONS output price indicator[‡] (Table 6a in ONS Monthly Construction Output[21]).

ONS construction sub-sectors for buildings are then assigned to each of the first three primary use applications, based on the predominant frame types determined by the market survey. Steel plus hollowcore frame and portal frame types have been included in 'buildings – steel composite frame', as the most similar application.

9.1.1. Buildings – steel composite frame

All ONS non-residential construction output, except for health, is assumed to be composite frame.

9.1.2. Buildings – concrete frame

Bespoke data provided by NHBC for the period 2006-present has been used to derive an average split for new housing between concrete-framed buildings (high-rise residential), masonry and other (mainly timber frame). Concrete-framed buildings comprise about 10% of new residential construction. The ONS new housing output is multiplied by this factor.

Table 5 New housing split between concrete frame, masonry and other, derived from NHBC statistics.

Percentage of ONS construction output in new housing which is …			
houses (non-timber)	**flats (non-timber)**		**houses and flats (timber/other)**
53%	**29%**		**18%**
% of which are …	*% of non-timber flats which are…*		
masonry	**masonry**	**concrete frame**	
100%	**66%**	**34%**	
Percentage split of ONS new housing construction output which is …			
masonry (houses and flats)		**concrete frame**	**timber frame**
72%		**10%**	**18%**

ONS construction output in the non-residential buildings health sub-sector is also assigned to the concrete-framed buildings primary use application. As confirmed by the market survey and expert opinion, construction output value in the health sub-sector is dominated by new hospital buildings, which are concrete-framed.

9.1.3. Buildings – masonry

Analysis of bespoke NHBC data shows that masonry buildings comprise about 72% of new housing over the period 2006-present. ONS new housing output is multiplied by this factor.

9.1.4. Infrastructure

All ONS construction output in infrastructure is included in this primary use application.

[‡] The multiplier for all construction is used in the current version of the model. Separate multipliers are available for some sub-sectors and could be used in a future model version.

9.1.5. Merchants and mortar

Activity data for merchants and mortar is derived from MPA industry statistics. Cement quantities for merchants are taken directly from the MPA Cement 'channels of sale' data.

MPA mortar sales are converted into cement consumption assuming a typical M4 mortar suitable for use in moderate environmental conditions[40].

9.2. Model parameters

9.2.1. ONS proxies for primary use applications

Assumptions based on industry practice and building standards were used to calculate and cross-check concrete volumes for the building projects sampled in the market survey. This data was then used to create proxies which are used in the model to convert ONS construction output from Pounds Sterling to concrete volumes for the first three primary use applications.

An ONS proxy was also created for the infrastructure sector. However, this is based on very limited data, so should be used with caution.

No proxy is required for the merchants and mortar application, which is derived from top-down MPA data.

9.2.2. Primary use emission factors and CEM I content

The model implements the EF derived from primary use prototypes (Section 8). CEM I content per m^3 of concrete for each primary use is also derived as part of the EF calculation. It is used in the model to reconcile the bottom-up AD with the top-down cement consumption data.

For the composite framed buildings and concrete-framed building applications, to represent evolution in concrete standards and mixes, EFs and CEM I content have been calculated for 1990-2000 and 2010-2020. The 1990 values are used in calculating carbonation of end-of-life and secondary life concrete. Within the limited scope of the current project, historic EFs and CEM I content have not been calculated for the other primary use concrete applications.

Table 6 Overview of primary use model structure, AD and EF sources and model parameters (all values to 3sf)

Primary use application	Activity data	AD ONS sectors/ sub-sectors	Additional AD parameters	ONS proxy to convert economic output to concrete volume	EF prototype	Historic period	CEM I content	Emissions sink factor
Units				*m^3 concrete/ £m construction output*		*Decade*	*kg CEM I/m^3 concrete*	*kg CO_2/m^3 concrete*
Buildings – steel composite frame	ONS construction output	Non-residential buildings – all except health		180	Six-storey composite frame office building	2010-2020	190	9.30
						1990-2000	277	12.5
Buildings – concrete frame	ONS construction output	New housing	10% of all new housing concrete frame	223	Six-storey concrete frame apartment block	2010-2020	166	12.2
	ONS construction output	Non-residential buildings – health				1990-2000	230	14.1
Buildings – masonry	ONS construction output	New housing	72% of all new housing masonry	209	Two-storey two-bed mid-terrace house	All *(historic factors not calculated)*	136	18.6
Infrastructure	ONS construction output	Infrastructure		133	Concrete slipform road barrier		300	5.65
Merchants and mortar	MPA merchant cement sales MPA mortar sales	n/a	Mortar to cement conversion factor	n/a	Mortar		199	43.9

10.UK model development: end-of-life, secondary use

10.1.Concrete entering the end-of-life stage

The general rules set out in BS EN 15804[41] allow for processes, such as carbonation, that occur during the building life cycle to be included in an environmental product declaration. An important aspect of this is the point at which end-of-waste is reached during the end-of-life stage, beyond which any subsequent carbonation lies outside the system boundary for the building life cycle. Clause 6.3.4.5 of BS EN 15804 states that end-of-waste is reached when a material, product or construction element produced by the demolition and deconstruction process satisfies all the following criteria:

1. The recovered material, product or construction element is commonly used for specific purposes,
2. A market or demand, identified for example, by a positive economic value, exists for such a recovered material, product or construction element,
3. The recovered material, product or construction element fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products,
4. The use of the recovered material, product or construction element will not lead to overall adverse environmental or human health impacts.

This general approach is also included in EN 16757[2], which says that crushed concrete reaches the end-of-waste state once it is subject to further processing to separate it into different size fractions and once an immediate market or demand is available and no risk of reverting to legal 'waste' status exists.

Typically, in the UK, these criteria will ultimately be met by the hardcore resulting from deconstruction and demolition. However, the point at which an immediate demand exists varies from site to site. For live projects/sites, the period is shorter than for speculative sites where no immediate construction activity follows the end-of-life stage. Expert opinion provided by the National Federation of Demolition Contractors (NFDC)[42,43] suggests that, for live projects, demolition concrete sits for around two to eight weeks before it is either removed, reused onsite (without crushing) or crushed onsite. Following this period, crushed concrete can sit for a further 10 weeks or so before it is removed or reused onsite. On speculative sites, this period is longer, at around 12 months. The split between live and speculative projects is not something that is recorded, but is thought to have shifted from around 50:50 in 2013-14, towards a greater proportion of live projects under current market conditions, giving a split that is probably closer to 80:20. Taking this into account and the timings detailed above, the average time spent on site by processed/crushed concrete before it is removed or reused onsite is approximately 19 weeks (Figure 10).

Essentially, the period that concrete crushed onsite remains unused will continue for as long as there is no immediate demand for it. This may also be because the deconstruction and demolition process is still underway. Figure 11 is based on 2018-19 NFDC waste returns data from its members and shows the percentage split for unprocessed and processed (crushed) hardcore, along with the amount either used onsite or taken offsite.

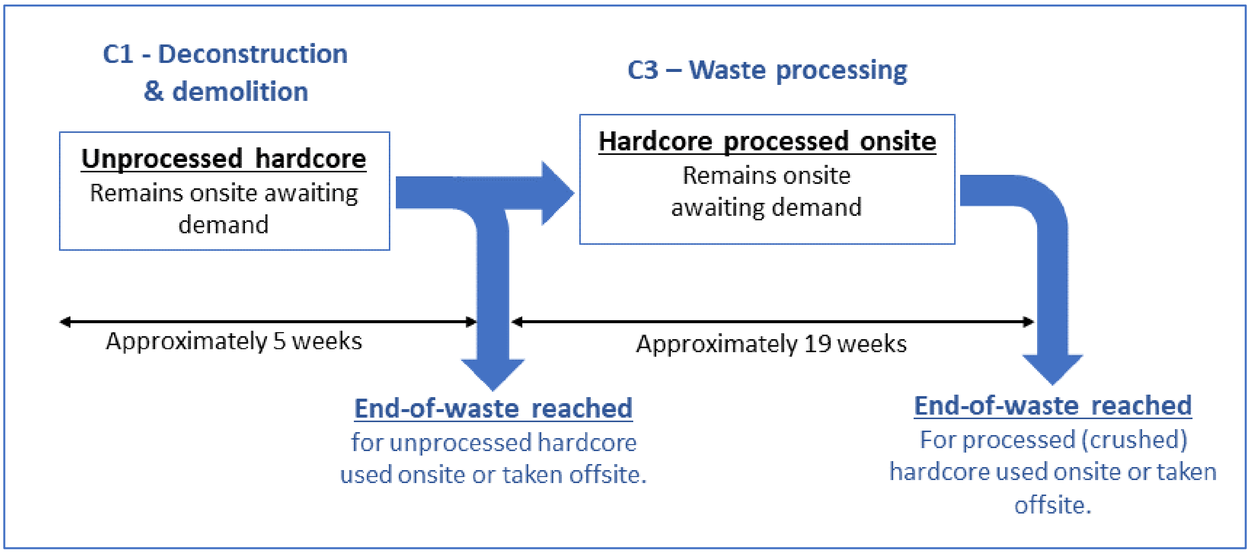


Figure 10 Time period before end-of-waste is reached for unprocessed and processed hardcore (based on 80:20 split between live and speculative sites[42])

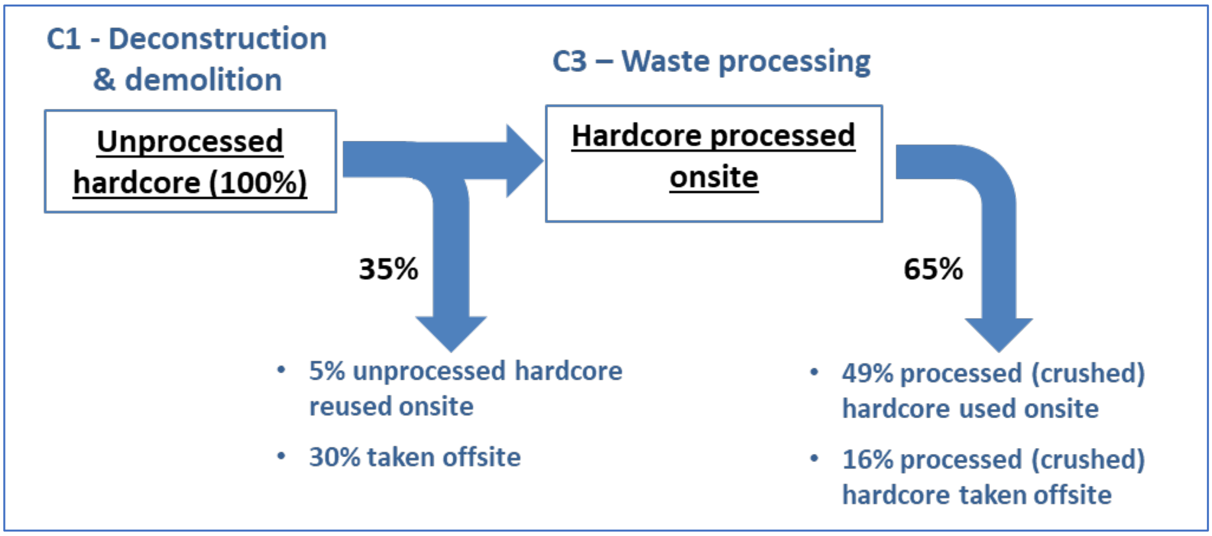


Figure 11 Split between unprocessed and processed hardcore (based on 2018-19 NFDC waste return data)

10.1.1. UK construction and demolition waste - concrete fraction

In addition to NFDC members' waste return data, Defra publishes UK statistics on waste to fulfil official reporting requirements. NFDC also provides waste return data from its members.

The Defra data is divided into seven categories, including construction and demolition waste (C&DW) and associated recovery rates. According to the latest Defra data[44], the UK generated 67.8 million tonnes of non-hazardous C&DW in 2018, of which 62.6 million tonnes was recovered. This represents a recovery rate of 92.3%. The recovery rate from non-hazardous C&DW has remained at similar levels from 2010 to 2018. It should be noted however that accurately quantifying C&DW is challenging and, while the absolute tonnage figures are subject to a relatively high level of uncertainty, there is not a significant impact on the final recovery rate.

Defra does not provide a breakdown of the materials that make up C&DW, but other sources provide a relatively consistent indication of the concrete content by percentage:

1. The European Concrete Platform estimates that concrete accounts for 60-70% of C&DW at the EU level
2. The US Environmental Protection Agency (EPA) estimates that concrete accounts for around 70% of C&DW material before recycling[45]

3. The Construction Resources & Waste Platform (CRWP) has published an average figure of 59.3% based on five pre-demolition audits carried out by BRE[46] (see Figure 12).

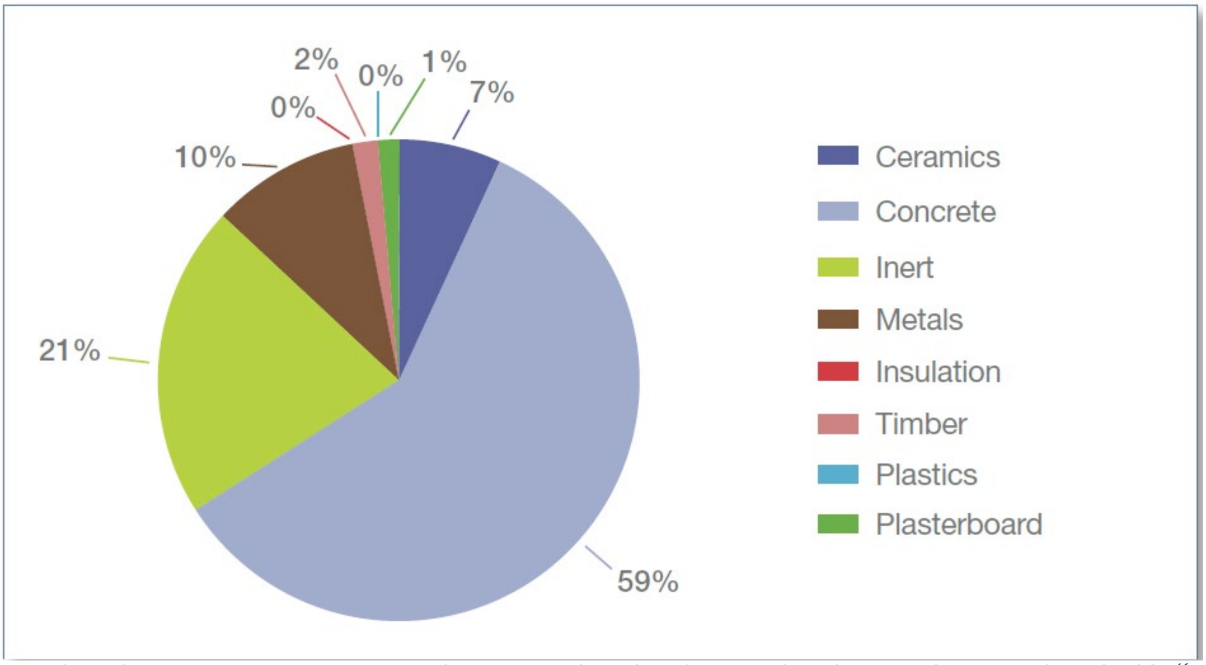


Figure 12 Demolition site waste composition by tonnage, based on five pre-demolition audits carried out by BRE[46]

Based on the consistency of the figures highlighted above, it seems reasonable to apply the figure of 59.3% published by the CRWP, particularly as this applies specifically to UK practice. This is at the more conservative end of the values detailed here and is based on data from 2008. However, it is unlikely that the concrete fraction of C&DW has changed significantly since then.

Table 7 provides a summary of concrete related C&DW data based on this average and the Defra C&D data for 2018.

Table 7 Estimate of UK concrete C&DW

2018 UK C&DW	67.8 million tonnes
2018 UK C&DW recovery	62.6 million tonnes (92.3%)
Percentage of C&DW made up of concrete	59.3% (approximately)
2018 concrete C&DW	40.2 million tonnes
2018 concrete C&DW recovered	37.1 million tonnes

10.2.Secondary use of recovered concrete C&DW

EN 16757 states that, from a carbonation perspective, there is no possibility or need to try and describe in detail what happens to recycled concrete aggregate (RCA) in the secondary use phase. However, to quantify UK RCA usage, the British Ready-Mixed Concrete Association (BRMCA) was contacted, which revealed that – due to the additional testing required – the amount of RCA from demolition used in ready-mixed concrete is negligible. MPA Precast provided a similar response, stating that very little demolition RCA is currently used, with block manufacturers being the biggest user at only 2-3% of the aggregates in blocks.

On this basis, it therefore seems reasonable to assume that the key use of RCA remains groundwork applications, including road bases and piling mats. Accordingly, the carbonation rate of RCA in secondary use should be that of concrete in the ground, with an appropriate deduction for the carbonation that has already occurred during the in-use and end-of-life stages.

10.3.UK Tier 2 model activity data – end-of-life and secondary use

Annual activity data for concrete volumes entering end-of-life and secondary use is based on the recovered tonnages of C&DW for the UK reported in the Defra waste statistics[44]. NFDC waste return data was also considered as a source of activity data. As not all demolition contractors are NFDC members, the NFDC and Defra data provided different volumes of construction waste. The Defra C&DW data was selected as more representative and a reliable source of activity data. As described in Section 10.1.1, the Defra data is multiplied by the model parameter – 59.3% – for the fraction of C&DW which is assumed to be concrete.

10.4.End-of-life and secondary use EF

It is assumed that all concrete in current C&DW is from commercial buildings, typically built in the last 30 to 60 years. Of this, 60% is high-strength concrete (from the structural frame) and 40% lower-strength concrete (such as concrete blocks used for partition walls in legacy buildings)[42]. For the high-strength concrete, only a surface layer will have carbonated during the primary service life, whereas the lower-strength concrete will have carbonated throughout.

Carbonation of the high-strength concrete will continue during the end-of-life and secondary use stages, especially after the concrete has been crushed. Most carbonation will occur during the secondary use in groundwork applications, when the crushed concrete will be buried but remain above groundwater level. Concrete which is reused onsite is assumed to be crushed to a 6F2 specification for particle size distribution[42]. Concrete which is crushed offsite and imported to a different site location is assumed to be crushed to a 6F5 specification, although some will be crushed to a finer particle size distribution, such as a Type 1 sub-base for roadworks ([42], MPA expert opinion).

Using an appropriate sieve size distribution for the 6F2/6F5 specifications, and the EN 16757 methodology, the EF for concrete at end-of-life and in secondary use is calculated as 21.39kg CO_2/tonne concrete (39.41kg CO_2/m^3 concrete). For further details see Appendix A6.4.

11.Model validation and quality assurance (QA)

The UK model has been developed to be consistent with the principles outlined in the Department of Energy Security and Net Zero (formerly BEIS) QA Guidance for Models and with the international inventory good practice outlined in the IPCC 2006 Guidelines[47]. Throughout the process of model development, the MPA team has compiled and then checked the implemented method per source/sink sub-category, and sought to ensure that the model meets the inventory data quality objectives of transparency, comparable, consistency, completeness and accuracy.

Ricardo has conducted independent QA of the model in order to align the model with the Department of Energy Security and Net Zero (formerly BEIS) QA Guidance for Models, including to score the model and deliver a QA log consistent with the Department of Energy Security and Net Zero requirements. Where issues were identified (for example, lack of transparency, errors in model algorithms or links), these were expedited iteratively between MPA and Ricardo.

11.1.Validation: comparison with independent experimental carbonation data

MPA has unrivalled access to two empirical datasets, specific to UK concretes, which are the most extensive in the UK. Since 2019, BRE has led a carbonation laboratory study as part of the MPA-led, "*Low carbon multi-component cements for UK concrete applications*" project under the BEIS Industry Energy Efficiency Accelerator programme. MPA and the University of Dundee also have a long-running laboratory-based carbonation project, providing data for concretes at ages of up to 19 years. (Figure 13 shows the application of the phenolphthalein indicator to the freshly cut concrete surfaces. The uncarbonated volume is coloured pink.)

Statistical analysis of measured carbonation data has been used to validate the EN 16757 carbonation rates and depths applied in the model for a variety of cement types and concrete mixes. The results show close alignment with EN 16757 for normal strength (up to 50MPa) CEM I concretes. For normal strength concretes containing SCMs, the experimental results are less consistent with the empirical *k*-values (for progression of the carbonation front) calculated from EN 16757. For the high-strength (>50MPa) concretes tested, the experimental *k*-values were significantly less than the EN 16757 empirical *k*-values (with one exception). In a future revision of EN 16757, it may be necessary to include additional higher strength classes, based on longer term experimental data. Appendix 5 contains details of the concrete samples tested and results.

Testing of the degree of carbonation (DoC) has not yet been carried out in these projects but is expected at completion of the testing (after 20 years).

	
CEM I concrete tested at 19 years (35.2MPa, 28-day strength)	CEM III/A concrete tested at 17 years (31.9MPa, 28-day strength)
	
CEM II/B-V concrete tested at 18 years (28.5MPa, 28-day strength)	CEM II/A-D concrete tested at 18 years (47.6MPa, 28-day strength)
	
CEM III/B concrete tested at 18 years (25.5MPa, 28-day strength)	

Figure 13 Concrete prisms tested for carbonation depth at the University of Dundee

11.2.Quantification of uncertainty

The IPCC 2006 Guidelines[47] state that an uncertainty assessment should be included in emissions or sink estimates. This is used principally to identify planned improvements in emission inventories but can also be used for comparison with atmospheric measurements and modelling and to inform mitigation measures.

The key uncertainties in the model are:

1. Uncertainties in the high-level activity data (AD), particularly in deriving concrete volumes for the different primary use applications from ONS construction output
2. Uncertainty in the EN 16757 methodology used to calculate the CO_2 uptake, notably the degree of carbonation
3. Uncertainty in the AD and EF for each of the primary use applications, for example due to differing concrete specifications
4. Uncertainty in the AD and EF for the end-of-life and secondary use applications.

Full details of the uncertainty analysis are contained in Appendix 6.

11.2.1.Uncertainty in high-level activity data

There is very high confidence in the top-down MPA cement industry production data. Uncertainty in the ONS construction output is difficult to quantify, as is the uncertainty in the ONS proxies which the model uses to convert construction output into concrete volumes.

11.2.2.EN 16757 carbonation methodology

Sensitivity of the model EFs to the degree of carbonation has been tested, by varying D_c between 40% and 90%.

11.2.3.Uncertainty in primary use AD and EFs

The uncertainty in AD and EFs has been tested for each of the primary use applications.

Buildings – steel composite frame, and buildings – concrete frame

Expert opinion is that concrete specifications for these types will vary, particularly for the superstructure. The cement content and CEM I and SCM proportions of the mix will impact the reconciliation of the bottom-up concrete volume data with the top-down cement production data.

The EF will also be affected. The maximum theoretical CO_2 uptake will be reduced by higher SCM content, but the progression of the carbonation front will increase.

Uncertainty in the AD and EF was tested by varying the GGBS content with the cement types and concrete specifications.

Buildings – masonry

The AD for masonry buildings depends upon the proportion of new dwellings, which are houses or low-rise apartments of masonry construction. The NHBC data used to measure this covers 75% of the market for new housing and is therefore considered relatively accurate. The amount of masonry construction in non-housing is expected to be a low proportion of total masonry construction.

To quantify the uncertainty in the AD and EF, two different types of commonly used masonry concrete blocks – lightweight aggregate blocks and aircrete blocks – have been considered.

Infrastructure

The uncertainty in both the AD and EF for infrastructure is very high. This sector includes a wide variety of applications, such as energy, roads, rail and water. Concrete use varies considerably between and within different sub-sectors.

Merchants and mortar

Confidence is high in the AD for cement volumes used for factory-made mortars and sold through merchants. There is much lower confidence in the end use. Mortars range in strength depending on the application. The uncertainty in AD has been tested by considering the variation in cement content for different industry standard mortar specifications.

The uncertainty in EF is much higher due to the low confidence in the end use of the products within this application. To test uncertainty, an EF calculation has been made for a typical post base buried in the ground.

11.2.4.Uncertainty in secondary use AD and EFs

The end-of-life and secondary use AD uses 59.3% as an estimate of the concrete fraction in recovered C&DW (Section 10.1.1), based on a UK case study. Uncertainty has been quantified by varying the AD by ±20%.

The calculated end-of-life and secondary use EF is 21.39 kg CO_2/tonne or 39.41kg CO_2/m^3 concrete, assuming a mixture a high and low-strength concretes.

As a lower limit on the EF uncertainty, the IVL default EF for normal handling at end-of-life and in secondary use of 20kg CO_2/m^3 concrete is used, but only applied to the 60% of concrete waste assumed to be high-strength. The lower limit on the EF uncertainty is therefore 6.51kg CO_2/tonne (12.00kg CO_2/m^3) concrete.

To estimate the upper limit on the EF, it is assumed that all concrete waste is high strength concrete. For an average high-strength concrete, IVL suggest that the CO_2 uptake, under favourable conditions for end-of-life handling and secondary use applications, could reach 110kg CO_2/m^3 concrete. This corresponds to ~75% of the maximum theoretical CO_2 uptake potential. If the degree of carbonation is increased to 90% - as proposed in the literature review (Appendix 7) - the EF is 132kg CO_2/m^3 concrete (57.64kg CO_2/tonne). This value is used as the upper limit in the uncertainty analysis.

12.Results

12.1.UK carbonation of concrete carbon emissions sink

Table 8 shows the carbon emissions sink calculated using the UK Tier 2 model developed in this project. CO_2 uptake is given for each primary use application and summed over all primary use applications. The total CO_2 uptake in primary use of concrete and for end-of-life and secondary use concrete is presented in ktonne CO_2. Two figures are given for the total CO_2 uptake as a percentage of calcination emissions in the given reporting year. The production basis value compares the CO_2 uptake with the calcination emissions from UK domestic cement production reported in the UK GHGI category 2A1. The consumption basis value compares the CO_2 uptake with the calcination emissions from UK domestic cement consumption including imports. The final column gives the total UK carbon emissions sink from CO_2 uptake by carbonation of concrete.

For 2020, the total CO_2 emissions sink from concrete carbonation is calculated as 1,548 ktonne CO_2, comprising 862 ktonne CO_2 from concrete in primary use and 686 ktonne CO_2 from concrete at end-of-life and in secondary use. This equates to 40% of the CO_2 calcination emissions from UK cement production, or 31% of the CO_2 calcination emissions from UK cement consumption, and 0.4% of the total UK GHG emissions.

12.2.Uncertainty

A combination of expert judgement and quantitative analysis based on sensitivity tests has been used to derived uncertainty ranges for the AD and EFs for each primary use application and for end-of-life and secondary use (Section 11.2, Appendix 6).

In 1990, the estimated total emissions sink, and overall uncertainty is 2.017 Mt CO_2 ± 27%.

In 2020, the estimated total emissions sink, and overall uncertainty is 1.548 Mt CO_2 ±34%.

Table 8 CO_2 uptake from concrete carbonation - UK Tier 2 model output

	Concrete applications – primary use					TOTAL primary use			Concrete – end-of-life, secondary life			
	Buildings											
	Steel composite frame	Concrete frame	Masonry	Infra-structure	Merchants and mortar	TOTAL	as % of UK calcination emissions		TOTAL	as % of UK calcination emissions		GRAND TOTAL
Output units	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*production basis*	*consumption basis*	*ktonne CO_2*	*production basis*	*consumption basis*	*ktonne CO_2*
1990	408	52	155	36	692	**1,343**	**18%**	**18%**	**674**	**9%**	**9%**	**2,017**
1991	325	43	131	43	597	**1,138**	**19%**	**19%**	**674**	**11%**	**11%**	**1,813**
1992	260	38	136	41	520	**995**	**18%**	**18%**	**674**	**12%**	**12%**	**1,669**
1993	244	39	162	43	524	**1,011**	**18%**	**18%**	**674**	**12%**	**12%**	**1,686**
1994	278	45	187	42	574	**1,126**	**18%**	**18%**	**674**	**11%**	**11%**	**1,800**
1995	276	42	160	41	552	**1,070**	**17%**	**17%**	**674**	**11%**	**11%**	**1,745**
1996	278	41	149	43	554	**1,064**	**17%**	**17%**	**674**	**11%**	**11%**	**1,739**
1997	290	43	162	40	537	**1,072**	**16%**	**16%**	**674**	**10%**	**10%**	**1,746**
1998	309	42	159	36	533	**1,079**	**16%**	**16%**	**674**	**10%**	**10%**	**1,753**
1999	322	41	141	32	501	**1,038**	**16%**	**16%**	**674**	**10%**	**10%**	**1,713**
2000	323	48	166	33	522	**1,093**	**17%**	**17%**	**674**	**11%**	**11%**	**1,767**
2001	306	44	151	33	414	**947**	**16%**	**15%**	**674**	**12%**	**10%**	**1,621**
2002	298	45	158	33	426	**961**	**16%**	**14%**	**674**	**11%**	**10%**	**1,635**
2003	289	51	184	28	482	**1,034**	**18%**	**16%**	**674**	**11%**	**11%**	**1,709**
2004	289	68	214	22	487	**1,079**	**18%**	**16%**	**674**	**11%**	**10%**	**1,753**
2005	277	71	288	28	452	**1,115**	**19%**	**17%**	**674**	**11%**	**10%**	**1,790**
2006	292	69	292	26	444	**1,122**	**19%**	**17%**	**674**	**11%**	**10%**	**1,796**
2007	314	72	296	27	451	**1,160**	**19%**	**17%**	**674**	**11%**	**10%**	**1,834**
2008	265	77	212	26	404	**984**	**19%**	**17%**	**674**	**13%**	**11%**	**1,658**
2009	195	57	144	26	319	**741**	**20%**	**17%**	**674**	**18%**	**16%**	**1,415**
2010	192	51	168	31	327	**768**	**20%**	**17%**	**670**	**18%**	**15%**	**1,438**
2011	196	57	191	35	337	**816**	**20%**	**17%**	**694**	**17%**	**15%**	**1,510**
2012	183	48	183	33	311	**758**	**20%**	**18%**	**641**	**17%**	**15%**	**1,400**
2013	195	50	214	37	321	**817**	**20%**	**17%**	**656**	**16%**	**14%**	**1,474**
2014	210	55	275	37	346	**924**	**22%**	**18%**	**710**	**17%**	**14%**	**1,634**

	Concrete applications – primary use					TOTAL primary use			Concrete – end-of-life, secondary life			GRAND TOTAL
	Buildings											
	Steel composite frame	Concrete frame	Masonry	Infra-structure	Merchants and mortar	TOTAL	as % of UK calcination emissions		TOTAL	as % of UK calcination emissions		
Output units	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*ktonne CO_2*	*production basis*	*consumption basis*	*ktonne CO_2*	*production basis*	*consumption basis*	*ktonne CO_2*
2015	218	53	286	44	353	**953**	**22%**	**18%**	**732**	**17%**	**14%**	**1,686**
2016	217	58	302	41	424	**1,042**	**23%**	**20%**	**757**	**17%**	**14%**	**1,799**
2017	214	54	314	42	380	**1,004**	**23%**	**17%**	**794**	**18%**	**14%**	**1,798**
2018	205	50	332	44	370	**1,001**	**23%**	**18%**	**791**	**18%**	**14%**	**1,792**
2019	196	52	341	45	356	**990**	**22%**	**17%**	**801**	**18%**	**14%**	**1,791**
2020	169	44	286	46	317	**862**	**22%**	**17%**	**686**	**18%**	**14%**	**1,548**

Table 9 Comparison of calculated UK EFs with EFs calculated for Sweden[2]

Primary use Application	**UK**		**Sweden**	
	Prototype	**Emissions sink factor** *(kg CO_2/m^3 concrete)*	***Prototype***	**Emissions sink factor** *(kg CO_2/m^3 concrete)*
Infrastructure	**Concrete slipform road barrier** Concrete strength (cylinder) 25-35MPa cement content 300kg/m^3 cement type CEM I service life: 50 years	5.65	**Portal-frame bridge** Concrete strength (cylinder) ≥35MPa cement content 400kg/m^3 cement type CEM I service life: 100 years	6.9
Buildings - concrete frame	**Residential building** Concrete strength (cylinder) 25-35MPa cement content 340kg/m^3 (substructure) 300kg/m^3 (superstructure) cement type CEM IIIB (substructure) CEM IIB (superstructure)	14.1	**Residential building** Concrete strength (cylinder) = 30MPa cement content 330kg/m^3 cement type CEM I	18.4

12.3. Discussion

12.3.1. Comparison with IVL Tier 1 methodology

The IVL Tier 1 methodology estimates that 23% of the raw material calcination CO_2 emitted during production of the cement consumed each year is reabsorbed: 20% by concrete in its primary use (based on current construction levels) and 3% by demolished and recycled concrete.

The total CO_2 uptake in primary use of concrete and for end-of-life and secondary use has been compared to UK calcination emissions as reported in the UK GHGI (production basis), and to UK calcination emissions calculated on a cement consumption basis.

On a consumption basis, the CO_2 uptake in primary use of concrete varies between 14% and 20% of UK calcination emissions. The calculated CO_2 uptake in primary use of concrete is therefore consistent with the IVL Tier 1 estimate.

The CO_2 uptake in end-of-life and secondary use of concrete varies between 9% and 16% of UK calcination emissions, on a consumption basis. Although higher than the IVL Tier 1 estimate, this is consistent with higher historic construction rates, and recovery and recycling rates in the UK. Also, nearly all secondary use of concrete is in unbound applications, such as road base and filling material, which the IVL reports acknowledges have large potential for carbonation.

12.3.2. Comparison with other primary use EFs

Table 9 compares the primary use emissions sink factors calculated in this project with two examples from EN 16757:2017 Annex BB[2] (Annex G in EN 16757:2022[48]) where EFs have been calculated for concrete structures in Sweden.

For a portal-frame bridge, which is taken as representative of the infrastructure sector, the CO_2 uptake EF is 6.9kg/m^3 concrete. The UK infrastructure EF calculated in this project, based on a concrete slipform road barrier, is lower, at 5.65kg/m^3 concrete. Although the UK prototype uses a somewhat lower strength concrete, leading to increased CO_2 uptake, the Swedish prototype has a higher cement content and a longer service life and therefore a higher overall EF.

For a concrete-frame residential apartment building, the CO_2 uptake EF is 18.4kg/m^3 concrete. Values for the UK concrete frame EF calculated in this project range from 14.1kg/m^3 concrete in 1990/2020 to 12.18kg/m^3 concrete for current construction. Most carbonation takes place in the substructure, for which the UK prototype has both lower cement content and uses a cement with lower clinker content than the Swedish building.

Although of similar magnitude, the UK-specific primary use EFs calculated in this project are lower than those calculated by IVL for applications in Sweden. This gives confidence that the UK model is conservative in its calculation of carbonation.

12.3.3. Historic concrete production assumption

The IVL Tier 2 methodology assumes stable levels of historic concrete production, so that for a given reporting year, the CO_2 uptake for all concrete products/structures in primary use in the built environment can be equated with the CO_2 uptake during their service life in new-build concrete products/structures – that is, concrete products and structures which enter their primary use stage during the reporting year.

For each of the building primary use applications in the model, a service life of 60 years has been assumed in the EF calculation, with a service life of 50 years for the infrastructure EF. The historic analysis (Section 7.1) showed that concrete has been consumed within the UK for the past 100 years, with production peaking 50-60 years ago. Therefore, the assumption of relatively constant levels of historic concrete production seems entirely reasonable in the mature UK market.

13.Model limitations and recommendations for future work

Comparison of the model outputs with previous work done elsewhere (Section 12.3) gives confidence that the UK Tier 2 model developed is robust for primary use concrete, and that the estimated CO_2 sink from carbonation of concrete could therefore be considered for inclusion within the next UK NIR.

The model has been designed to facilitate future improvement and potential extension to a UK Tier 3 model. Reporting results for each primary use application separately allows each category to be easily disaggregated. High priorities to reduce the uncertainty in the model include improvement of the quality of the bottom-up activity data – especially for the diverse infrastructure sector – and more experimental data on the rate and degree of carbonation within UK concretes, especially at higher strengths (>50MPa).

13.1.Recommendations for model improvements

13.1.1.Bottom-up primary use activity data and emissions sink factors

Improving the accuracy of the primary use activity data is a key priority for future research to reduce uncertainty. No direct data is available for the volumes of concrete used in different sub-sectors of the UK economy. Instead, economic indicators of construction activity per sub-sector from ONS construction output data are used. Proxy relationships of economic indicators to concrete consumption have been developed based on a targeted market survey and expert opinion. However, there remains a high level of uncertainty that the resulting sector and sub-sector estimates of concrete consumption are accurate.

Suggestions to improve bottom-up activity data for primary uses of concrete include:

- deeper integration of the model with the ONS methodology – for example, the potential to obtain volumes for concrete and other construction materials within the ONS construction output statistics
- exploitation of developing data sources, such as the Built Environment Carbon Database (BECD).

Non-residential buildings

All ONS non-housing construction output sectors (except health) are assumed to have a steel composite frame. While this is typical of current commercial construction practice, possible improvements include further disaggregation, such as:

- other common frame types in current use for non-residential buildings, such as steel plus hollowcore (20% by value for offices, education and retail sub-sectors) and portal frames for the rapidly expanding warehouse sub-sector
- historical distribution of construction types to reflect the shift from concrete frame towards composite and other steel frame types, especially before 2000.

Residential buildings

The split of new residential construction output into concrete-framed buildings (high-rise residential), masonry (low-rise residential and houses) and other types (mainly timber frame) is based on bespoke data provided by the NHBC for the period 2006-present, which has been averaged to create annual input parameters. However, the distribution of dwelling types (houses vs flats) and construction types does vary from year to year. The residential AD could be improved by:

- inputting annual type data (from NHBC or elsewhere)
- disaggregating into other construction types, such as timber-framed low-rise or steel-framed high-rise. Data would also be needed for typical concrete volumes in these types.

Buildings – masonry

The masonry EF is based upon a mid-terrace house. Future work could consider EFs for other masonry types, such as detached or semi-detached houses, or low-rise apartments.

Infrastructure

This sector has the highest uncertainty and should be a high priority for improvement. Future work should focus on disaggregation of AD into key sub-sectors, such as energy, roads and rail, alongside development of appropriate EFs. Projects such as new nuclear power stations and HS2 are expected to consume high volumes of concrete in bespoke applications and mixes.

Merchants and mortar

Uncertainty in AD could be reduced by developing a better understanding of the wide range of potential and actual uses of cement within this use application. Potentially, data differentiating between different factory-made mortars could be collected from producers. However, it is much harder to disaggregate AD between the different disparate uses of bagged cement sold via merchants, other than by relying on expert opinion. Nonetheless, improved AD and EFs for in-ground or partially in-ground applications, such as shed and post bases, could be considered.

End-of-life

Reasonable assumptions have been made, within the model, for UK end-of-life handling and secondary use of concrete, based on expert opinion and the limited evidence available. Given the importance of this sink, future work should focus on improving the evidence base for the extent of carbonation in end-of-life and secondary use, especially UK-specific evidence, and experimental work to confirm the extent of carbonation of secondary use concrete.

13.1.2.Top-down production data

The current model uses MPA data for cement consumption, sales of cement via merchants, and factory-made mortar sales. Top-down cement consumption is reconciled with bottom-up estimates of CEM I consumption.

Other data already collected in the MPA statistics, such as SCM consumption and cement sales to other channels, including ready-mix concrete and other concrete products, could potentially be used as additional checks on the model or to improve the top-down, bottom-up data reconciliation.

13.2.Recommendations for research into carbonation

UK experimental data from BRE and the University of Dundee gives grounds for reasonable confidence in the rate of progression of the carbonation front for normal-strength CEM I based concretes, but less confidence for concretes containing SCMs. The literature review (Appendix 7) identified the need for more experimental data on the degree of carbonation behind the carbonation front.

The experimental data also suggests much slower progression of the carbonation for very high-strength concretes – that is, with cylinder strength >45MPa. None of the calculations in the present model include such high-strength concretes. However, stakeholders have told us that high-strength concretes (50-100MPa) are being used in large infrastructure projects such as HS2 and Hinkley Point C. More long-term experimental data is needed on the progression of the carbonation front in high-strength concretes.

Such experimental data could inform UK-specific input parameters for rates and degree of carbonation to be included in a future UK Tier 3 model.

13.3.Wider recommendations

Recommendations arising from this novel and innovative research reach beyond potential future improvements to the UK model:

- International collaboration and knowledge exchange to help other countries to develop similar models – for example, with the IPCC TFI Technical Support Unit and EFDB panel.
- Consider how the carbonation sink may be incorporated, not just within the next UK NIR, but also into other UK GHG evidence and reporting systems, such as carbon budgets.
- Consider how to maximise opportunities to exploit the full potential of the concrete carbonation sink to use, store and permanently remove CO_2 from the atmosphere. Opportunities range from scaling up industrial enhanced carbonation technologies to encouraging and incentivising demolition practices to maximise carbonation of end-of-life and recycled concrete.

14.Acknowledgments

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Guildmore

H Mealing & Sons

Halsall Construction

Hanson UK

Jerram Falkus

JWG Construction

KAM Project Consultants

Lindum Peterborough

M & J Cosgrove Construction

McDermott Building Company

Moor Manage & I.V.A.S

Oliver Curran Construction

Ostin Construction

REAL Consulting

Rex Proctor & Partners

Robust Developments

Roger Casey Associates

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Timeless Building Services

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15. References

1. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. (Cambridge University Press, 2021).
2. BSI Standards Publication. BS EN 16757:2017 Sustainability of construction works - Environmental product declarations - Product Category Rules for concrete and concrete elements. (2017).
3. BSI Standards Publication. PD CEN/TR 17310:2019 Carbonation and CO2 uptake in Concrete. (2019).
4. Stripple, H., Ljungkrantz, C., Gustafsson, T. & Andersson, R. CO2 uptake in cement-containing products. 66 https://www.ivl.se/download/18.34244ba71728fcb3f3f8f9/1591705289370/B2309.pdf (2018).
5. Stripple, H., Ljungkrantz, C., Gustafsson, T. & Andersson, R. CO2 uptake in cement-containing products Background and calculation models for implementation in national greenhouse gas emission inventories. 77 https://www.ivl.se/download/18.34244ba71728fcb3f3f8f9/1622457897161/B2309.pdf (2021).
6. Swedish Environmental Protection Agency. National Inventory Report Sweden 2020 Greenhouse Gas Emission Inventories 1990-2018 Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. https://unfccc.int/documents/224123 (2020).
7. Friedlingstein, P. et al. Global Carbon Budget 2020. Earth Syst. Sci. Data **12**, 3269–3340 (2020).
8. IPCC - Task Force on National Greenhouse Gas Inventories. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol4.html (2019).
9. IPCC - Task Force on National Greenhouse Gas Inventories. 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Volume 3 Industrial Processes and Product Use. https://www.ipcc-nggip.iges.or.jp/public/2019rf/vol3.html (2019).
10. Andersson, R., Stripple, H., Gustafsson, T. & Ljungkrantz, C. Carbonation as a method to improve climate performance for cement based material. Cem. Concr. Res. **124**, 105819 (2019).

11. Clear, C. & De Saulles, T. BCA Recarbonation Scoping Study. (2007).
12. XPRIZE ANNOUNCES THE TWO WINNERS OF $20M NRG COSIA CARBON XP. XPRIZE https://www.xprize.org/prizes/carbon/articles/xprize-announces-the-two-winners-of-20m-nrg-cosia-carbon-xprize-with-each-team-creating-valuable-products-out-of-co2-emissions.
13. CarbonBuilt. CarbonBuilt https://www.carbonbuilt.com.
14. CarbonCure's Sustainable Concrete Solution. CarbonCure Technologies Inc. https://www.carboncure.com/.
15. Carbon8. Carbon8. Carbon8 https://www.carbon8.co.uk.
16. O.C.O Technology | Leaders in carbon capture. https://oco.co.uk/.
17. FastCarb. FastCarb https://fastcarb.fr/en/home/.
18. Solidia® – Making Sustainability Business As Usual℠. https://www.solidiatech.com/.
19. Andersson, R., Fridh, K., Stripple, H. & Häglund, M. Calculating CO_2 Uptake for Existing Concrete Structures during and after Service Life. Environ. Sci. Technol. **47**, 11625–11633 (2013).
20. ONS. Construction statistics annual tables - Office for National Statistics. https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/datasets/constructionstatisticsannualtables.
21. ONS. Construction output QMI - Office for National Statistics. https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/methodologies/constructionoutputqualityandmethodologyinformation.
22. ONS. Output in the construction industry: sub-national and sub-sector - Office for National Statistics. https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/datasets/outputintheconstructionindustrysubnationalandsubsector.
23. NHBC. NHBC Housing Market Reports. https://www.nhbc.co.uk/builders/products-and-services/data-consultancy-services/housing-market-reports.
24. DLUHC. Live tables on housing supply: indicators of new supply. GOV.UK https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building.

25. DLUHC & MHCLG. English Housing Survey. GOV.UK https://www.gov.uk/government/collections/english-housing-survey.
26. Infrastructure and Projects Authority & HM Treasury. National Infrastructure and Construction Procurement Pipeline 2020/21. GOV.UK https://www.gov.uk/government/publications/national-infrastructure-and-construction-procurement-pipeline-202021.
27. Transport Scotland. Projects | Transport Scotland. https://www.transport.gov.scot/projects/.
28. Department for Transport & Highways England. Road Investment Strategy 2 (RIS2): 2020 to 2025. GOV.UK https://www.gov.uk/government/publications/road-investment-strategy-2-ris2-2020-to-2025.
29. National Highways. Pipeline of possible future schemes - National Highways. https://nationalhighways.co.uk/our-roads/pipeline-of-possible-future-schemes/ (2022).
30. NHBC. Housing Market Report January 2021. (2021).
31. NHBC. Housing Market Report July 2021. (2021).
32. MLUHC. Live tables on housing supply: indicators of new supply. GOV.UK https://www.gov.uk/government/statistical-data-sets/live-tables-on-house-building.
33. Clear, C. Evolution of Concrete Standards and Future Developments. in Proceedings of 50th Anniversary ICT Technical Symposium (2022).
34. Trout. Market trends 1966-2006. Concrete 47–48 (2006).
35. BCSA Limited. BCSA Annual-Review 2020-2021. https://steelconstruction.org/wp-content/uploads/2021/09/BCSA-Annual-Review-2020-2021-spreads.pdf (2021).
36. Somerville, G. & International Association for Bridge and Structural Engineering. The Design life of structures: Colloquium : Workshop on the feasibility and practical application of design life principles to structures : Papers / Edited by G. Somerville. (Blackie Academic, 1991).
37. Concrete Centre (Great Britain). Cost model study - commercial buildings: a comparative cost assessment of the construction of multi-storey office buildings : a report. (Concrete Centre, 2007).

38. MPA The Concrete Centre. Office Cost Study. (2014).
39. MPA The Concrete Centre. Life cycle carbon analysis of a six-storey residential building. (2022).
40. BSI Standards Publication. BS EN 998-2:2016 Incorporating corrigendum July 2019. Specification for mortar for masonry. Masonry mortar. (2019).
41. BSI Standards Publication. BS EN 15804:2012+A2:2019. (2019).
42. NFDC. NFDC expert opinion from MPA - NFDC discussion. (2023).
43. NFDC. Correspondence between the Mineral Products Association (MPA) and the National Federation of Demolition Contractors (NFDC). (2021).
44. Defra. Defra UK Statistics on Waste. https://www.gov.uk/government/statistical-data-sets/env23-uk-waste-data-and-management (2022).
45. US EPA, O. Construction and Demolition Debris: Material-Specific Data. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/construction-and-demolition-debris-material (2017).
46. CRWP (Construction Resources and Waste Platform). Overview of Demolition Waste in the UK.
47. Eggleston, H. S., Intergovernmental Panel on Climate Change, National Greenhouse Gas Inventories Programme, & Chikyū Kankyō Senryaku Kenkyū Kikan. 2006 IPCC guidelines for national greenhouse gas inventories. (2006).
48. BSI Standards Publication. BS EN 16757:2022 Sustainability of construction works. Environmental product declarations. Product Category Rules for concrete and concrete elements. (2022).
49. European Committee for Standardization & British Standards Institution. BS EN 197-1:2011. (2011).
50. BSI Standards Publication. BS 8500-1:2015+A2:2019 Concrete. Complementary British Standard to BS EN 206. Part 1, Part 1,. (2020).
51. Harrison, H., Mullin, S., Reeves, B. & Stevens, A. Non-traditional houses: Identifying non-traditional houses in the UK 1918-75. Part 2 - Precast concrete houses. https://cis.ihs.com//CIS/search?t=non-traditional%20housing (2004).

52. Modern Masonry. MPA Masonry Easy Guides for Housing. https://www.mpamasonry.org/MMA/Construction/Easy-Guides.aspx (2018).
53. Concrete Block Association. Aggregate Concrete Blocks: Walls Below Damp Proof Course. https://www.cba-blocks.org.uk/wp-content/uploads/2020/05/Walls-Below-Damp-Proof-Cours-4.pdf (2017).
54. RICS. Retrofitting to decarbonise UK existing housing stock RICS net zero policy position paper. https://www.rics.org/globalassets/rics-website/media/news/news--opinion/retrofitting-to-decarbonise-the-uk-existing-housing-stock-v2.pdf (2020).
55. Renforth, P. Correspondence between MPA and Dr Phil Renforth, Heriot-Watt University. (2022).
56. BSI Standards Publication. BS 1377-2:2022 — Methods of test for soils for civil engineering purposes Part 2: Classification tests and determination of geotechnical properties. (2022).
57. BSI Standards Publication. BS EN 13285:2018 Unbound mixtures - Specifications. (2018).
58. BSI Standards Publication. BS EN 933-1:2012 Tests for geometrical properties of aggregates Part 1: Determination of particle size distribution — Sieving method. (2012).
59. Leemann, A., Nygaard, P., Kaufmann, J. & Loser, R. Relation between carbonation resistance, mix design and exposure of mortar and concrete. Cem. Concr. Compos. **62**, 33–43 (2015).
60. Andrade, C. Evaluation of the degree of carbonation of concretes in three environments. Constr. Build. Mater. **230**, 116804 (2020).
61. Houst, Y. F. & Wittmann, F. H. Influence of porosity and water content on the diffusivity of CO2 and O2 through hydrated cement paste. Cem. Concr. Res. **24**, 1165–1176 (1994).
62. Galan, I., Andrade, C., Mora, P. & Sanjuan, M. A. Sequestration of CO2 by concrete carbonation. Environ. Sci. Technol. **44**, 3181–3186 (2010).

Appendix 1.Cement types and concrete mixes

A1.1. Cement types and terminology

Table 10 lists the cement types and secondary cementitious materials (SCMs) referred to in this report, according to their broad designations. See [49,50] for further details.

Table 10 Cement types referred to in this report - broad designations

Cement type - broad designation	SCMs	SCMs
	Low - high content (%)	
CEM I Portland cement	-	-
CEM IIA	6-20%	Fly ash, GGBS or limestone
CEM IIB	21-35%	Fly ash or GGBS
CEM IIIA	36-65%	GGBS
CEM IIIB	66-80%	GGBS

A1.2. Secondary cementitious materials (SCMs)

Figure 14 shows the amount of cement and additions, or SCMs, produced in Great Britain from 1980 to 2020. Fly ash and GGBS were used as SCMs in concrete before 1980 but largely for major infrastructure projects and figures were not routinely collected. The recorded percentage of SCMs in cementitious material has increased since 1980 to nearly 24% in 2019[33].

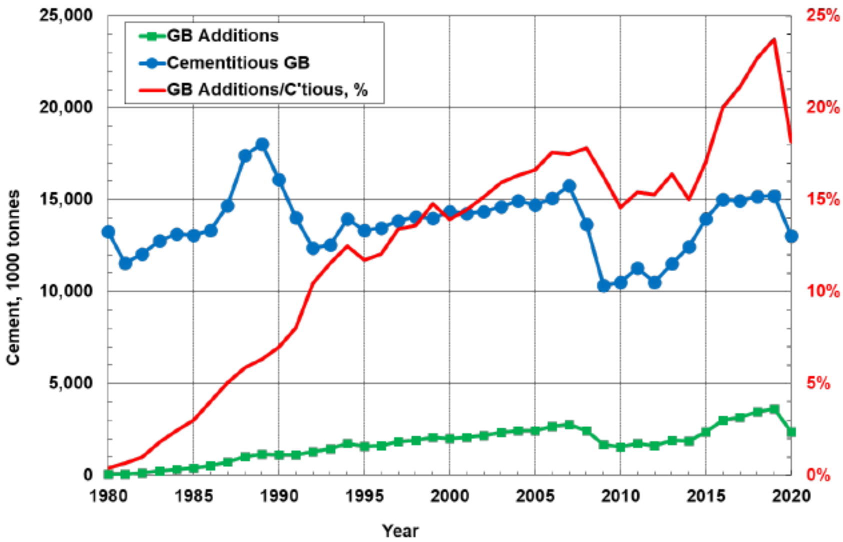


Figure 14 Growth in use of SCMs in concrete from 1980 to 2020[33]

A1.3. Concrete mixes

Expert opinion was solicited on appropriate concrete mixes to use in modelling the activity data and emissions sink factors. For the two framed building applications, different mixes were used in the AD and EF calculations for the decades centred on 1990 and 2000, and 2010 and 2020 (Table 11, Table 12). The model therefore accounts for changes in concrete mixes over this period, notably the increasing use of SCMs (Appendix A1.2), reflecting the evolution in industry practice and standards. N.B. Current cement terminology is used for all mixes. Different cement type definitions were in use in 1990 and 2000.

Table 11 Model baseline concrete mix used in Buildings -Steel Composite Frame Office AD and EF calculations

BUILDINGS - STEEL COMPOSITE FRAME	Sub/superstructure	Concrete specification	Cement type	min cement of combination content	GGBS fraction of cementitious
Year/ decade				kg cement/m^3 concrete	
2020, 2010	substructure	C28/35	CEM III A	320	50%
	superstructure	C32/40	CEM II B	300	30%
2000, 1990	substructure	C28/35	CEM III A	340	40%
	superstructure	C32/40	CEM I	325	0%

Table 12 Model baseline concrete mix used in Buildings - Concrete Frame AD and EF calculations

BUILDINGS - CONCRETE FRAME	Sub/super structure	Concrete specification	Cement type	min cement of combination content	GGBS fraction of cementitious
Year/ decade				kg cement/m^3 concrete	
2020, 2010	substructure	C25/30	CEM IIIB	340	70%
	superstructure	RC32/40	CEM II B	300	30%
2000, 1990	substructure	C28/35	CEM IIIB	340 (380 for pile caps)	70%
	superstructure	RC40	CEM I	325	0%

Appendix 2.Historical use of concrete in construction

A2.1. History of building in concrete

A2.1.1. Building boom of the 1920s and 30s

Growth during this period centred on housing and suburbia, with ribbon development, much of which remains in use, and factories. South East England also saw the development of new industries and factories. During this period, concrete became increasingly accepted as an architectural material, and there was also growth in the use of precast concrete, particularly the adoption of concrete blocks to form a double skin in housing.

A2.1.2. The Second World War

A huge extension to national infrastructure was completed in a very short period of time, much reliant on concrete as steel was required for armaments. Accordingly, cement production was a reserved occupation. Concrete was used extensively for applications as varied as aerodrome buildings and runways, gun emplacements, air-raid shelters, camps, factories for war production in dispersed locations, hospitals, pillboxes and other static defences; even barges and caissons for the Mulberry harbours [see official history (HMSO) and D. Simpson in *Concrete*].

A2.1.3. Postwar reconstruction

The use of concrete was central to postwar reconstruction, in part due to its continued greater availability compared with steel and its increasing desirability as a medium of Modern architecture. This combination was particularly evident in the rapid development of the 'new towns': Stevenage, Harlow, Crawley and Bracknell in England, Glenrothes and Cumbernauld in Scotland. This was the peak period of local authority housing, with the widespread adoption of prefabs – many systems of which were reliant on concrete components[51]. While concrete never dominated the trunk road network, concrete estate roads – now often covered with asphalt – were a feature of this period.

Away from architecture, actual construction was torn between urgent demand and rationed materials. The use of steel, even reinforcing steel, was licensed and subject to quotas well into the 1950s. For some time after the War, the diversion of steel from construction to more nationally advantageous purposes, such as car manufacture, represented both an opportunity and a difficulty for reinforced concrete.

To minimise the requirement for steel, prestressing was adopted, especially in the search for ever-greater spans for bridges, factories, aircraft hangars and bus garages. In the latter case, wartime restrictions on buses were lifted in 1948 and local authorities all over the UK commenced planning for garage construction, with most coming into service in the early 1950s. The Prestressed Concrete Development Group was established by the Cement & Concrete Association (C&CA) in 1951.

Prestressed beams became widespread, and shell roofs increasingly favoured. (Between 1948 and 1960, the peak of shell construction in the UK, 50% of shell designs were by GKN / Twisteel and 35% by BRC.) With road building having been suspended since the late 1930s, there was considerable pent-up demand for improved communications and the C&CA saw a major opportunity for concrete. Just as it did for prestressed concrete, it established a development group for paving. At the overlap of these two interests was the development of the prestressed road bridge in the mid-1950s, with Northam Bridge, Southampton the first of any significance. And in the railway sector, engineers such as Paul Abeles developed prestressed or partially prestressed bridges in the postwar period. The prestressed railway sleeper, developed during the War, soon found widespread use too. (By the early 1980s, despite the contraction of the network since Beeching, British Rail was producing 1.5 million sleepers a year.)

A2.1.4. The 1960s

By most measures, the 1960s – up to 1973 – were the (long) decade of maximum growth for the use of concrete, a period characterised by ongoing urban development, the erection of tower blocks, continued house building, the expansion of the higher education sector, building the motorway network and several extended viaducts such as the Mancunian Way, Hammersmith Flyover and the Westway. Concrete played a major role in all of these sectors: especially in the development of 'industrialised building' with panel systems (discredited by the collapse of Ronan Point), housing in proprietary methods such as Wimpey No Fines, a wide range of proprietary floor components (which during the 1950s had risen from 0 to 1.3m sq yds by 1960), and the agreement of standard designs for motorway bridges (concrete being overwhelmingly the dominant structural material at the time).

A2.1.5. Since 1974

The vogue for industrialised building in the 1960s was short-lived and PRC housing finally came to an end by the mid-1970s. The water supply industry reached its peak in the 1960s, and ceased to enjoy such high levels of investment after the mid-1980s. Much the same could be said of agricultural building in the 1970s; the concrete portal frames so widely used in this sector are now no longer available. The motorways programme came to an end, and major road building was largely suspended in 1997. Concrete as a paving material was phased out at the turn of the century. Out-of-town shopping in the 1990s and 2000s and the current (2020s) boom in distribution warehouses represent limited opportunities for concrete, apart from flooring. Housebuilding, increasingly confined to the private sector after the mid-1980s, has adopted more timber-frame methods in recent years, and the latest generation of bridges is being strongly challenged by steel.

To counter these challenges, the industry has sought to improve the image of concrete (emphasising the range of finishes, for instance, in the 1970s), develop technical responses (tilt-up construction in the 1990s, insulated concrete formwork, thin-joint masonry and offsite construction more recently) and target specific new markets (such as domestic basements).

And many market segments *have* seen growth as the economy has changed; others have developed in response to technical innovation. The promotion of foamed concrete was associated with the utilities boom of the early 1990s. In the residential sector there has been the development of beam-and-block flooring and a steady increase in hard landscaping for private gardens, the adoption of pattern-imprinted concrete for driveways in the early 1990s and further growth in rival block paving. The current concentration on apartment building has opened a new market for in-situ concrete, and precast 'flat pack rooms' for hostels, prisons, and student accommodation received a boost in the late 1990s, associated with PFI investment in the public sector. Other infrastructure work has concentrated on the health and education sectors and bridge strengthening.

More traditionally, considerable demand for concrete has been created by such headline projects as the London, Severn, and Humber bridges in the 1970s, the Channel Tunnel and Canary Wharf in the late 1980s and 90s, and facilities for the Olympic Games in the late 2000s and early 2010s[34].

A2.2. Concrete vs steel

Since the collapse of manufacture in 1979-81 and the car and ship building industries in particular, steel has sought alternative use in rival sectors – notably construction. Multi-storey buildings were a key battleground in the early 1990s, which coincided with, and prompted the launch of, the 'Better Build in Concrete' campaign and the RCC. Earlier, the Steel Construction Review had been established in 1989 to "sharpen the competitive edge of steel at a time when it is already making headway in the market against concrete" [IID 34348]. In 1993, steel accounted for 61.6% of buildings two storeys or taller, according to British Steel [IID 72330].

	Structural steel	In-situ concrete	Masonry	Precast	
1980	33.3%	48.5%	14.3%	-	
[1990	52.3%	27.4%	15%	5.3%	IID 42526]
[1990	51%	27%	17%	5%	IID 49540]
1992	56.9%	26.8%	13.7%	2%	
1993	61.6%	23.3%	11.9%	2%	

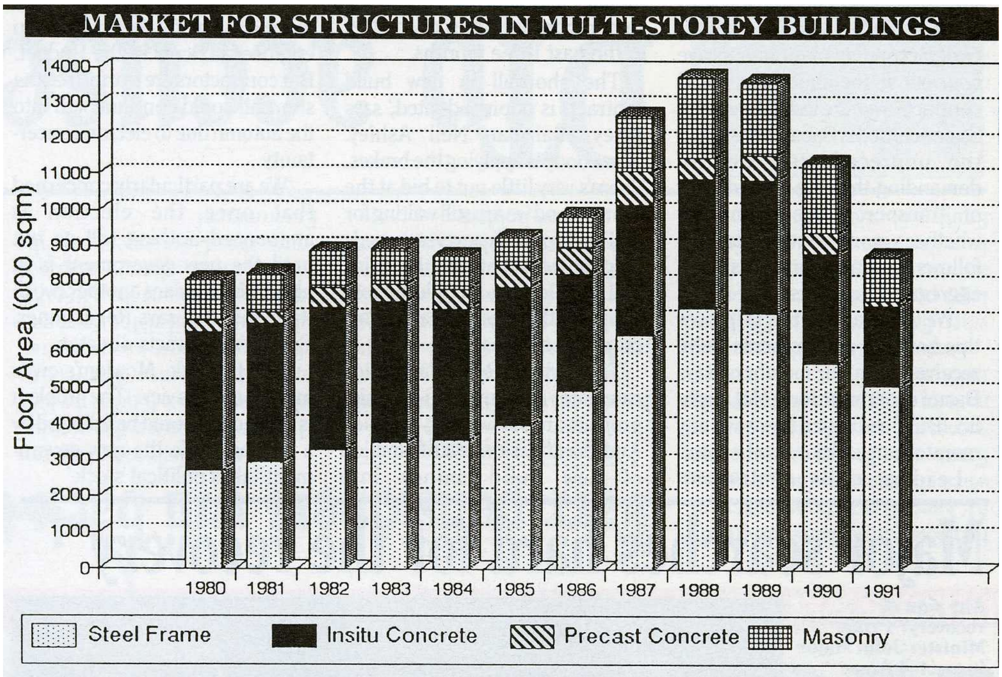


Figure 15 Concrete Journal, 27 February 1992

A2.3. Service life

A2.3.1. Expected service life

Clearly buildings are designed and expected to last a variety of durations. The expected service life, as specified (and insured for) with economically acceptable maintenance, depends on function and conditions of operation, and the requirements and budget of the client. However, there are conventional expectations, and these were set out in 1950 as CP3: Life expectancy & Durability of buildings. In 1991 this document was updated (see Section 7.3).

A2.3.2. Age at demolition

For service life in practice, we might consider the characteristic age of classes of building at the time of demolition. This is challenging and difficult to document with any comprehensiveness (even impossible to trace systematically). However, some trends seem apparent under a broad historical review:

- Demolition since the 1990s probably includes an increasing proportion of concrete structures from the heyday of concrete construction in the 1960s and 70s
- After the War, there was bomb damage and slum clearance within towns, and expansion on greenfield sites outside. (Little demolition of concrete)
- Then by the 1960s, new infrastructure and reuse of redundant railway estate (traditionally a major user of concrete)
- In the 1970s, docks closures freed large areas of concrete infrastructure for redevelopment, and in the 1980s, many established industrial sites closed (though these represented a wider variety of materials). From 1987-91, Garden Festivals sought to generate redevelopment

- The Housing Defects Act of 1984 initiated the remediation of postwar concrete housing
- High profile demolitions include such landmark buildings as the Brynmawr rubber factory (1946-52), listed in 1986 but later demolished in 2001

A2.4. Historic trends and changes in typical concrete mixes

A2.4.1. Strength

The strength of concrete test cubes was monitored by BRE on a consistent basis from 1934 to the 1980s, and the results reveal an increase in cement strengths over this time. [Lea p.21]

“Modern Portland cements (1983) produce significantly greater compressive strengths in mortars and concretes than did the cements of the 1950s and earlier. The observed strength increases allow significant reductions in cement content and increases in water/cement ratio while still achieving specified strengths. Such reductions are sufficient to produce adverse effects on durability.” [P.J. Nixon, BRE, Sept 1983]

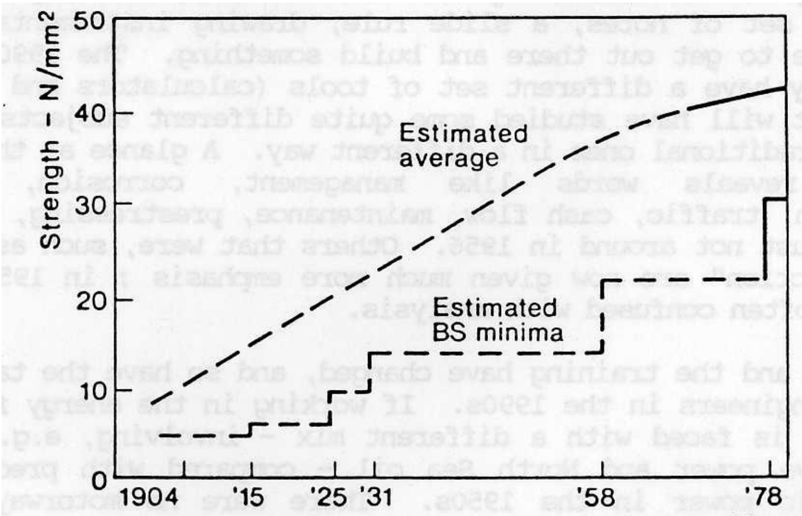


Figure 16 Increase in cement strengths when measured on standard concrete cubes with a w/c ratio of 0.6 (Somerville 1990 PP/528)

A2.4.2. Cement intensity

“The demand for cementitious materials in the UK is no higher now than it was 30 years ago, but construction output has increased by around 30%. This decline has, on average, subtracted around 1% from cementitious demand each year since the early 1960s.” This is due to the increasing sophistication of buildings and competition from other materials. “While cement strength has increased significantly since the mid-1970s, the amount of cement used in a cubic metre of ready mixed concrete has increased rather than declined.” Review of changes in cement intensity in the UK (MMD for BCA, April 1997)

Depending on the selection and proportioning of constituents, the strength of concrete can be greatly increased in line with codes and costs, though in practice this is difficult to quantify.

In the 1950s, “minimum strengths may be 1,200 to 1,500 lbs per sq in below the average strength, but in poorly supervised work, more than 2000 lbs” [Notes for students, based on CP 114:1957]. However, increasing cement strengths up to the mid-1980s, new design codes and other technical factors have also chipped away at the quantities of concrete needed for a given level of construction.

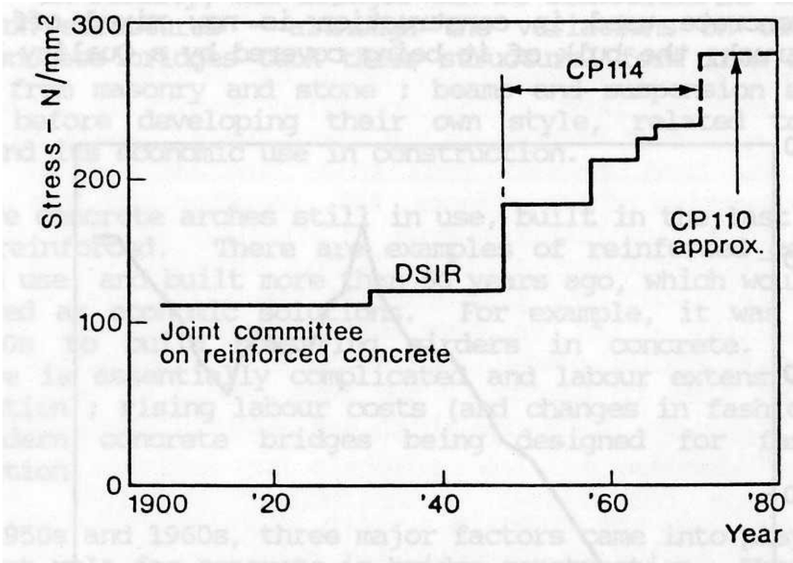


Figure 17 Increase in reinforcement stresses indicating increasing strength, and increasing proportion of that strength permitted in design (Somerville 1990 PP/528)

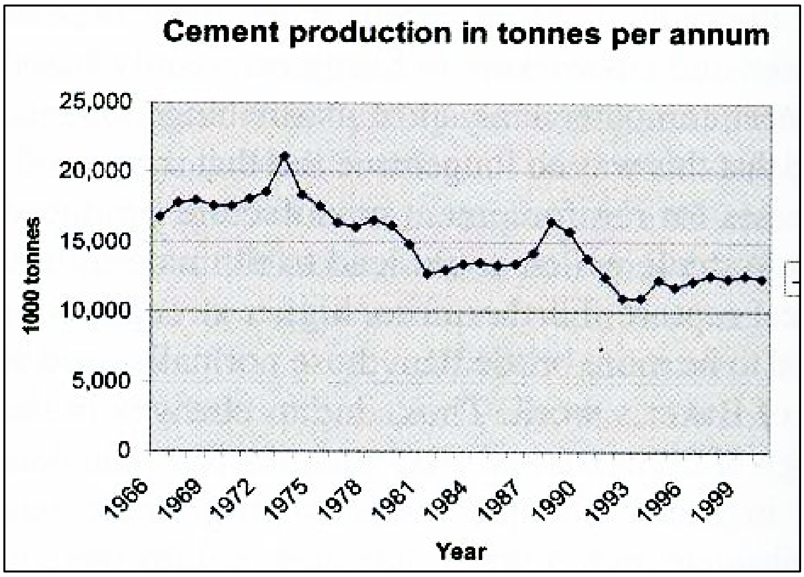
For further details of change Codes, see: Standards and Codes of Practice (and, for the period to 1985/87, commentary in TR70: 'Mix proportions and strength' pp.10-24)

A2.5. Historic concrete consumption

Consumption may be measured in various ways: by volume of material, method of delivery (ready-mix v precast) and application by element or market segment.

Table 13 Cement and clinker production (tonnes)

1966	16,836,000	1984	13,552,000	2016	9,370,000
1967	17,789,000	1985	13,403,000	2017	9,359,000
1968	17,977,000	1986	13,465,000	2018	9,197,000
1969	17,573,000	1987	14,311,000	2019	9,079,000
1970	17,583,000	1988	16,506,000		
1971	18,141,000	1989	15,764,000		
1972	18,664,000	1990	13,910,000		
1973	21,182,000	1991	12,506,000		
1974	18,408,000	1992	11,006,000		
1975	17,575,000	1993	11,039,000		
1976	16,357,000	1994	12,307,000		
1977	16,054,000	1995	11,805,000		
1978	16,564,000	1996	12,214,000		
1979	16,240,000	1997	12,638,000		
1980	14,916,000	1998	12,429,000		
1981	12,788,000	1999	12,697,000		
1982	13,030,000	2000	12,452,000		
1983	13,457,000				



Concrete building blocks (000m²)

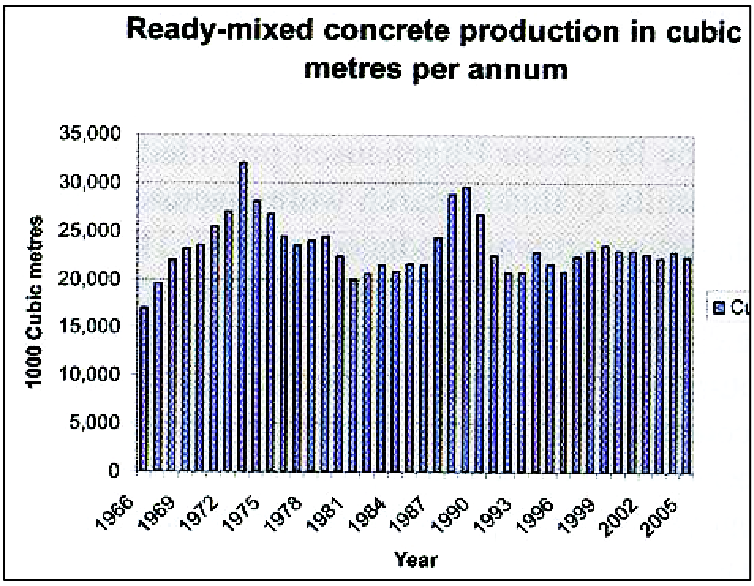
1982	63,685	2015	64,920
1983	75,641	2016	70,893
1984	81,842	2017	71,929
1985	74,445	2018	71,603
1986	87,154	2019	70,326
2011	52,901	2013	57,995
2012	52,021	2014	56,953

Concrete roofing tiles (000m² of roof area covered)

1982	25,551	2016	24,615
1983	33,243	2017	26,111
1984	34,685	2018	26,931
1985	27,870	2019	25,927
1986	30,843		

Table 14 Ready-mixed concrete (m³)

1966	17,000,000	1977	23,500,000	1988	28,844,000	1999	23,550,000
1967	19,500,000	1978	24,000,000	1989	29,596,000	2000	23,043,000
1968	22,000,000	1979	24,447,000	1990	26,782,000	2001	23,008,000
1969	23,200,000	1980	22,411,000	1991	22,527,000	2002	22,597,000
1970	23,500,000	1981	19,881,000	1992	20,776,000	2003	22,289,000
1971	25,500,000	1982	20,651,000	1993	20,776,000	2004	22,856,000
1972	27,000,000	1983	21,533,000	1994	22,931,000	2005	22,432,000
1973	32,000,000	1984	20,806,000	1995	21,676,000	2016	17,670,000
1974	28,000,000	1985	21,612,000	1996	20,892,000	2017	17,209,000
1975	26,716,000	1986	21,537,000	1997	22,327,000	2018	17,060,000
1976	24,500,000	1987	24,363,000	1998	22,983,000	2019	16,426,000



Based on figures from government and the then Quarry Products Association (now MPA)

A2.5.1. Form of delivery

While sales of ready-mixed concrete are identified in the government statistics, the relative proportions of concrete delivery for site-mixed and precast are not systematically recorded, though they are indicated by the channels of sale into which cement deliveries are divided: bulk to ready-mixed concrete producers, bulk to precast producers, bagged to builders' merchants and 'other'. The relative proportion of these segments has changed over time (see BCA and MPA Cement statistics for historical and current channels of sale figures).

A2.5.2. Market application / end use

Further historic information on market application and end use is not included in the current model. However, reports by Construction Markets from 1991 to 2004 contain extensive statistics and commentary (for example, Table 15 and Table 16). This data could be used in future extension of the current project to develop a Tier 3 carbonation model.

Table 15 The market for cement by type of delivery/use by building sectors. (CM 1995)

	Ready-mixed concrete	Bagged	Direct to site	Precast manufacturer
Private dwellings	21%	49%	-	38%
Public dwellings	6.5%	8.8%	-	6.9%
Private commercial	15.9%	20.2%	-	12.3%
Industrial	7.4%	5.2%	-	2.7%
Other public	8.7%	5.3%	-	6.2%
Non-building uses	40.3%	12.1%	100%	33.1%

Table 16 In-situ concrete uses by end use by type of delivery (RMC) 1994

	% Ready-mixed concrete	cement (kt)
Oversite concrete	86.0%	1,390
Civil engineering	80.0%	867
Piling	86.8%	834
Suspended floors	95.4%	866
Roads	80.1%	864
Footings	71.1%	493
Brick mortar	31.5%	226
Block mortar	31.2%	219
Frames	99.1%	687
Other foundations	95.4%	458
Water and sewerage	74.9%	254
Bridges	63.4%	239
Soil stabilisation	49.4%	154
Floor screeds	52.3%	158
Farms	34.9%	22
Other	37.4%	125
Total	72.9%	7,676

Appendix 3.Market survey

Table 17 shows the key ONS construction output sub-sectors sampled in the market survey. Table 18 summarises the raw data from the market survey. Collecting the data posed several challenges. Respondents were often time-poor and unwilling to devote time to collect the data required. Frequently, respondents were unable to provide a response to all the required questions. Respondents who requested a follow-up email so they could source the missing information, overall, did not respond to provide the data.

Although all responses included the project value, data on GIFA or concrete volumes was missing from some responses. MPA therefore carried out data cleansing and gap filling (Appendix A3.2), using assumptions which aligned with standard industry practice. The resulting completed responses were also checked to ensure that they were consistent with the complete survey responses received without any gaps.

A3.1. Survey – breakdown of frame types

All survey responses included the project value and the frame type. Some projects reported multiple frame types, giving the % floor area for each frame type. (Two office projects combined steel composite frame with steel plus hollowcore. One health project was mainly concrete but included some steel composite.)

The responses were used to calculate the % of the total value surveyed in each sub-sector by frame type and therefore determine the dominant frame type (by value) within each building use category.

Table 17 ONS construction output sub-sectors sampled in market survey

<table>
<tr><th>2019</th><th colspan="2">Value of ONS construction output by type of work
New work for public and private sectors, Great Britain, current prices</th><th>(£million)</th><th>% of total</th><th>Number of projects surveyed</th><th colspan="2">Model sector/ application</th></tr>
<tr><td colspan="3" rowspan="2">New housing</td><td rowspan="2">47,588</td><td rowspan="2">40%</td><td>36</td><td colspan="2">Load-bearing masonry</td></tr>
<tr><td>34</td><td colspan="2">Framed buildings</td></tr>
<tr><td colspan="2" rowspan="3">Infrastructure</td><td>Electricity (Hinkley)</td><td>6,550</td><td>6%</td><td>1</td><td colspan="2">Infrastructure</td></tr>
<tr><td>Railways (HS2)</td><td>7,662</td><td>6%</td><td>1</td><td colspan="2">Infrastructure</td></tr>
<tr><td>Roads</td><td>4,930</td><td>4%</td><td>6</td><td colspan="2">Infrastructure</td></tr>
<tr><td rowspan="5">Other non-housing excluding infrastructure</td><td>Industrial buildings</td><td>Warehouses</td><td>3,550</td><td>3%</td><td>5</td><td colspan="2">Framed buildings</td></tr>
<tr><td rowspan="4">Non-residential buildings</td><td>Schools, colleges, and universities</td><td>10,806</td><td>9%</td><td>10</td><td>Framed buildings</td><td>Load-bearing masonry</td></tr>
<tr><td>Health</td><td>2,993</td><td>3%</td><td>11</td><td>Framed buildings</td><td>Load-bearing masonry</td></tr>
<tr><td>Offices</td><td>10,479</td><td>9%</td><td>40</td><td>Framed buildings</td><td>Load-bearing masonry</td></tr>
<tr><td>Garages, shops</td><td>5,184</td><td>4%</td><td>8</td><td>Framed buildings</td><td>Load-bearing masonry</td></tr>
</table>

Table 18 Summary of market survey results prior to data cleansing and gap filling

Sub-sector	Number of projects	Region					Construction type		Average value	Average GIFA	Framed buildings - average volume of concrete	Load-bearing buildings - average volume of concrete	Average length of road	Roads - average volume of concrete
		North	Central	South	London	Scotland, Wales, NI	Frame	Load-bearing						
									£m	m^2	m^3	m^3	km	m^3
Offices	40	10	10	8	9	3	40	-	28.03	14,874	1,112	-	-	-
Education	10	1	4	4	1	-	8	2	12.09	5,142	1,169	50	-	-
Health	11	2	3	5	-	1	9	2	18.15	3,771	795	130	-	-
Retail	8	1	3	2	1	1	7	1	3.63	943	379	54	-	-
Warehouses	5	1	3	-	-	1	5	-	3.62	4,798	1,706	-	-	-
Residential - load-bearing masonry	36	7	9	6	8	6	-	36	9.67	-	-	14,780	-	-
Residential - framed	34	6	3	7	17	1	34	-	26.38	8,119	3,824	-	-	-
Roads	6	-	2	2	1	1	n/a	n/a	31.64	-	-	-	2.1	3,250

A3.1.1. Offices

	Surveyed	Steel composite	Steel plus hollowcore	Concrete
Number of projects	40	29	7	5
% of total value		81%	11%	9%

A3.1.2. Education

	Surveyed	Steel composite	Steel plus hollowcore	Concrete	Masonry
Number of projects	10	7	2	3	2
% of total value		69%	20%	7%	3%

A3.1.3. Health

	Surveyed	Steel composite	Concrete	Masonry
Number of projects	11	8	2	2
% of total value		45%	53%	2%

A3.1.4. Retail

	Surveyed	Steel composite	Steel plus hollowcore	Concrete	Other (portal/ parabolic)	Masonry
Number of projects	8	3	3	1	1	1
% of total value		50%	15%	7%	24%	3%

A3.1.5. Warehouses

	Surveyed	Portal frame	Steel composite
Number of projects	5	3	2
% of total value		64%	36%

A3.1.6. Residential – framed

	Surveyed	Steel composite	Steel plus hollowcore (or beam-and-block)	Concrete	Other (steel)
Number of projects	34	4	3	26	2
% of total value		9%	2%	87%	2%

A3.2. Data cleansing and gap filling

Although all responses included the project value, data on GIFA or concrete volumes was missing from some responses. MPA carried out some data cleansing and gap filling, using assumptions which aligned with standard industry practice. Details of the assumptions and methodology for each primary use application are given below. The resulting completed responses were also checked to ensure that they were consistent with the complete survey responses received without any gaps.

Filling of the data gaps enabled the creation of proxies, used in the model to relate cement and concrete consumption to economic values for ONS construction output for each primary use application.

A3.2.1. Commercial buildings – for example, offices

All projects give the value. To calculate the concrete volumes used in each building, the following assumptions were used:

- GIFA
  - If unrealistic, assume response in sqft and convert to m^2
  - If not given, calculate by assuming £3,000/m^2, consistent with range of values reported in survey
- Main slab depth – assume 150mm, consistent with industry practice, for steel composite frame if not given
- Roof – assume roof will accommodate plant and is therefore also structural, as in the model case study used to calculate the EF
- Core perimeter – assume 24m, consistent with EF model
- Thickness of core walls – assume 200mm, consistent with industry practice
- Foundations requirements vary considerably with ground conditions. A conservative rule of thumb design method has been taken.
  - Assume ground conditions are London clay with an undrained shear strength of 150kPa
  - Piles – 750mm diameter, straight shafted, 30m long, consistent with EF model
- Basement – assume thickness of walls and floor 250mm, consistent with industry practice.

A3.2.2. Residential framed

All projects give the value. To calculate the concrete volumes used in each building, the following assumptions were used:

- GIFA
  - If unrealistic, assume response in sqft and convert to m^2
  - If not given, calculate by assuming £3000/m^2, consistent with range of values reported in survey
- Main slab depth – assume 225 mm where not given (only one project), consistent with EF model
- Roof
  - Pitched roof – not calculated. Roof tiles, if concrete, will be a very small fraction of the overall volume
  - If not pitched, assume concrete slab to accommodate plant, consistent with EF model
  - If “both” pitched and not pitched, assume 50% of roof area is concrete slab
- Core perimeter – assume 30m, consistent with EF model
- Thickness of core walls – 200mm, consistent with industry practice
- Foundations requirements vary considerably with ground conditions. A conservative rule of thumb design method has been taken.
  - Assume ground conditions are London clay with an undrained shear strength of 150kPa.

A3.2.3. Residential load-bearing

Houses

- GIFA – if not given
  - Detached house 120m^2
  - Semi-detached house 100m^2
  - Terraced house 80m^2

- Two storeys
- Ground floor – concrete beam-and-block above ventilated void
- Upper floor – not concrete
- Roof – 30° pitch with concrete roof tiles
- Party walls – 200mm concrete blocks
- External walls – concrete brick cavity wall with 25% openings (windows, doors)
- Strip foundations

Flats/apartments

- GIFA – 67m^2 if not given
- Three storeys with four apartments per storey
- Ground floor – concrete beam-and-block above ventilated void
- Upper floor – concrete hollowcore planks
- Roof
    - Pitched roof – 30° pitch with concrete roof tiles
    - Flat roof – no concrete as non-structural
- Party walls – 200mm concrete blocks
- External walls – concrete brick cavity wall with 25% openings (windows, doors)
- Strip foundations

A3.2.4. Infrastructure

Stakeholders shared concrete volumes for Hinkley Point C and elements of HS2 (Northolt and Euston tunnels). However, given the bespoke and technically challenging nature of these projects, it was not considered appropriate to use them to create a proxy relationship between construction value and concrete consumption for the current Tier 2 model. Further disaggregation of the infrastructure sector is recommended for future model development and could make valuable use of this data.

Roads were considered to be more representative of typical infrastructure projects and therefore used to calculate a proxy relationship between construction value and concrete consumption for the infrastructure sector.

The survey obtained data for roads from three small-scale projects (<£3m) and three large-scale (£25m – £80m). Of these, only two of the large-scale projects provided detailed information on concrete use and volumes. (The other project was at an earlier stage and therefore lacked detailed data). These two high-value projects were used to calculate the proxy value.

The first project was an urban roundabout spur road improvement. Concrete volumes were given for the pavement build-up and the precast access chambers. The second project was motorway junction upgrades. Concrete was used in, and concrete volumes given for, precast access chambers, precast concrete drainage products (culvers, drainage pipes and gully pots), concrete slipform safety barriers and bridges.

Appendix 4.Calculation of emission factors

A4.1. Calculation of CO_2 uptake

The calculation of CO_2 uptake in the primary use phase follows the methodology in Annex BB of EN 16757:2017[2]. For CEM I, assuming 95% cement clinker content, the maximum theoretical CO_2 uptake:

$$U_{tcc\ (CEM\ I)} = 0.49\text{kg } CO_2/\text{kg cement} \tag{1}$$

The depth of carbonation is given by Equation (BB.4)

$$d = k \sqrt{t} \tag{2}$$

where

d is the depth of carbonation (mm)
k is the *k*-factor (mm/year$^{0.5}$)
t is the time (year)

The CO_2 uptake per m^2 concrete surface is then

$$CO_2 \text{ uptake} = (k/1000) \sqrt{t} * U_{tcc} * C * D_c \tag{3}$$

where

k, D_c are given in Table 19
U_{tcc} is the maximum theoretical CO_2 uptake of cement (kg CO_2/kg cement)
C is the cement content of concrete (kg/m^3 concrete).

EN 16757 recommends that, as a conservative approach, the maximum theoretical CO_2 uptake, U_{tcc}, should be based on cement clinker content only.

Current concrete mix designs frequently include SCMs such as fly ash and GGBS. The clinker content is therefore lower than if only CEM I was used. Therefore, the calculation of U_{tcc} is based on the CEM I content only.

For example, if the cementitious content of the concrete mix is 30% CEM I and 70% GGBS, then

$$U_{tcc} = 30\% * U_{tcc\ (CEM\ I)}$$
$$= 0.147\text{kg } CO_2/\text{kg cement} \tag{4}$$

However, the carbonation front will progress more quickly through concretes containing SCMs. EN 16757:2017 Table BB.2 (Table 20) gives corrections to the *k*-factor for different proportions of SCMs (nb. the current British Standard for concrete, BS 8500, only allows the inclusion of one type of SCM, although this is expected to change in the forthcoming revision). For a concrete mix containing SCMs in addition to CEM I, the depth of carbonation (in mm) is

$$d = k * K_k * \sqrt{t} \tag{5}$$

the CO_2 uptake per m^2 concrete surface area is

$$CO_2 \text{ uptake} = (k/1000) * K_k * \sqrt{t} * U_{tcc} * C * D_c \tag{6}$$

where

k, D_c are given in Table 19

K_k is the SCM correction factor given in Table 20
t is the time (year)
U_{tcc} is the maximum theoretical CO_2 uptake of cement (kg CO_2/kg cement)
C is the cementitious content of concrete (kg/m^3 concrete).

For example, for a concrete mix with cementitious content 30% CEM I and 70% GGBS, K_k = 1.30, and U_{tcc} = 0.147kg CO_2/kg cement, the CO_2 uptake per m^2 concrete surface is

$$CO_2\ uptake = (k/1000) * 1.30 * \sqrt{t} * 0.147 * C * D_c \tag{7}$$

Table 19 : EN 16757:2017 Table BB.1 k-factors and degree of carbonation for different concrete strength classes (cylinder) and exposure conditions

Concrete strength	**<15MPa**	**15-20 Mpa**	**25-35 Mpa**	**>35 Mpa**	**Degree of carbonation (D_c)**
	k-factor (mm year$^{-0.5}$)				%
Civil engineering structures					
Exposed to rain		2.7	1.6	1.1	85
Sheltered from rain		6.6	4.4	2.7	75
Buried (above groundwater level)		1.1	0.8	0.5	85
Below groundwater level		0.2	0.2	0.2	85
Buildings					
Outdoor/exposed	5.5	2.7	1.6	1.1	85
Outdoor/sheltered	11.0	6.6	4.4	2.7	75
Indoor/covered (paint/wallpaper)	11.6	6.9	4.6	2.7	40
Indoor/no cover	16.5	9.9	6.6	3.8	40
Indoor/covered (tiles/ parquet/ laminate)	0.0	0.0	0.0	0.0	
Buried (above groundwater level)		1.1	0.8	0.5	85
Below groundwater level		0.2	0.2	0.2	85

Table 20 Table BB.2 — Correction for the k-factor for cement with additional major constituents or concrete with mineral additions

Amount of addition (weight %)	**≤ 10**	**10-20**	**20-30**	**30-40**	**40-60**	**60-80**
Limestone		1.05	1.10			
Silica fume	1.05	1.10				
Fly ash		1.05		1.10		
GGBS	1.05	1.10	1.15	1.20	1.25	1.30

Over a flat surface with area A (m^2), (for example, a flat slab in a concrete-framed building), the CO_2 uptake is

$$CO_2\ uptake = (k/1000) * K_k * \sqrt{t} * U_{tcc} * C * D_c * A \tag{8}$$

For surfaces which are not flat, the calculation of CO_2 uptake must take the geometry of the concrete into account. We have assumed that the carbonation depth is still given by Equation (5).

For a cylinder with radius, r (m), and height, h (m), such as a pile, assume that the carbonated volume will take the form of a cylindrical shell. The CO_2 uptake is

$$CO_2\ uptake = \pi \{r^2 - (r - d/1000)^2\} * U_{tcc} * C * D_c * h \tag{9}$$

where $d = k * K_k * \sqrt{t}$, is the depth of carbonation (in mm) as given by Equation (5).

For a sphere with radius, r, the CO_2 uptake is

$$CO_2\ uptake = (4/3)\ \pi \{r^3 - (r - d/1000)^3\} * U_{tcc} * C * D_c \tag{10}$$

A4.2. Emission factor prototypes

A4.2.1. Buildings – steel composite frame EF

The prototype used for the calculation of the emissions sink factor is a 16,500m^2, six-storey city-centre commercial building based upon typical current design practice(similar to Building B in [37,38]). The GIFA and number of storeys are consistent with the market survey results.

The building has a composite steel frame with piled foundations. Figure 18 and Figure 19 show details of the construction.

Building elements containing concrete are:

- concrete foundations (piles and pile caps) and ground slab
- concrete cores (containing stairs)
- upper floors and roof comprise a concrete slab on a metal deck (Figure 3, Figure 19).

For 2010-2020, in the superstructure, a CEM II/B with 30% GGBS content has been assumed as a typical 'average'. The foundations are CEM III/A with 50% GGBS content.

An EF has also been calculated for 1990-2000 using a CEM I mix in the superstructure and CEM III/A with 40% GGBS in the foundations. The minimum cement content is also higher, to align with standards in use at the time. See Table 11 for full details of the concrete mixes.

The assumed building service life is 60 years.

Table 21 details the building surfaces for consideration in the EF calculation.

The façade may or may not have concrete elements – none have been included in this calculation.

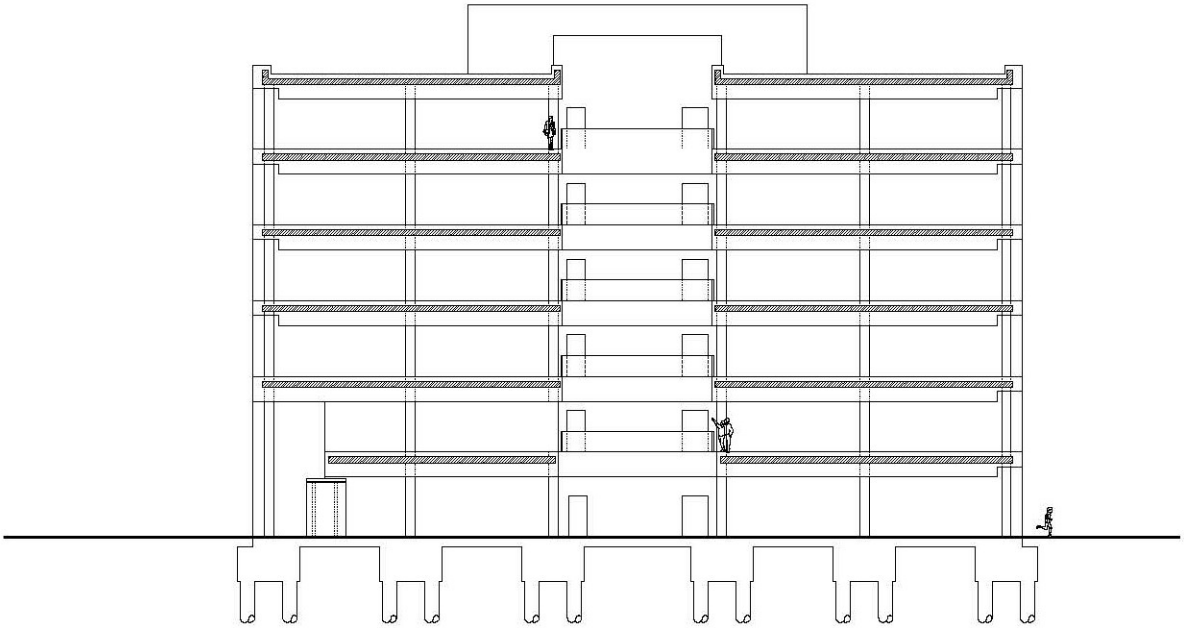
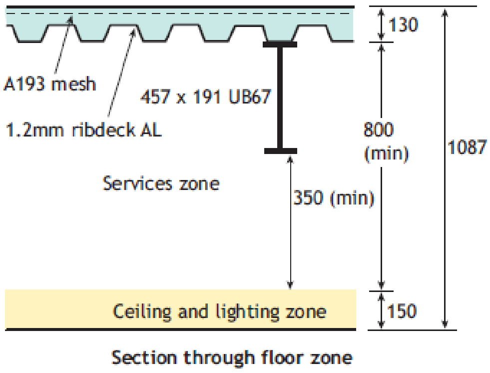


Figure 18 Cross-Section of steel composite frame office building



Composite

1. 130mm lightweight concrete slab on 1.2mm Ribdeck AL on steel frame to upper floors and roof.
2. Lightweight concrete class C 32/40.
3. Steel grade S355.
4. Assumed design imposed loads:

Roof:	0.75kN/m²
Plant room:	7.5kN/m²
Offices:	5.0kN/m²

5. Vertical dimensions:

Slab:	130mm	
Services zone(1):	807mm(2)	Floor zone = 1087mm
Ceiling/lighting:	150mm	≈ 1090mm
Floor to ceiling:		2700mm(3)
Raised floor:		250mm
Total:		**4040mm**

(1) including downstand beams
(2) increase to 950mm for GF - 1st
(3) increase to 3200mm for GF - 1st

Figure 19 Section through floor zone for steel composite frame office building

Table 21 Concrete building elements, surfaces, and exposures for composite frame office EF calculation.

Exposure condition for EF calculation *(see Table 19)*	**Building surfaces for EF calculation**	**Comment**
Outdoor/exposed	not included	roof covered with waterproof membrane
Outdoor/sheltered		façade may have concrete elements
Indoor/covered (paint/wallpaper)	none	
Indoor/no cover	floors	raised access floors allow air circulation underneath
	core walls	either exposed or under plasterboard, which also allows air circulation
Indoor/covered (tiles/ parquet/ laminate)	ceilings	covered by metal deck
Buried (above groundwater level)	substructure down to groundwater level	assume groundwater level is 3m
Buried/covered	underside of ground slab	covered by dampproof membrane so no air circulation
Below groundwater level	piles below groundwater level	

A4.2.2. Buildings – concrete frame EF

The prototype used for the EF calculation is a 2,500m^2, six-storey apartment block containing 22 flats based upon typical current design practice (similar to the concrete-frame building in [39]). The GIFA and number of storeys are consistent with the market survey results.

The building is of concrete-frame construction with piled foundations. Figure 20 shows the architectural design and layout.

Building elements containing concrete are:

- concrete foundations (piles and pile caps) and ground slab
- concrete cores (containing stairs and lift shafts)
- upper floors and roof are concrete flat slabs
- external walls are lightweight aggregate block and brick masonry construction (nb lightweight aggregate blocks used as they are more typical than the dense aggregate concrete blocks used in [39]).

For 2010-2020, for the superstructure, a CEM II/B with 30% GGBS content has been assumed as a typical 'average'. The foundations are CEM III/B with 70% GGBS content.

An EF has also been calculated for 1990-2000 using a CEM I mix in the superstructure and CEM III/A with 70% GGBS in the foundations. The minimum cement content is higher, to align with standards in use at the time. See Table 12 for full details of the concrete mixes.

The assumed building service life is 60 years. Table 22 details the building surfaces for consideration in the EF calculation. (The mortar in the external walls will also carbonate but comes under the 'merchants and mortar' primary use application.)

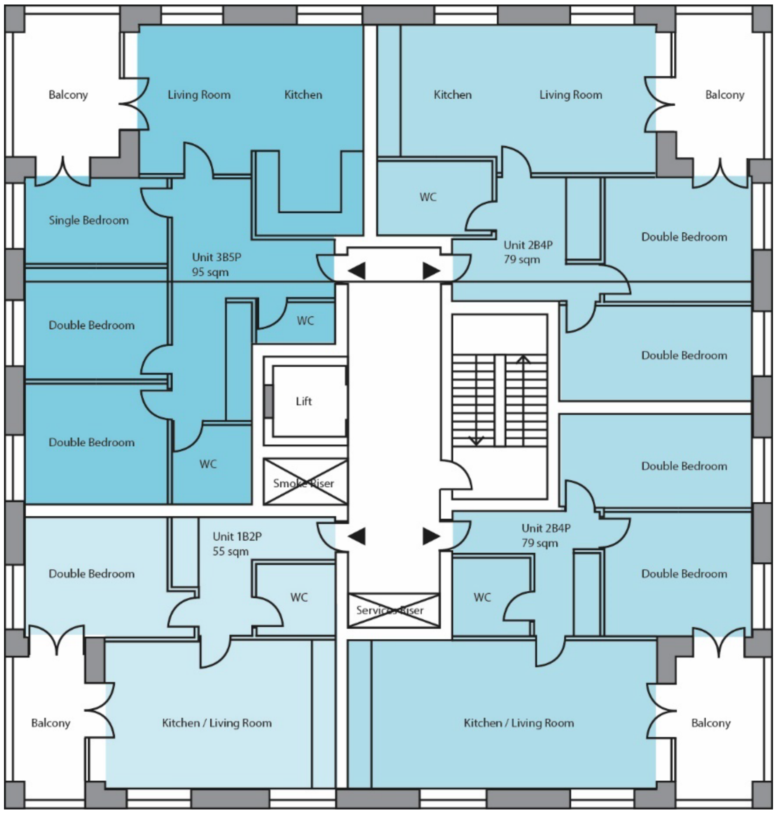


Figure 20 Layout for concrete-frame residential apartment block

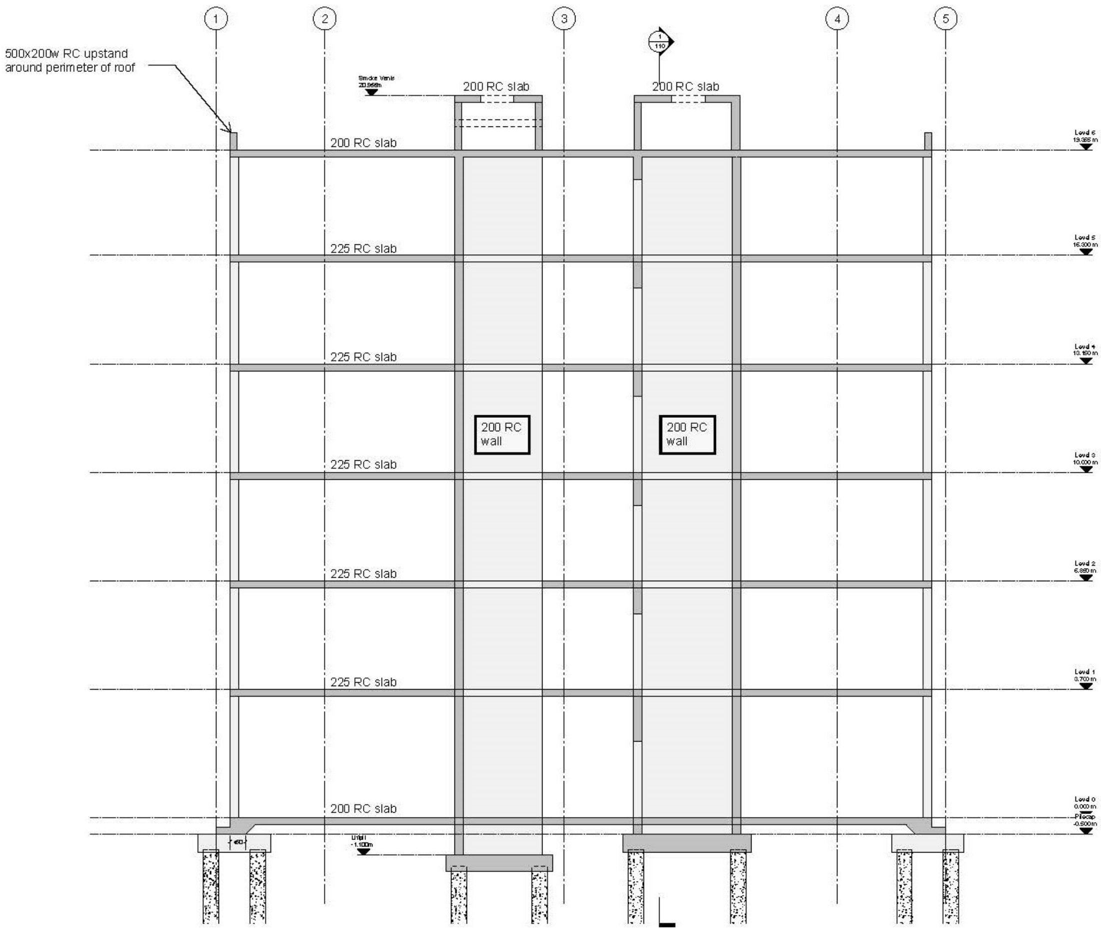


Figure 21 Cross-section of concrete-frame residential apartment block

Table 22 Concrete building elements, surfaces, and exposures for concrete-frame residential EF calculation

Exposure condition *(Table 19)*	**Building surfaces**	**Comment**
Outdoor/exposed		roof covered with waterproof membrane
Outdoor/sheltered		façade may have concrete elements
Indoor/covered (paint/wallpaper)	external walls cavity face	covered by cavity vapour barrier
Indoor/no cover	ceilings	plasterboard finish allows air circulation underneath
	core walls	either exposed or under plasterboard, which also allows air circulation
	external walls internal face	plasterboard finish allows air circulation underneath
Indoor/covered (tiles/ parquet/ laminate)	floors	all covered, no air circulation
Buried (above groundwater level)	substructure down to groundwater level	assume groundwater level is 3m
Buried/covered	underside of ground slab	covered by damp-proof membrane so no air circulation
Below groundwater level	piles below groundwater level	

A4.2.3. Buildings – masonry EF

House

The prototype used for the masonry EF calculation is a typical 80m², two-bed, two-storey mid-terrace house with masonry construction, pitched roof and concrete roof tiles (Figure 22). The house has strip foundations, beam-and-block ground floor and block-cavity-brick external walls (see Figure 24, Figure 25, from[52], for details).

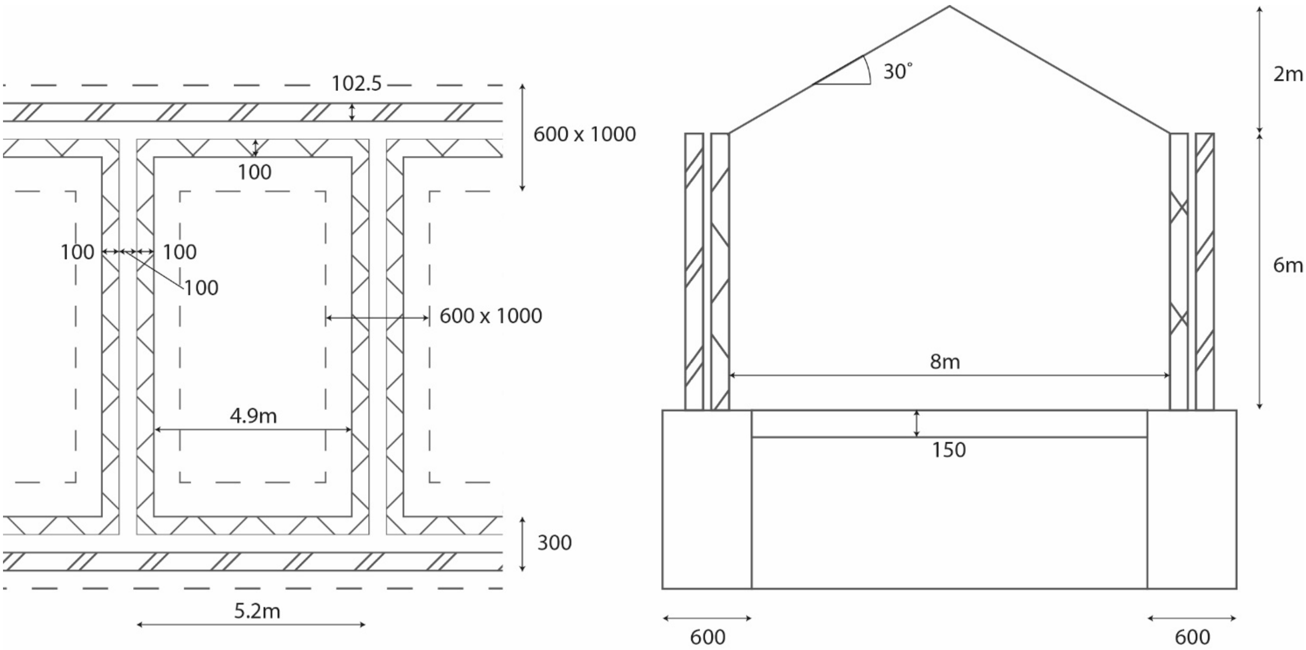


Figure 22 Plan and cross-section of 2-bed, 2-storey mid-terrace masonry house

Building elements containing concrete are:

- strip foundations
- foundation blocks
- ground floor beam-and-block construction
- party walls concrete block construction
- external walls block-cavity-brick construction (assumed 25% area for openings, such as doors and windows)
- pitched roof with concrete roof tiles.

The mortar in the external walls will also carbonate but comes under the 'merchants and mortar' primary use application (Appendix A4.2.5).

The assumed building service life is 60 years.

For the lightweight aggregate blocks in the external and party walls, and the concrete roof tiles, the carbonation calculation shows that the carbonation front will have progressed through the full depth of the blocks or tiles by the end of the building service life.

Table 23 details the building surfaces for consideration in the EF calculation.

Table 23 Concrete building elements, surfaces, and exposures for masonry EF calculation

Exposure condition *(Table 19)*	**Building surfaces**	**Comment**
Outdoor/exposed	roof	
Outdoor/sheltered	underside of ground floor	ventilation void
	upper course of foundation blocks inner surface	ventilation void
	underside of roof	
Indoor/covered (paint/wallpaper)	external walls - blockwork inner leaf face to cavity	assume vapour barrier to insulation
Indoor/no cover	external walls - blockwork inner leaf internal face	under plasterboard - allows air circulation
	party walls - internal face	either exposed (in roof space) or under plasterboard, which also allows air circulation
Indoor/covered (tiles/ parquet/ laminate)	ground floor	covered by insulation and screed
	party walls - face to cavity	no air circulation in insulated party wall cavity
Buried (above groundwater level)	strip foundations	no carbonation rates given for buried low-strength concrete in EN 16757
	foundation blocks (part)	
Below groundwater level	none	

A4.2.4. Infrastructure EF

Concrete slipform road barrier

The infrastructure EF calculation is based on a typical concrete slipform road barrier. This is regarded as an appropriate prototype as most infrastructure constructions will be outdoor and exposed to rain, whereas a tunnel (such as for HS2) is an atypical construction. Choice of this prototype is also consistent with the use of road data to calculate the proxy relationship between ONS construction output and concrete volumes for infrastructure.

For a typical concrete slipform road barrier construction, the concrete requirements include:

- A strength class normally C28/35 or above
- Cement with a minimum strength class of 42.5
- Minimum cement content 300kg/m^3
- Maximum water/cement ratio 0.55
- Crushed coarse aggregate for stability (this may be crushed rock or crushed gravel)
- A fine aggregate content to produce characteristics suitable for slipforming
- Consistence to suit the process
    - vertical slipforming S3 (120mm slump)
    - horizontal slipforming S1 (20mm slump).

The assumed service life is 50 years.

The typical geometry used in the calculation is shown in Figure 23.

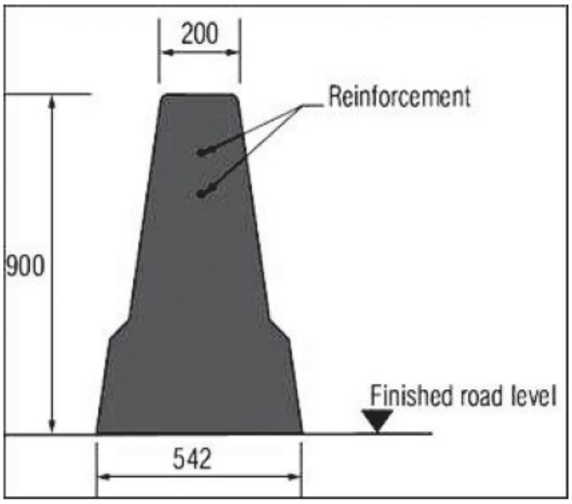


Figure 23 Typical geometry of concrete barrier (Britpave 2008: Barrier Cost Comparison)

A4.2.5. Merchants and mortar EF

The merchants and mortar EF calculation is based on the mortar use within the masonry house construction prototype used for calculation of the masonry EF. Mortar is used in the following building elements:

- party walls – concrete block construction
- external cavity walls – block and brick leafs.

The assumed building service life is 60 years. The carbonation calculation shows that the carbonation front will have progressed through the full depth of the mortar in these walls by the end of the building service life.

A small amount of mortar will also be used between the foundation blocks but, in order to simplify the calculation, this has not been included.

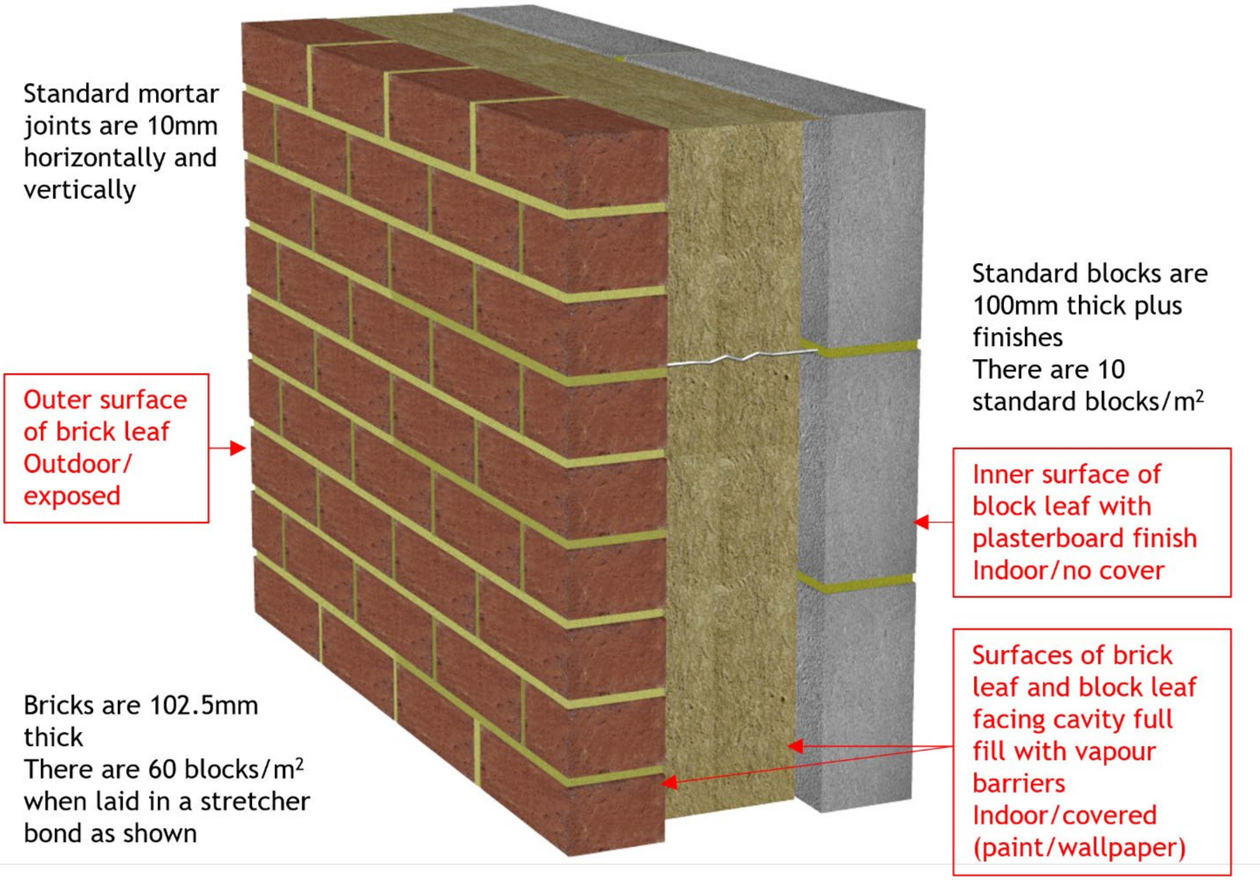


Figure 24 Cavity wall construction for external wall of masonry house. Also used for external walls of concrete-frame residential apartment building. Callout boxes show exposed surfaces used in the EF calculations.

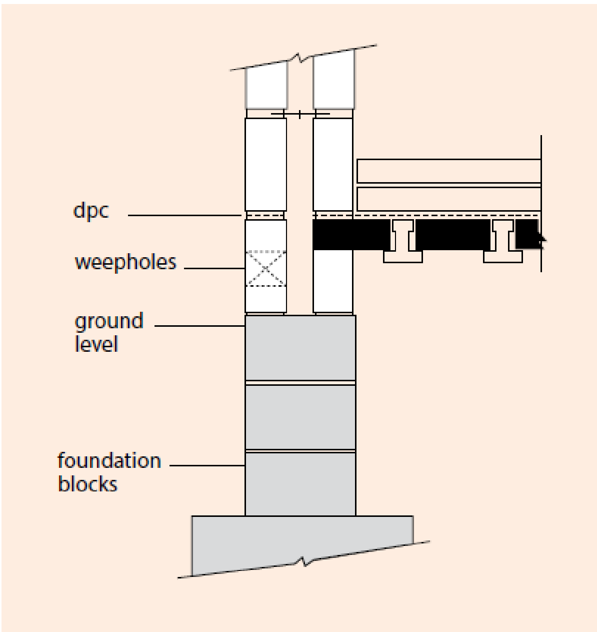


Figure 25 Detail of blockwork foundations for masonry construction[53] (dpc indicates the damp-proof course)

A4.2.6. End-of-life and secondary use

The following assumptions are used in calculating the end-of-life and secondary use EF:

- The end-of-life and secondary use stages are considered together in one EF (unlike in EPDs, where they are separated into different modules),
- All concrete currently entering end-of-life is from commercial buildings, which have a much higher stock turnover than housing[54],
- Concrete C&DW comprises approximately 60% (by mass) high strength concrete (e.g. concrete frames), and 40% (by mass) lower strength concrete (e.g. concrete blocks used for partition walls in legacy commercial buildings)[42],
- Commercial buildings currently undergoing demolition are expected to be 30-50 years old (expert opinion) and therefore will comprise a mixture of steel, in-situ concrete and other frame types. Based on BCSA data (Figure 6), the model assumes that 50% of concrete entering end-of-life is from steel composite frame building types and 50% from concrete-frame buildings,
- Only the above-ground elements – that is, the building superstructure – undergo demolition; therefore construction and demolition waste does not include foundation elements, such as piles and pads,
- Lower strength concrete C&DW is assumed to have the same characteristics (e.g. density) as the lightweight aggregate blocks used in the masonry EF calculation. It is also assumed that carbonation will have already penetrated through the full depth during its primary use life,
- For high strength concrete, the concrete characteristics and the amount of carbonation which has occurred in the primary use life is based on the 1990 EFs for buildings – steel composite frame, and buildings – concrete frame,
- Deconstruction and demolition of concrete will increase its surface area. However, the most significant increase in surface area, and corresponding acceleration of carbonation, occurs after crushing. Therefore, the five week period between demolition and crushing (Figure 10) is not included in the calculation,
- After crushing and prior to secondary use, the crushed concrete will be partially buried and partially exposed to rain[55]. Under current UK practice, this period is limited to a few weeks. Therefore, the carbonation occurring will be relatively small compared to carbonation occurring during the secondary use, and is ignored in the current calculation,
- For the purposes of the model, the EF calculation is based solely on the secondary use service life, during which the concrete will be buried but above the groundwater levels,
- In secondary life, 49% of the crushed concrete is reused onsite. The assumed sieve size distribution is based on a midpoint distribution satisfying a 6F2 specification (BS EN 1377-2[56]) for crushed concrete reused onsite (Table 24),
- 46% of the concrete C&DW is taken offsite, either before or after crushing. It is assumed that this is all crushed to a 6F5 specification (mixture requirements to BS EN 13285[57], graded to BS 933-1[58]) before being imported to a different site. The assumed sieve size distribution is based on the following mid-point distribution satisfying a 6F5 specification for crushed concrete imported from an offsite facility (Table 25).

Table 24 6F2 specification showing midpoint sieve size distribution assumed in secondary use EF calculation.

Secondary use concrete crushed to 6F2 specification **Testing to BS 1377-2**			
BS/BBS EN Test sieve *(mm)*	**6F2 Specification** *(% range)*	**Middle of 6F2 site material** *(%)*	**% of total mass at this sieve size**
125	100	100	7%
90	80-100	93	10%
75	65-100	83	10%
37.5	45-100	73	35%
10	15-60	38	11%
5	10-45	28	15%
0.6	0-25	13	7%
0.063	0-12	6	6%

Table 25 6F5 specification showing midpoint sieve size distribution assumed in secondary use EF calculation.

Secondary use concrete crushed to 6F5 specification **Mixture Requirements to BS EN 13285** **Grading to BS EN 933-1**				
BS/BBS EN Test sieve *(mm)*	**6F5 Specification** *(% range)*	**Comment**	**Middle of 6F5 imported to site** *(%)*	**% of total mass at this sieve size**
125	100		100	13%
80	75-99		87	17%
40	50-90	*40mm - 20mm Difference <35*	70	17%
20	30-75	*20mm - 10mm Difference >5*	53	15%
10	15-60		38	20%
2	0-35		18	12%
0.063	0-12		6	6%

Appendix 5. Model validation – comparison with independent experimental carbonation data

MPA has unrivalled access to two empirical datasets, specific to UK concretes, which are the most extensive in the UK. Statistical analysis of measured carbonation data has been used to validate and/or calibrate the carbonation rates and depths applied in the model.

Since 2019, BRE has led a carbonation laboratory study to evaluate the effect of cement type or concrete strength class on concrete carbonation rate and depth as part of the MPA-led, BEIS IEEA programme *“Low carbon multi-component cements for UK concrete applications”* project. Cement types CEM I, CEM II/B-V and CEM III/A were used for the study. Two standard concrete mixes were prepared per cement type – one designed to meet ‘normal strength’ (25-45MPa) and another designed to meet ‘high strength’ (>45MPa) – giving a total of six concrete mixes. A natural carbonation test (BS EN 12390-10:2018) exposed concrete cubes (cured for three days in water) to atmospheric levels of CO_2 in an outdoor area sheltered from rain.

MPA and the University of Dundee have run a similar project since for indoor (dry) conditions since 2006, providing data for concretes at ages of up to 19 years. In the Dundee programme, cement types CEM I, CEM II/B-V, CEM II/A-D, CEM III/A and CEM III/B were investigated. One standard concrete mix was prepared per cement type using a w/c of 0.60, which targeted a normal-strength concrete. Mixes containing CEM I, CEM II/B-V, CEM III/A and CEM III/B achieved the requirements for normal strength. However, the mix containing CEM II/A-D achieved high strength, which was likely due to the accelerating effect of silica fume. During the current project, long-term measurements were carried out on Dundee specimens to complete 19 years of carbonation testing under atmospheric CO_2 levels.

Experimental *k* values from the BRE and Dundee projects are compared against the EN 16757 empirical *k*-vales in Table 26. These data are plotted in Figure 26.

Table 26 Concrete samples tested: Comparison of k-values from experimental carbonation data with EN 16757

Test dataset	Age at which tested	Cylinder strength	Cement type	SCM content	Exposure	Experimental k-value	EN 16757 k-value - no SCM correction factor	EN 16757 k-value including SCM correction factor
Units	*years*	*MPa*		*%*		*mm/year$^{0.5}$*	*mm/year$^{0.5}$*	*mm/year$^{0.5}$*
Normal strength 25-35MPa								
Dundee	18	25.5	CEM III/B	70	Indoor dry	5.8	6.6	8.58
Dundee	18	28.475	CEM II/B-V	30	Indoor dry	6.4	6.6	6.93
BRE	2	30.345	CEM II/B-V	27	Outdoor sheltered from rain	5.73	4.4	4.62
Dundee	17	31.875	CEM III/A	40	Indoor dry	4.7	6.6 (3.8)[§]	7.92 (4.75)
BRE	2	31.96	CEM III/A	45	Outdoor sheltered from rain	5.73	4.4	5.5
Normal strength 35-45MPa								
Dundee	19	35.105	CEM I	0	Indoor dry	4	3.8	3.8
BRE	2	38.59	CEM I	0	Outdoor sheltered from rain	2.8	2.7	2.7
High strength >45MPa								
Dundee	18	47.6	CEM II/A-D	10	Indoor dry	2.9	3.8	3.99
BRE	2	53.295	CEM III/A	45	Outdoor sheltered from rain	1.7	2.7	3.375
BRE	2	64.515	CEM II/B-V	27	Outdoor sheltered from rain	2.9	2.7	2.835
BRE	2	70.55	CEM I	0	Outdoor sheltered from rain	0.42	2.7	2.7

[§] Values in brackets for cylinder strength class (>35MPa) show closer agreement with experimental data.

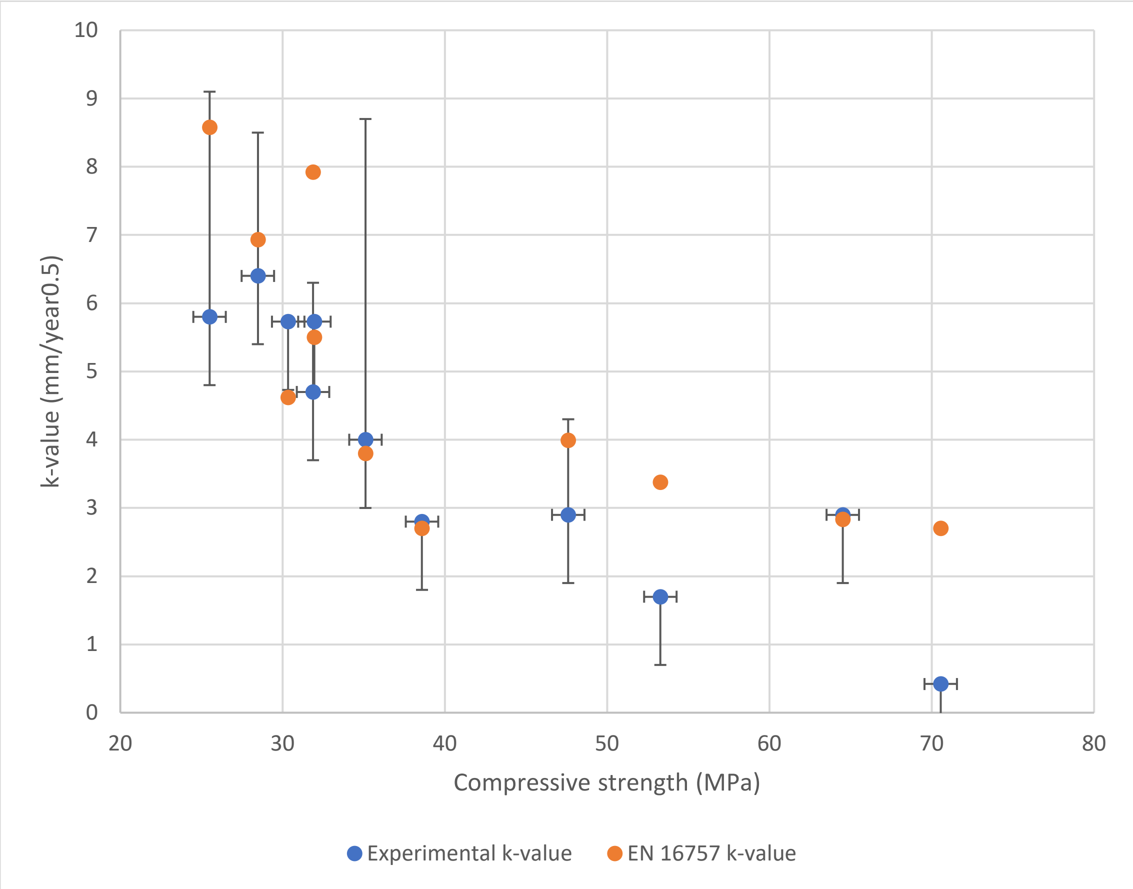


Figure 26 Comparison of experimental k-values with empirical values from EN 16757 for various concrete strengths

From the data presented, it is demonstrated from both laboratory studies that the empirical *k*-values from EN 16757 for normal strength CEM I concretes give very accurate estimations. The CEM II/B-V normal-strength concrete at Dundee measured very close to the empirical value. This was also the case for the CEM III/A concrete from the BRE study. Of all the normal-strength concretes studied, the CEM II/B-V from the BRE study and the CEM III/A from Dundee gave the least accurate values.

One high-strength concrete from the BRE study measured very close to the empirical value. However, all the other high-strength concretes measured significantly less than the empirical values at two years. In a future revision of EN 16757, it may be necessary to include an additional higher strength class in Table BB.1, with *k*-values, based on longer-term experimental data. Continuation of the BRE testing on high-strength concretes will be necessary to help validate the empirical values in EN 16757.

Testing of the degree of carbonation (D_c) has not been carried out in this project. Data for the D_c calculations will be obtained at the end of Dundee testing (that is, 20 years).

The final data points of the BRE and Dundee testing will provide the UK with further validation of the approaches in EN 16757 for calculating carbonation.

With regards to test methods, the indicator test is still considered to provide sufficient precision to make a comparison between different cements and concretes. Full validation of the indicator test will be possible after Dundee completes the testing at 20 years, and later when BRE completes testing of higher strength concretes.

Appendix 6. Uncertainty analysis

The key uncertainties in the model are:

1. Uncertainties in the activity data, particularly in deriving concrete volumes for the different primary use applications from ONS construction output.
2. Uncertainty in the EN 16757 methodology used to calculate the CO_2 uptake.
3. Uncertainty in the AD and EFs for each of the primary use applications due to variations in the concrete specifications.
4. Uncertainty in the AD and EF for the end-of-life and secondary use applications

Uncertainty in the ONS construction output is difficult to quantify.

Quantitative uncertainty calculations have been carried out for the other factors.

A6.1. High-level activity data

A6.1.1. MPA data

UK cement consumption

There is very high confidence and low uncertainty in MPA cement production data. Figures for other cement imports (by MPA non-cement producing members and non-members) are partially based on estimates so are subject to some uncertainty, but this is expected to be low (<5%) compared to total cement consumption.

A6.1.2. ONS construction output

Analysis of the uncertainty with ONS construction output, for example at sectoral and sub-sectoral construction output, is outside the scope of this project.

The main uncertainty within this project is in ONS proxies which the model uses to convert construction output into concrete volumes. These are based on a small market survey, so cannot be fully representative.

This uncertainty is difficult to quantify independently. It is expected to be covered by the uncertainty in the AD for each primary use application (considered in the following sections) and the reconciliation of bottom-up and top-down cement volumes.

A6.2. EN 16757 carbonation methodology

A6.2.1. Degree of carbonation

As suggested in the literature review (Appendix 7), sensitivity of the model to the degree of carbonation has been tested, by varying values of D_c between 40% and 90%.

In the EN 16757 methodology, the degree of carbonation, D_c, depends upon the exposure conditions of the concrete surface. D_c = 40% for indoor surfaces, D_c = 75% for sheltered outdoor surfaces and D_c = 85% for outdoor surfaces exposed to rain or buried in the ground.

This range of values is reflected in the EF calculations. For composite-framed and concrete-framed buildings, most of the carbonation occurs on internal, indoor surfaces within the superstructure, for which D_c = 40%.

For the masonry EF, carbonation occurs on both indoor surfaces and surfaces exposed to outdoor air. Values of D_c vary from 40%, on the internal surfaces of the party and external walls, to 85%, on the upper side of the roof.

For the infrastructure EF, the assumed D_c is 85%, but this could be lower for different exposure conditions.

For the merchants and mortar EF, D_c is 40% on the internal surfaces of the party and external walls, and 85% for externally exposed brickwork.

A6.2.2. Carbonation in very high-strength concretes

Independent experimental data from tests carried out at BRE and Dundee suggests that the progression of the carbonation front for very high-strength concretes – with cylinder strength >50MPa – is slower than any of the *k*-values given in EN 16757. None of the calculations in the present model include such high-strength concretes.

A6.3. Primary use applications

A6.3.1. Concrete mix

Different concrete specifications are required for different primary use concrete applications. However, even within each primary use application, variations in the concrete mix are expected.

For a given concrete strength, the minimum cement content, that is, kg cement/m^3 concrete, is set by standards. However, there may be considerable variation in the SCM content and therefore the CEM I content.

This will impact upon the EFs. The calculation of the maximum theoretical CO_2 uptake, U_{tcc}, is based only on CEM I content (as a proxy for cement clinker content) (Appendix A4.1 Equation (4)). U_{tcc} will decrease with increased SCM content. However, the rate of progression of the carbonation front, *k*, will increase with increased SCM content (Appendix A4.1 Equation (5)).

Higher SCM content and reduced CEM I content will also impact upon the reconciliation of the bottom-up concrete volume data with the top-down cement production data.

A6.3.2. Buildings – steel composite frame

Uncertainty in concrete mix

Expert opinion was solicited on the concrete mixes which could be specified for composite-framed buildings.

Less variation is expected in the substructure, which depends on the ground conditions. There is also less CO_2 uptake per concrete volume in the substructure compared to the superstructure. Therefore, only variation in the concrete specification for the superstructure was quantified. Concrete specifications currently in common use for this type of application are CEM II/A, CEM II/B, CEM III/A. For purposes of the uncertainty analysis, variation in the GGBS content between these specifications was considered (see Table 27). CEM II/B-V (which contains fly ash as an SCM) may also be specified and gives an EF and CEM I content within the range of values considered.

For 1990-2000, a CEM III/A option with 40% GGBS has been considered alongside the baseline CEM I mix for the superstructure.

Table 27 Concrete mixes considered for sensitivity testing of framed building types for 2010-20

	Cement type				
GGBS content (%)	**CEM I**	**CEM II/A**	**CEM II/B**	**CEM III/A**	**CEM III/B**
median	-	14%	30%	50%	
range (low-high)	-	6-20%	21-35%	35-65%	66-80%

Other uncertainty factors

While there may be variation in some elements of the structural design – for example, the depth of in-situ concrete on metal deck can vary from 130mm to 150mm – their impact on the overall EF and AD is expected to be small compared to the impact of the concrete mix.

Construction type may contribute to uncertainty. In this initial version of the model, two further frame types, steel plus hollowcore and portal-frame buildings, are included in the buildings – steel composite frame primary use application. However, differences in the EF and AD are to be expected and could be calculated in a future version of the model.

- A steel plus hollowcore framed building will have a greater concrete volume than a comparable composite-framed building. The EF is also expected to be higher, as the hollow cores greatly increase the surface area available for carbonation and therefore the CO_2 uptake.
- For portal-frame buildings, concrete is only contained in the foundations and the ground slab. The relationship of concrete volumes to economic value may be differ from that assumed for composite-framed buildings in the model. While the upper face of the ground slab is exposed to air, the lower face and foundations will be buried. Therefore, the overall CO_2 uptake per concrete volume and subsequent EF will be lower.

A6.3.3. Buildings – concrete frame

Uncertainty in AD

The AD for concrete-framed buildings depends upon the proportion of new dwellings, specifically apartments, which are high-rise, and therefore concrete-framed, or low-rise. The NHBC data used to create the parameter for this split cover 75% of the market for new housing and is therefore considered relatively accurate.

Uncertainty in concrete mix

Expert opinion was solicited on the concrete mixes which could be specified for composite-framed buildings.

Less variation is expected in the substructure, which depends on the ground conditions. There is also less CO_2 uptake per concrete volume in the substructure compared to the superstructure. Therefore, only variation in the concrete specification for the superstructure was quantified. Concrete specifications currently in common use for this type of application are CEM II/A, CEM II/B and CEM III/A. For purposes of the uncertainty analysis, variation in the GGBS content between these specifications was considered (see Table 27). CEM II/B-V (which contains fly ash as an SCM) may also be specified and gives an EF and CEM I content within the range of values considered.

For 1990-2000, a CEM III/A option with 40% GGBS has been considered alongside the baseline CEM I mix for the superstructure.

Construction type

The party walls may or may not contain concrete masonry blocks. The default EF model assumes stud partition – that is, there is no concrete in the walls separating different apartments.

The façade infill may or may not contain concrete masonry blocks. The model used to calculate the default EF assumes a concrete block-brick cavity wall infill to the external façade. However, some apartment blocks surveyed have brick, rather than block, facades, or less commonly, other types of cladding. A sensitivity test of the EF model, without the block façade, gives a lower EF but higher CEM I content.

Other elements of the structural design may vary – for example, the depth of concrete slabs can vary from 200mm to 250mm. However, these will have less impact on the overall EF.

A6.3.4. Buildings – masonry

Uncertainty in AD

The AD for masonry buildings depends upon the proportion of new dwellings, which are houses or low-rise apartments of masonry construction. The NHBC data used to create a parameter for this split cover 75% of the market for new housing and is therefore considered relatively accurate. The model does not include any interannual variability in the split between houses, flats and different construction types.

The market survey also found some masonry construction in non-housing. This is expected to be a low proportion of total masonry construction.

Uncertainty in concrete block type

The modelled EF assumes the use of lightweight aggregate concrete blocks[**] with 8% cement content (assumed all CEM I) and density of 1,425kg/m^3 – that is, CEM I content, 114kg/m^3 concrete.

Some builders will use aircrete blocks, with a typical 14% cement content (assumed all CEM I) and density of 600kg/m^3 – that is, CEM I content of 84kg/m^3 concrete.

This variation in block type has been considered within the uncertainty analysis.

Construction type

The EF is modelled on a terraced house with two external walls (block-cavity-brick) and two party walls (block).

Low-rise masonry apartment blocks can differ from masonry houses in two ways.

- Roofs may be flat or pitched. A pitched roof may be covered with concrete tiles, as assumed for houses. Such a roof will make a significant contribution to the overall CO_2 uptake. However, a flat roof is unlikely to be structural or contain concrete. Therefore there will be no CO_2 uptake and a reduced EF.
- Upper floors are likely to be hollowcore and will carbonate – at least partially – thereby increasing the CO_2 uptake and EF.

Variations within house types will have less impact on the uncertainty. A detached masonry house will have four external walls (block-cavity-brick); a semi-detached masonry house will have three external walls (block-cavity-brick) and oneparty wall (block). The EF calculation shows that blocks in both party and external walls carbonate through their full depth within their service life and this will apply regardless of the house sub-type.

A6.3.5. Infrastructure

Uncertainty in AD and EF

The uncertainty in AD and EF for infrastructure is very high. This sector includes a wide variety of applications, such as energy, roads, rail and water. Concrete use varies considerably between and within different sub-sectors, notably energy (Section 6.4).

For example, very high-strength concretes (50-100MPa) are being used in large infrastructure projects such as HS2 and Hinkley. The *k*-values for the progress of the carbonation front are therefore likely to be lower in practice than those given in EN 16757. However, both Hinkley and HS2 are using bespoke concrete mixes with high proportions of GGBS in the concrete specification, which will increase *k*. Information provided by these two projects has been used to test the uncertainty in the infrastructure AD and EF.

[**] https://epd-online.com/PublishedEpd/Detail/9477

A6.3.6. Merchants and mortar

Uncertainty in merchants and mortar AD

Confidence is high in the AD for cement volumes used for factory-made mortars and sold through merchants. There is much lower confidence in the end use.

Based on expert opinion, it assumed all merchant sales will also be used in mortar. Small builders now use ready-mix products for other applications such as foundations and screeds. Nonetheless, some cement sold via merchants will be used in other applications, such as shed bases or post bases, which are either completely or partially buried and therefore undergo reduced or no carbonation.

Uncertainty in AD has been tested by considering the variation in cement content for different industry standard mortar specifications[40].

Uncertainty in merchants and mortar EF

Uncertainty has been tested by considering a range of EFs, with the calculated mortar EF at the top end of the range. For the lower limit on the merchants and mortar EF, an EF calculation has been made for a typical post base buried in the ground.

The merchants and mortar EF is based on the masonry EF prototype. The variations in construction type discussed in Appendix A6.3.4 may have greater impact on this EF than the masonry EF. The walls of a detached house will have a greater proportion of brick leaves, with outdoor exposure, and therefore a higher degree of carbonation. However, this uncertainty is expected to be captured within the analysis for the degree of carbonation (Appendix A6.2.1) and so has not been tested separately.

A6.4. End-of-life and secondary use

Uncertainty in end-of-life and secondary use AD

The end-of-life and secondary use AD is derived from Defra C&DW statistics. The Defra data is multiplied by a model parameter for the concrete fraction in recovered C&DW (Section 10.1.1). The concrete fraction, 59%, is based on a specific UK case study. Concrete fractions of up to 70% have been citied in European and US studies. To quantify uncertainty, the AD has been varied by ±20%.

Uncertainty in end-of-life and secondary use EF

The calculated CO_2 uptake EF from carbonation in end-of-life and secondary use is 21.39kg CO_2/tonne concrete (39.41kg CO_2/m^3 concrete). This can be compared to the values recommended in the IVL methodology[5].

The IVL Tier 1 estimation for end-of-life and secondary use is that the CO_2 uptake is 3% of calcination emissions in the reporting year. This is based on much lower historic construction levels, typical global demolition practices and low recycling rates.

For the UK, the concrete market is very mature. Cement production and concrete construction levels peaked in the 1970s. Many of the buildings currently being demolished date from this era. Furthermore, recovery rates for C&DW are high, with nearly all concrete being recycled into secondary uses. Therefore, the IVL Tier 1 estimation is likely to underestimate the end-of-life and secondary use CO_2 uptake in the UK.

The IVL Tier 2 methodology gives possible EFs where concrete volumes entering the end-of-life and secondary use are known:

- 10kg CO_2/m^3 concrete in the end-of-life stage, as a conservative estimate,
- 20kg CO_2/m^3 concrete for improved end-of-life handling procedures,
- 10kg CO_2/m^3 concrete in the secondary use stage, for unbound applications of crushed material,

- about 110kg CO_2/m^3 concrete in the end-of-life and secondary use stages, corresponding to ~75% of the maximum theoretical CO_2 uptake potential for an average [high-strength CEM I] concrete, under favourable conditions for end-of-life handling and secondary use application,
- assuming a 90% degree of carbonation (as recommended by the literature review Appendix 7), this rises to 132kg CO_2/m^3 for an average high-strength concrete.

The calculated UK EF is 39.41kg CO_2/m^3 concrete (21.39kg CO_2/tonne). This assumes a mixture of strengths in concrete C&DW: 60% (by mass) high strength concrete and 40% (by mass) low strength concrete.

For the uncertainty analysis, a lower limit EF of 20kg CO_2/m^3 concrete (10kg CO_2/m^3 concrete in the end-of-life stage plus 10kg CO_2/m^3 concrete in the secondary use stage) is applied to the high strength fraction of the concrete waste. (The low strength fraction is already carbonated throughout). This gives a lower limit on the EF uncertainty of 6.51kg CO_2/tonne or 12.00kg CO_2/m^3 concrete.

The upper limit considered for the EF assumes that all the waste concrete is high strength concrete, that will achieve a 90% degree of carbonation by the end of its secondary life. The upper limit considered for the EF is therefore taken as 132kg CO_2/m^3 (57.64kg CO_2/tonne) concrete.

A6.5. Quantitative uncertainty analysis

The study team has generated quantitative estimates of the primary use, secondary use and overall uncertainty of the carbonation estimates, using a combination of expert judgement and quantitative analysis based on sensitivity tests to derive AD and EF uncertainty ranges per primary use application and for end-of-life / secondary use.

In all cases, the uncertainty was assumed to follow a normal distribution, and that all sub-sector uncertainties are independent. The uncertainties shown are a 95% confidence interval around the modelled value.

The results are summarised below for the years 1990 (base year) and 2020 (latest year).

A6.5.1. Uncertainties in 1990

Sector	AD	U-AD	CEF	U-CEF	Emission / sink	U-Em	Share of total carbonation
Units	*1,000m^3 concrete (mortar)*		*kg CO_2/m^3*		*Mt CO_2*		
Buildings - steel composite frame	32,636	20%	12.5	24%	0.408	32%	20%
Buildings - concrete frame	3,698	20%	14.14	14%	0.052	24%	3%
Buildings - masonry	8,310	30%	18.6	20%	0.155	36%	8%
Infrastructure	6,357	50%	5.65	122%	0.036	132%	2%
Merchants and mortar	15,766	20%	43.93	20%	0.692	28%	34%
Units	*kt*		*kg CO_2/t*				
End-of-life / 2^y life	31,530	20%	21.39	70%	0.674	73%	33%

Where AD = activity data; U-AD = uncertainty in AD; CEF = carbonation emissions sink factor; U-CEF = uncertainty in CEF; Emission / sink = annual carbonation; U-Em = uncertainty in the annual carbonation estimate.

By calculating the square root of the sum of the squares of U-Em per sub-sector, an estimate of total emissions and overall uncertainty can be derived: 2.017 Mt CO_2 ± 27%.

A6.5.2. Uncertainties in 2020

Sector	AD	U-AD	CEF	U-CEF	Emission / sink	U-Em	Share of total carbonation
Units	*1000 m^3 concrete (mortar)*		*kg CO_2/m^3*		*Mt CO_2*		
Buildings - steel composite frame	18,201	20%	9.3	22%	0.169	30%	11%
Buildings - concrete frame	3,605	35%	12.18	10%	0.044	37%	3%
Buildings - masonry	15,387	25%	18.6	20%	0.286	32%	18%
Infrastructure	8,096	50%	5.65	122%	0.046	132%	3%
Merchants and mortar	7,218	20%	43.93	20%	0.317	28%	20%
Units	*kt*		*kg CO_2/t*		*Mt CO_2*		
End-of-life / 2^y life	32,091	20%	21.39	70%	0.686	73%	44%

By calculating the square root of the sum of the squares of U-Em per sub-sector, an estimate of total emissions and overall uncertainty can be derived: 1.548 Mt CO_2 ±34%.

A6.5.3. Uncertainty comments

The overall level of uncertainty is higher in 2020 compared to 1990 due to:

(i) the higher contribution in 2020 to the total carbonation of the end-of-life / secondary use sink, up to 44% from 33%, which is highly uncertain compared to most of the primary use applications, and

(ii) the lower contribution in 2020 to the total carbonation of the merchants and mortar primary use application, down from 34% to 20%, as this is among the least uncertain estimates.

Note that these uncertainty estimates are derived from the limited dataset available during this first development of a UK Tier 2 model. Clearly significant additional research and data mining is warranted to investigate further some of the key parameters that underpin these estimates. Further research will of course also improve the estimates of uncertainty for each parameter.

The analysis presented above applies the expert judgement of the study team and helps to indicate the priorities for future work, with the highest uncertainties in % terms identified for Infrastructure and End-of-life and secondary use.

Appendix 7. Literature review – recarbonation of concrete

Dr Phil Renforth, Heriot-Watt University, March 2022

A7.1. Summary

Concrete reacts with atmospheric CO_2 in all parts of its life cycle (during use, following demolition, and subsequent use). Accounting for passive CO_2 uptake during the service life, and maximising uptake following demolition, together with deep emissions reduction in the production of cement, could result in a net negative CO_2 emission during its life cycle.

The IVL Swedish Environmental Research Institute commissioned a study to create a standard model for CO_2 uptake in concrete, with the intention of informing international greenhouse gas emission accounting (and subsequently published in a white paper, herein described as 'IVL report'). The model suggested three tiers for accounting for CO_2 uptake. Tier 2 of the hierarchy put forward in the IVL report and adopted in the EN 16757 appears to provide a robust method for calculating the progression of a carbonation front through concrete and mortar during their service life. There appears little merit in the application of Tier 1, and Tier 3 speculates at the creation of more robust model frameworks, without specifying detail.

Not all of the material within the carbonation front fully carbonates (that is, the complete conversion of calcium silicates/oxides to calcium carbonate). A fundamental weakness of this approach is that the proportion of the total carbonation potential (or the 'degree of carbonation') needs to be assumed. Previously, research has assumed ~70-80%, but empirical evidence suggests substantial variability. There is no predictive model for calculating the degree of carbonation.

If the IVL/EN 16757 Tier 2 model is applied to calculate CO_2 uptake during the service life of the concrete, sensitivity of outcomes to the possible variations in the degree of carbonation should also be simulated. A probability density function for a degree of carbonation between 40% and 100% coupled to a Monte Carlo simulation would be suitable.

Carbonation of concrete products at the end of the service life is poorly defined in EN 16757. The IVL suggestion for an arbitrary value of 10kg CO_2m^{-3} (or 20kg CO_2m^{-3} for 'enhanced handling') is insufficiently robust (as is the assumption of a fixed proportion of calcination emissions) to have meaningful use in a national GHG inventory calculation. Instead, the approach adopted in global models considers applying a diffusion model (for example, like that applied to CO_2 uptake during service life) to crushed and stockpiled material of known particle size assuming that it is exposed for ~140 days. It is also possible to incorporate recycled material into the Tier 2 service life carbonation model by varying the cement content of concrete at each time step (such that the cement content in the model equates to fresh cement and the additional unreacted recycled material).

Given that there will be a premium demand for atmospheric CO_2 removal, it is likely that demolition waste management practices may be altered to exploit the maximum carbonation potential. The UK model should highlight this potential, even if it is not accounted for at present.

Further work should include the development of a mechanistic model, backed up by experimentation, that can better describe the degree of carbonation. A more sophisticated method of quantifying carbonation of reused concrete would also benefit service life CO_2 uptake estimates. It is unclear how best to maximise the end-of-life carbonation potential in the context of waste handling practices – horizon scanning is needed for the development of waste handling practices that can economically promote CO_2 uptake as well as reuse material in secondary products.

A7.2. Report scope

1. Provide an overview of existing knowledge of the recarbonation process in concrete and cement-containing products in the built environment in all life stages: the primary use stage, the end-of-life stage and the secondary use stage.

2. Compile and assess generic empirical and/or experimental recarbonation data, focusing on UK empirical carbonation data which could be applied to the bespoke UK recarbonation model to be developed during the project.
3. Examine relevant methodologies to calculate the CO_2 uptake by recarbonation for concrete and cement-containing products, including current IPCC methodologies and international ISO/EN standards. The review should determine the appropriateness of the methodology recommended at Tier 2 in the IVL report, from EN 16757 Annex BB, for a bespoke UK model.

A7.3. Background

A7.3.1. Climate and national and international policy context

In the 2015 Paris Agreement, nations committed to limit climate change to well below 2°C, which has precipitated national 'net-zero' emission targets[1]. Within these targets, emissions will need to be rapidly reduced and residual emissions be offset by CO_2 removal from the atmosphere. Cement is a ubiquitous construction material, the production of which generates CO_2 from both the chemical decomposition of the limestone raw material, but also from the combustion of fuel in the kiln. Understandably, emissions reduction in cement production has received considerable attention. However, cement is (geo)chemically unstable at the Earth's surface (see Section 3.1) and will absorb CO_2 and transform back to calcium carbonate over time. This reabsorption of CO_2 can be seen on historic concrete structures (for example, carbonate staining under mortars, or stalactites on the underside of bridges).

This CO_2 uptake has been largely ignored when considering the contribution of cement to the global carbon cycle and national emission inventories. For instance, the 2006 IPCC guidelines for national CO_2 inventories[2] (Section 2.2.1.4 in the report) from cement productions suggests:

"There is one additional issue that, while not included in the current methodology, may become relevant for consideration in the future. Free lime (CaO not part of the formulae of the clinker minerals mentioned above) released during the curing of concrete (that is, from the hydration of the clinker minerals) can potentially re-absorb atmospheric CO_2 – a process called carbonation. However, the rate of carbonation is very slow (years to centuries) and, as a practical matter, should not be considered for good practice. This is an area for future work before inclusion into national inventories"

A similar statement is also included later, referring to lime-based mortars, although the report allows for demonstrable recarbonation of lime waste.

Over the last 20 years, research has explored CO_2 uptake in cement during its service life which has promoted a change in the inclusion of this process in global carbon budgets (key components of which are reviewed in this report). Friedlingstein et al.,[3] suggests 200MtC (720Mt CO_2) yr^{-1} is taken up by existing concrete structures. A figure that has been included in AR6 IPCC (2021)[4] and is equivalent to about one half of the carbonate emissions from current cement production[3]. These figures are largely based on the work of Xi et al.,[5] which is reviewed in Section 6.2.

The potential uptake of CO_2 from cement recarbonation has been promoted in Sweden, where much of the early research was conducted, to highlight it within the annex of its greenhouse gas inventory, although yet to be adopted in the main reporting protocol (Sweden National Inventory[6]), and by others to suggest that recarbonation should be included in the life-cycle inventories of cement emissions[7], which is already the case in some concrete environmental product declarations[6].

A7.3.2. Mineral carbonation

The natural weathering of silicate rocks is responsible for consuming atmospheric and soil CO_2 at a rate of 250–300 million tonnes of carbon per year (~1,000Mt CO_2 yr^{-1})[8]. While this is relatively small

[6] e.g., https://www.britishprecast.org/Sustainability/EPDs/BPAS-1m2-Single-Leaf-Precast-Cladding.aspx

compared to the natural carbon cycle (hundreds of billions of tonnes C yr^{-1}), it is responsible for sequestering CO_2 released by volcanic degassing over geological time periods. Methods to increase the rate of this reaction in the context of climate change mitigation were first discussed by Seifritz[9], Dunsmore[10], and Lackner et al.,[11]. Over the last 20 years there has been growing interest in the field of 'mineral carbonation', which has been extensively reviewed elsewhere[12]. This work also includes the carbonation of artificial alkaline materials ([13] Sections 3 and 4 herein).

A7.3.3. Cement production and CO_2 balance

Cement clinker is produced by heating limestone with clay or shale in a kiln at ~1,500°C. The clinker is ground with gypsum, secondary cementitious material (SCM) and minor additional constituents (MAC) to produce various cement types. In the UK, 78% of factory-made cement sales is type CEM I, CEM II types make up 21% and the remaining 1% are other cement types, such as CEM III. CEM I typically contains 91% clinker, 5% gypsum and 4% MAC. CEM II types contain upwards of 58% clinker, 5% gypsum, and up to 4% MAC; the balance is typically made up of SCMs such as GGBS (or other high silica containing products). CEM III types can contain even higher proportions of SCMs.

China, the US and Europe use 70-80% of cement in concrete[5]. The balance largely being made up by use in mortar. Globally, it is estimated that ~75 % of cement is used in concrete[5].

Over 4 billion tonnes of cement are produced globally every year[14], with the figure expected to increase to meet the demand of a growing global population, possibly increasing up to 8Gt yr^{-1} by 2100[15]. The potential CO_2 absorption capacity of this material may be in the order of 1.5-3.5Gt CO_2 yr^{-1} by 2100 (Figure 1[15]). Given that humanity may need to remove ~10-20Gt CO_2 yr^{-1} by 2100 to account for residual emissions even under deep and rapid emission reduction scenarios[16], the potential contribution of CO_2 absorption capacity of concrete is significant.

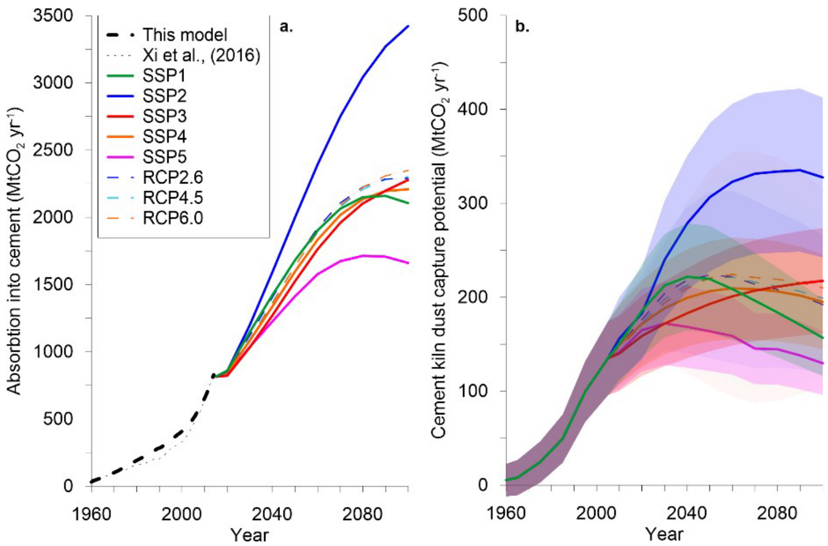


Figure 1: Estimates of global CO2 absorption potential into cement (left) and cement kiln dust(right)[15]

CO_2 emissions in cement manufacturing are primarily a result of a) the chemical decomposition, called 'calcination', of limestone and b) fuel combustion in the kiln in order to heat the raw materials and drive their chemical transformation into cement clinker. The emissions from calcination are also known as 'process' emissions. On average, a cement kiln requires around 3.7GJ of fuel input per tonne of cement clinker, which produces approximately 0.64t CO_2 per tonne of cement (GNR 2019 data for EU-28[7]). These values depend on the fuel mix in the kiln and so will vary. Decomposition of limestone is responsible for approximately 60-65% of the CO_2 emissions. In the UK, calcination is responsible for around ~70% of the total net emissions because of the relatively high levels of biomass used, where the biomass is considered CO_2 neutral. Recarbonation of cement is conceptually the reformation of this calcined limestone, and the maximum CO_2 uptake

[7] https://gccassociation.org/gnr/

is equivalent to the CO_2 emitted by calcination during production. Emission reduction strategies for the cement industry are particularly focused on using lower carbon fuels (for example, those based on biomass, hydrogen or low-carbon electricity), and the deployment of carbon capture and storage to kiln flue gases[e.g.17]. From a global perspective, the Global Cement and Concrete Association (GCCA) Roadmap[b] shows that the sector can achieve zero emissions by 2050. For Europe, the CEMBUREAU decarbonisation roadmap suggests that, with fuel switching to biomass plus small amounts of H_2 and electrification, making thermal efficiency savings, new cement formulations and CCUS, an emissions intensity of 0.227t CO_2 $t_{clinker}^{-1}$ might be possible. However, when transport and grid savings are considered in cement and concrete manufacture and recarbonation is taken into account, the total carbon balance over the life cycle of the material is net negative by -0.022t CO_2 t_{cement}^{-1}.

The UK produces approximately 10Mt yr^{-1} of cement and releasing approximately 7.3Mt of CO_2[17]. Given the stability of the UK population, the maturity of its infrastructure, modest levels of urbanisation and decreasing intensity of cement use per capita, cement clinker production may decrease to ~5Mt yr^{-1} by mid-century (Figure 2a). Contemporary demolition crushed concrete production in the UK is not well monitored, with DLUHC[19] suggesting on the order of 80Mt yr^{-1}, much of which is recycled as secondary aggregate. More recent estimates[8] suggest that this may be lower. This may increase in the coming decades, and the UK may not yet have surpassed 'peak crushed concrete' (Figure 2b).

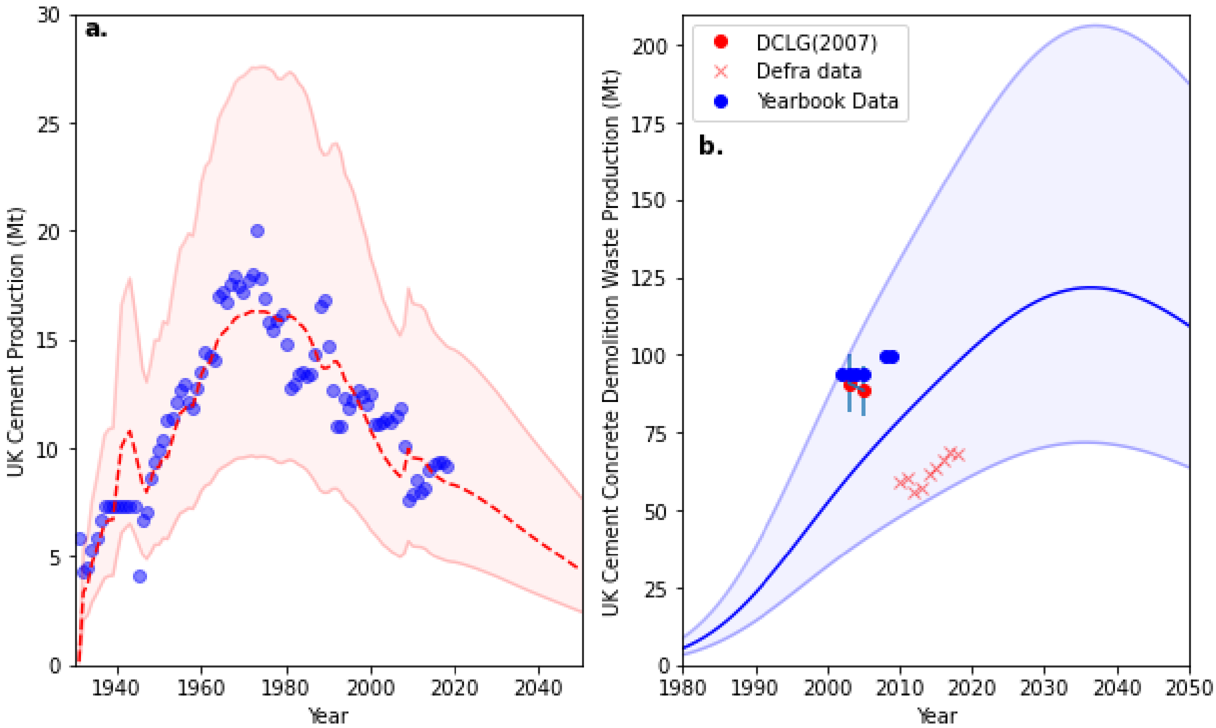


Figure 2: a) UK Production of cement from 1930 to 2018 (blue circles) and a prediction based on a material saturation model that relates per capita consumption to GDP per capita. The shaded region shows the standard error about the mean value. b) UK concrete demolition waste production based on the cement production model. Here, a 60-year cement service life is assumed (together with an average 125kg cement per tonne of concrete. Data collected from DLUHC[19] (red dots), Minerals Yearbook of the British Geological Survey (blue dots) and data from Defra[c] (crosses) are also shown. (Source, Renforth, unpublished, based on the methodology described in[15])

[8] https://www.gov.uk/government/statistical-data-sets/env23-uk-waste-data-and-management

A7.4. The chemistry of cement carbonation

A7.4.1. Cement as a material for carbonation

Portland cement is primarily composed of meta-stable poorly crystalline calcium silicate compounds. In cement chemistry, the main clinker compounds are 'Alite' Ca_3SiO_5 and 'Belite' Ca_2SiO_4, although substitution with impurities or other elements in the raw materials (primarily alumina, iron oxide and magnesium) is common[20]. SCMs, such as iron and steel slag, contain a range of calcium, magnesium, alumino-silicates and oxides[21,22].

Cement is combined with crushed rock aggregate, sand and water to create concrete. The meta-stable calcium silicates undergo a hydration reaction to produce a 'calcium-silicate-hydrate' gel with a composition that can approximately be described by mineral counterparts of jennite ($Ca_9Si_6O_{18}(OH)_6$ $8H_2O$) or tobermorite ($Ca_5Si_6O_{12}(OH)_{10}$ $5H_2O$)[23,24]. The strength of concrete derives from interaction between the gel, aggregate and sand. Other phases in concrete can include unreacted cement, hydrated lime, hydrated alkali silicate or hydrated sulphate minerals[20].

An example of the range of cement minerals and their associated carbonation reactions is presented in Table 1 and Equations 1-6. It is possible to simplify the carbon capture potential of alkaline materials using the bulk chemistry (expressed as oxides) and the modified 'Steinor equations' ([25] Equations 7 and 8), which are further explained in[15].

Table 1: Typical carbonation reactions of cement minerals

Cement component	Carbonation reaction	ΔG_r (kJ mol.C^{-1})	Equation
'Belite' mineral name: Larnite	$Ca_2SiO_4 + 2CO_2 + 2H_2O$ ---- > $2CaCO_3 + H_4SiO_4$	-65.3	1
'Alite' mineral name rankinite	$Ca_3Si_2O_7 + 3CO_2 + 4H_2O$ -----> $3CaCO_3 + 2H_4SiO_4$	-50.5	2
Tobermorite	$Ca_5Si_6O_{12}(OH)_{10}$ $5H_2O + 5CO_2 + 2H_2O$ ----> $5CaCO_3 + 6H_4SiO_4$	-125.4	3
Jennite	$Ca_9Si_6O_{18}(OH)_6$ $8H_2O + 9CO_2 + H_2O$ ----> $9CaCO_3 + 6H_4SiO_4$	-73.6	4
Gehlenite	$Ca_2Al_2SiO_7 + 2CO_2 + 5H_2O$---- > $2CaCO_3 + 2Al(OH)_3 + H_2SiO_4$	-55.8	5
Portlandite	$Ca(OH)_2 + CO_2$-------> $CaCO_3 + H_2O$	-82.8	6
Thermodynamic data were derived from Matschei et al.,[24] for Jennite and Tobermorite, Robie and Hemingway[26] was used for all others.			

$$E_{pot} = \frac{M_{CO_2}}{100} \cdot \left(\alpha \frac{CaO}{M_{CaO}} + \beta \frac{MgO}{M_{MgO}} + \varepsilon \frac{Na_2O}{M_{Na_2O}} + \theta \frac{K_2O}{M_{K_2O}} + \gamma \frac{SO_3}{M_{SO_3}} + \delta \frac{P_2O_5}{M_{P_2O_5}}\right) \cdot 10^3 \cdot \eta \qquad \text{Equation 7}$$

$$C_{pot} = \frac{M_{CO_2}}{100} \cdot \left(\alpha \frac{CaO}{M_{CaO}} + \beta \frac{MgO}{M_{MgO}} + \gamma \frac{SO_3}{M_{SO_3}} + \delta \frac{P_2O_5}{M_{P_2O_5}}\right) \cdot 10^3 \qquad \text{Equation 8}$$

CaO, MgO, SO_3, P_2O_5, Na_2O and K_2O are the elemental concentrations of Ca, Mg, S, P, Na and K, expressed as oxides, M is the molecular mass of those oxides; coefficients α, β,ϵ, θ (equal to +1), γ (equal to -1), and δ (equal to -2) consider the relative contribution of each oxide. E_{pot} (kg CO_2 tonne^{-1}) is the CO_2 removed during weathering of the material (in which the CO_2 is captured as dissolved bicarbonate, see Renforth and Henderson[27]). In this expression η is molar ratio of CO_2 to divalent cation sequestered during enhanced weathering, (typically η = 1.4-1.8). E_{pot}, which for the purposes of this review is cement dissolution products that are leached to the environment, is generally ignored in literature when considering CO_2 uptake in cement and concrete. It is more typical to find simplified versions of C_{pot} (kg CO_2 t^{-1}) often referred to as 'carbonation potential' which considers CO_2 removal due to the formation of secondary carbonate minerals. Equations 7 and 8 imply that the potential is reduced by the presence of sulphur and phosphorus within the material.

For conservative estimates of CO_2 uptake potential during concrete carbonation, EN 16757 recommends that only the CaO of the cement clinker be used, which equates to a potential of 490, 410, and 360kg CO_2 t^{-1} for CEMI, II and III respectively. Whereas ~510kg CO_2 t^{-1} may be possible based on bulk chemistry or if secondary cementitious materials are included[15].

A7.4.2. Adjusting for pre-existing carbonate

The Steinor equations consider the total carbon uptake potential without considering existing carbonate minerals present in the material. This is particularly problematic for assessing the potential of waste concrete containing carbonate-bearing sand or aggregate (for example, limestone or dolomite) with uncertain provenance, and less of an issue for CO_2 curing where the chemistry of the raw materials can be assessed, and CO_2 uptake can be calculated through process mass balancing.

To quantify the provenance of pre-existing carbonate in demolition waste, Renforth et al.,[28] proposed the use of a stable carbon isotope mixing model. There is a unique isotopic 'fingerprint' of carbonate minerals that form on carbonated cement[29] caused by the hydroxylation of CO_2 in solution, which is distinct from lithogenic carbonates. It is therefore possible to quantitatively distinguish between older lithogenic carbonate and recent carbonation (Equation 9).

$$X = \frac{\delta^{13}C_{Sample} - \delta^{13}C_{Lith}}{\delta^{13}C_{Cem} - \delta^{13}C_{Lith}} \qquad \text{Equation 9}$$

Where X is the proportion of newly formed carbonate in the sample. δ^{13}C is the carbon isotopic ratio between ^{12}C and ^{13}C (in ‰) for the sample, cement carbonation, and lithogenic carbonate. $\delta^{13}C_{Lith}$ for lithogenic sources is typically ~0 ‰ (against a Vienna pee dee belemnite standard), $\delta^{13}C_{Cem}$ is typically ~25 ‰.

A7.5. Modelling methods for CO_2 uptake

A7.5.1. Empirical approaches

A range of empirical models have been created to fit observed data of cement carbonation. The simplest of those fit a power-time relationship to carbonation depth[30] (Equation 10).

$$x_c = K \cdot t^n \qquad \text{Equation 10}$$

Where the exponent n is typically 0.5 (although some suggest this may be material chemistry or concrete use dependent between 0.2-0.7[31]). The expression is a simplification of Fick's laws of diffusion for a constant source concentration ($x_c = f(\sqrt{Dt})$)[32] in which the $D^{0.5}$ is incorporated into K. However, evolving reactive transport in porous media may result in changes in porosity or diffusion pathways and D may also change as a function of time. As such, Equation 10 may be inaccurate for mature reaction systems. The parameter K (units in mm yr^{-n}) has been derived from experimental work and is thought to vary depending on the strength class of the concrete and how it is exposed to CO_2 (indoor, outdoor, buried, surface coated, exposed to rain). A summary of these data are presented in Table 2, and a general solution is presented in Figure 3.

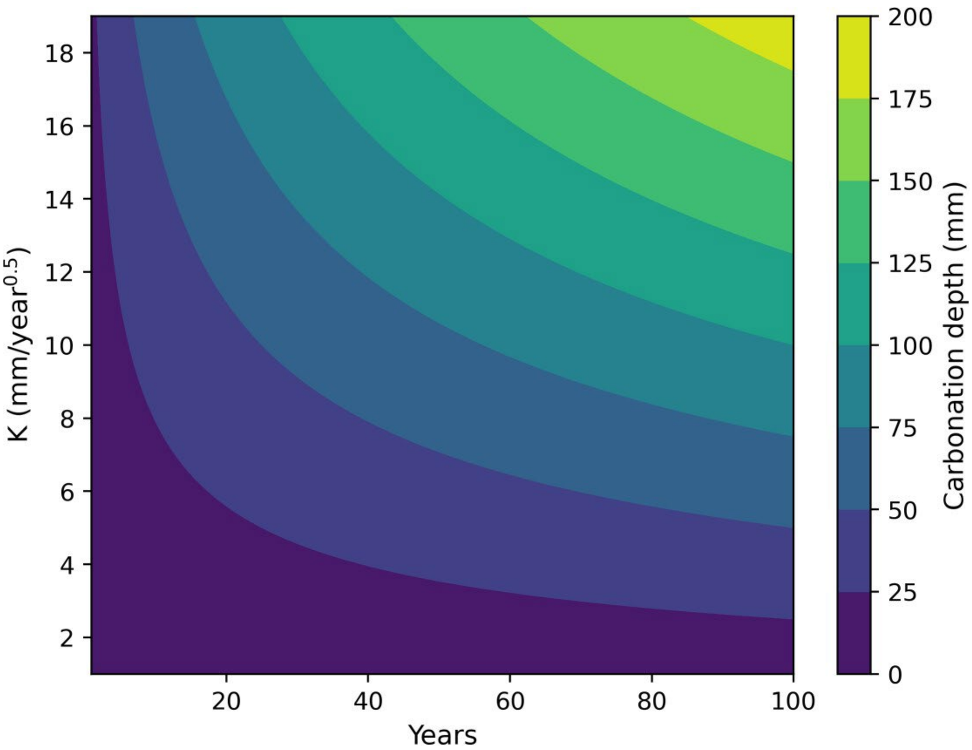


Figure 3: The general solution to Equation 10, assuming n = 0.5. The colour map shows the carbonation depth over time for a range of values of K.

A7.5.2. Mechanistic approaches

There are five primary processes that occur during cement carbonation: i) the diffusion of CO_2 from the ambient air through the pore structure of the concrete, ii) the dissolution of that CO_2 into solution, iii) the hydration of the CO_2 to form carbonic acid, iv) the solid dissolution of the cement minerals, and v) the formation of carbonate minerals. While it may be possible to create a model to simulate these parameters (see the review You et al.,[31]), there is no established model that has been verified against experimental data.

A7.6. Methodologies for assessing concrete carbonation

A7.6.1. Hierarchy of models proposed by IVL

The Swedish Environmental Research Institute has proposed a hierarchy of models that may be used in IPCC Greenhouse Gas Inventory calculations[33].

The Tier 1 model assumes a fixed conversion factor for carbonation during service life. 15-20% of the 'reported emissions [are] from calcination of consumed cement clinker', which is specifically referring to emissions generated from the chemical decomposition of limestone within the cement kiln. The model attempts to correct for additional removal due to mortar rendering. Carbonation at end-of-life in the Tier 1 model is assumed 10kg CO_2 m^{-3} (or 20kg CO_2 m^{-3} for 'enhanced handling') if the annual end-of-life concrete production is known or 2% of the annual calcination emissions if annual production is unknown. For secondary use, carbonation is assumed to be 10kg CO_2 m^{-3} if the annual end-of-life concrete production is known or 1% of the annual calcination emissions if annual production is unknown.

The Tier 2 model is identical to that described in EN 16757 (Section 5.2) for service life carbonation (although with an additional 25kg CO_2 for every tonne of GGBS slag used). For end-of-life carbonation, the procedure is the same as Tier 1. It suggests that a further 2% increase in removal (based on calcination emissions) is possible due to carbonation in waste handling activities. For secondary use of crushed concrete, the procedure is equivalent to Tier 1 and 10kg CO_2 m^{-3} can be applied if the volume of recycle is known (or 1% of annual calcination emissions if it is unknown).

The report suggest a Tier 3 based on more sophisticated models could be used to calculate CO_2 uptake. While there is some suggestion about what outcomes the models should be able to replicate, there is little detail on the nature, scope or parameterisation of such models.

A7.6.2. EN 16757 Annex BB

EN 16757[34] "Sustainability of construction works – Environmental product declarations – Product Category Rules for concrete and concrete elements" is a European standard implemented in the UK, and is intended to complement core rules for construction product characterisation (EN 15643, 15978, 15941, 15942, 15804). It covers rules for the creation and implementation of life cycle inventories for concrete. Interestingly, it omits mortars.

Annex BB of the report provides guidance on how CO_2 uptake can be calculated. It suggests using Equation 11 (Equation BB.5 in the standard, with an exponent of n = 0.5) to calculate carbonation depth and to derive CO_2 uptake during the service life using Equation 10.

$$U = d \cdot U_{max} \cdot C \cdot D_c \cdot 10^{-3} \quad \text{Equation 11}$$

Where U is the uptake per m^2 of exposed concrete, d is the carbonation depth (mm, from Equation 10), U_{max} is the maximum uptake potential ('U_{tcc}' in the standard, C_{Pot} in Equation 8, kg CO_2 tonne^{-1}, the standard simplifies this to a constant value of 490), C is the volumetric cement content of the concrete (tonne m^{-3}), and D_c is the 'degree of carbonation' or the proportion of the cement CaO within the carbonation zone that undergoes carbonation (effectively the percentage of C_{pot} in Equation 8 that has been realised, see limitations below in Section 5.3, Equation 12). The standard suggests values for K (Equation 10), and D_c that might be used with known values of cement content to derive CO_2 uptake in particular applications and strength categories of concrete (Table 2), data which is largely derived from reports published by the Swedish Cement and Concrete Research Institute[35].

Table 2: K values and degree of carbonation for input into Equation 11 summarised from EN 16757

	<15MPa	15 – 20MPa	15 – 35MPa	>35MPa	Degree of carbonation (D_c)
	k-coefficient (mm year$^{-0.5}$)				%
Civil engineering structures					
Exposed to rain		2.7	1.6	1.1	85
Sheltered from rain		6.6	4.4	2.7	75
Buried		1.1	0.8	0.5	85
Buildings					
Outdoor/exposed	5.5	2.7	1.6	1.1	85
Outdoor/sheltered	11.0	6.6	4.4	2.7	75
Indoor/covered	11.6	6.9	4.6	2.7	40
Indoor/no cover	16.5	9.9	6.6	3.8	40
Buried		1.1	0.8	0.5	85

EN 16757 suggests correction factors for K ranging from 1.05 to 1.3 for limestone, silica fume, fly ash and GGBS additives in cement (also sourced from[35]). Guidance on how to calculate CO_2 uptake at the end-of-life is limited, deferring to national provisions, or suggesting end-of-life uptake be ignored. National provisions have been advised to set a maximum degree of carbonation potential of 75% of total clinker potential (see Section 5.3 for further discussion).

A7.6.3. Methodological limitations

Values of K used in Equation 10 (for example, Table 2) are derived through experimentation by spraying phenolphthalein indicator onto a cross-section of carbonated concrete (Figure 4). The indicator solution, otherwise colourless, is pink at pH>9. Uncarbonated cement mineral surfaces (particularly calcium hydroxide and hydrated calcium silicates) will quickly equilibrate with the small volumes of indicator solution resulting in a high pH. Whereas carbonate phases when equilibrated will result in a pH <9.

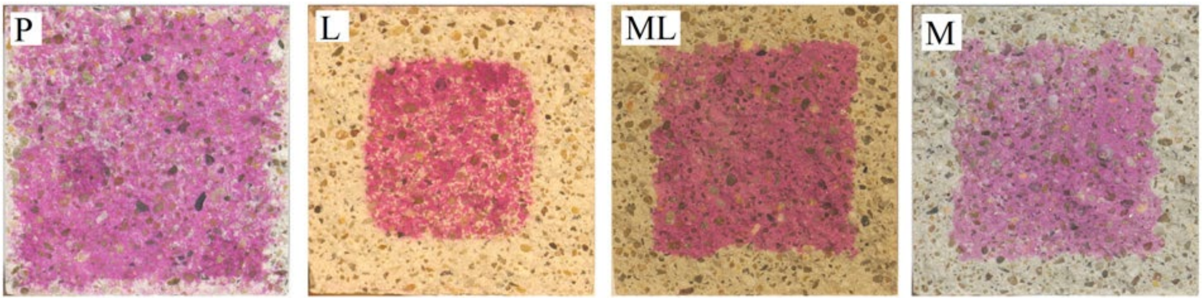


Figure 4: Carbonation depth measured using the phenolphthalein indicator (from Shi et al.,[36]).

While the indicator is useful in identifying the progression of a reaction front (or 'carbonation zone'), it does not directly relate to the extent of conversion of cement phases to carbonate. Unreacted cement phases may remain in the carbonation zone but may be i) occluded from reaction with the indicator by precipitated secondary phases, ii) cement mineral grains may have formed a silicon-rich weathering rind, iii) they may not be in sufficient quantity to rapidly equilibrate with the indicator.

The ratio between the theoretical maximum CO_2 uptake (Equation 8) and the actual CO_2 uptake within the carbonation zone is referred to the 'degree of carbonation (D_c)' used in Equation 11. The degree of carbonation considered by Lagerblad[35] is 75%, which was arbitrarily chosen assuming that all of the free $Ca(OH)_2$ and half of the hydrated calcium silicate phases in the cement undergo carbonation. It is not clear if this assumption is based on observation. This value has subsequently been used in a range of published research[37-39]. It appears that this assumption has been revised for the range of concrete applications (40-85% in EN 16757), but the derivation of this assumption is unclear. Measurements of the degree of carbonation range between 0 and >100% (Figure 5), and do not appear to be related to carbonation rate K. The lack of relationship between K and D_c suggests fundamentally different controlling mechanisms. The empirical model derived from phenolphthalein indicator measurements appears to simulate CO_2 gas diffusion, the extent of D_c is possibly controlled by pore/grain scale processes (particularly mineral dissolution, ion transport, secondary mineral formation).

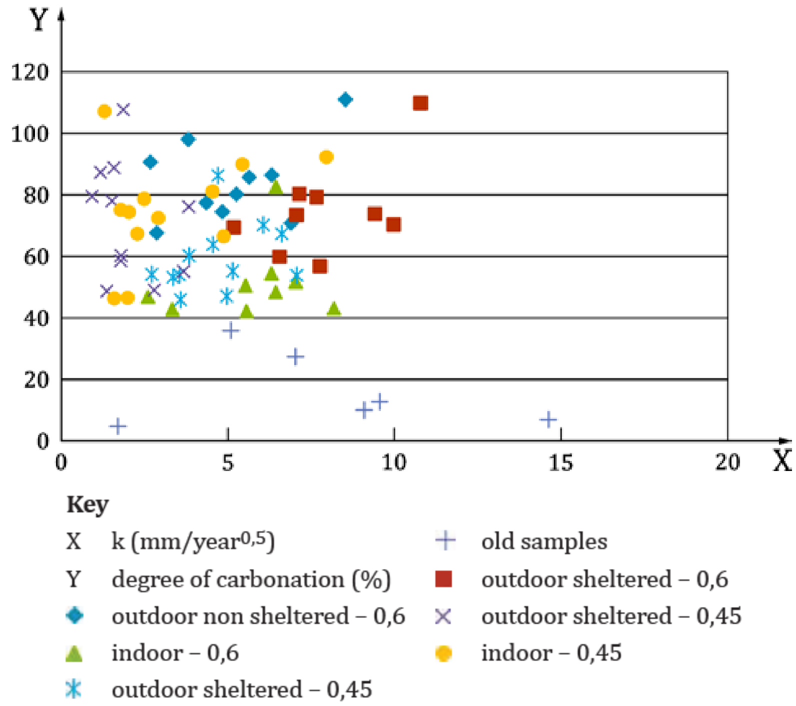


Figure 5: The degree of carbonation (y-axis) against carbonation rate k (x-axis). 0.6 and 0.45 refer to the water-cement ratio used when manufacturing the test samples. 'Old samples' refers to material collected from existing structures (in service for 10-20 years prior to sample collection), Source CEN/TR17310[40] and references therein.

D_c can be determined by normalising the amount of CO_2 reacted (C_{actual}), with the maximum CO_2 capture potential of the material (Equation 12).

$$D_c = \frac{C_{actual}}{C_{pot}} \qquad \text{Equation 12.}$$

As previously described, C_{pot} is typically calculated through a simplification of Equation 8 in which only the CaO content of the clinker is considered. This is reasonable approximation given the predominance of this material in CEM I based concrete carbonation, although the simplification may be less accurate in blended cements (particularly blends containing SCMs, such as GGBS, with their own carbonation potential).

C_{actual} is determined experimentally either through thermogravimetric analysis, thermal decomposition and CO_2 gas analysis, acid digestion and CO_2 gas analysis, or elemental mapping under a scanning electron microscope. Although, given the additional complexity of these measurements compared to using phenolphthalein indicator, reporting of D_c is limited (Table 3).

Table 3: An overview of literature that reports values for D_c.

Study	**Degree of carbonation (in the carbonation zone)**
Leemann et al., [59]	Average D_c = 63% (16 – 93%). While no details are given on how these were derived, it was presumably by elemental mapping during scanning electron microscopy. There appears to be no relationship between these and aggregate ratio, sand/gravel ratio, hydration, cement mass or paste volume. There was a strong relationship between C_{pot} and C_{actual}, suggesting a systematic cement material controlled influence on D_c.(Figure 6)
Andrade[60]	Average D_c = 63% for all cement types, OPC = 61%, CEM III 79-389%. There are possible errors from limestone, the quantities of which were assumed rather than measured.

Houst and Wittmann[61]	Average D_c = 8%. A depth profile was measured for concrete with D_c ranging between 1 and 20% through the depth profile)
Galan et al.,[62]	Average D_c = 16% for a range of treatments and additives (range 5-24%)

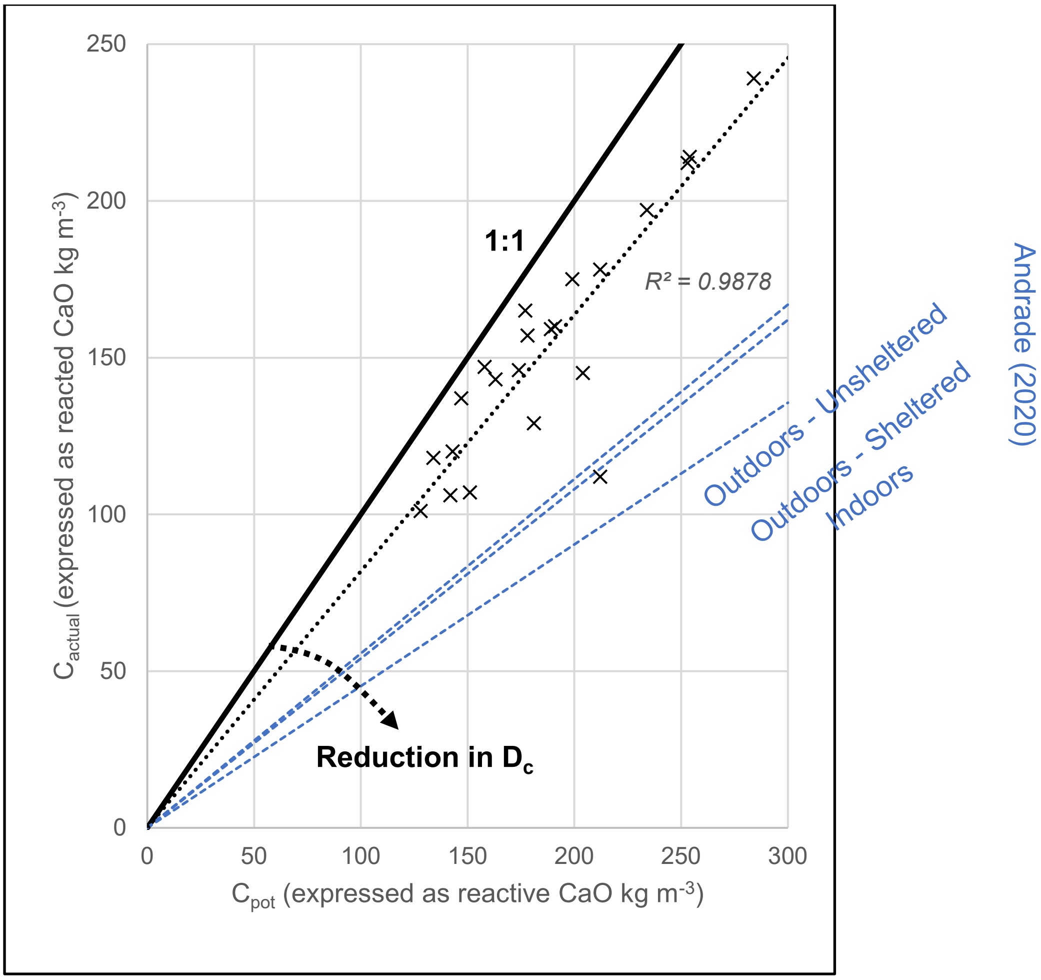


Figure 6: Relationship between the maximum carbonation potential (C_{pot}) and those measured (C_{actual}). A 1:1 relationship equates to a D_c = 100%. Data points are those from Leemann et al.,[41] show an expected positive trend (dotted line) between carbonation potential and measured values, but do not represent a 100% D_c.

A7.7. Data on carbonation for a range of life stages

A7.7.1. CO_2 uptake during manufacture

Some have suggested that by exposing fresh concrete to elevated CO_2 concentrations, it may be possible to promote carbonation as well as modest increases in the compressive strength of the material[45]. Such work has been extensively reviewed[46]. While the scalability for CO_2 curing of cement is probably limited to precast concrete production, and the life-cycle environmental benefit is disputed[47], the use of CO_2 as an admixture is a technology that could be implemented in most concrete plants. The experimental results may be useful in considering the mechanisms and rate of CO_2 uptake at ambient conditions (Figure 7). Carbonation degrees of the order of 10-50% appear possible on the order of a typical curing time of 28 days.

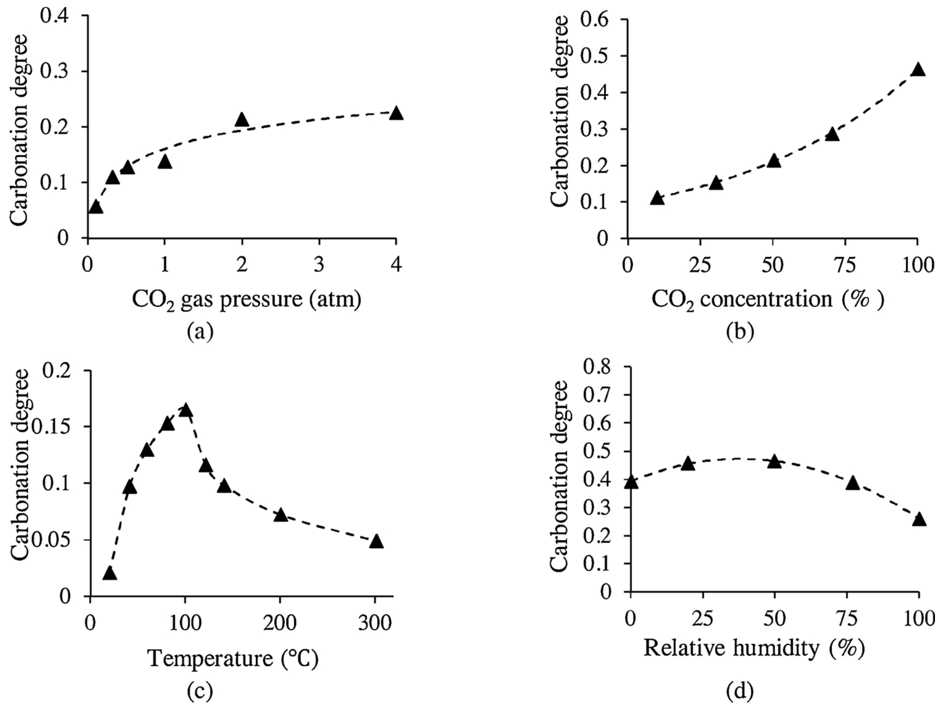


Figure 7: The relationship between gas pressure, CO_2 concentration, temperature and relative humidity, and the degree of carbonation. See[45] and references therein.

A7.7.2. CO_2 uptake during service life

The IVL report[33] distinguishes the calculation of CO_2 at a national level ('The Swedish[39], Dutch[48], Norwegian[49,50], Irish[51], Swiss[52], Spanish[53] or global[5,54] methods'). These methods are not derivations of national or international policy, so their labelling is somewhat misleading, although the CO_2 uptake is based on the national context of cement production and use. Possan et al.[37] review the methodologies for these carbonation studies, suggesting a range of approaches taken and attempt to harmonise using a method similar to that produced in the IVL report. A summary of the parameters used in these national assessments is included in the annex (Table A1). Most of the national studies consider that between 3% and 23% of the calcination emissions may be reabsorbed into concrete during its service life, with the exception of the global study, which suggests >40%. While the difference between the national and global studies was not explained by Xi et al.,[5] the inclusion of rapidly carbonating mortars (average K value of 12 – 27 mm $yr^{-0.5}$, and a degree of carbonation of 92%) appears to be reasonable. Accounting for concrete carbonation only, the rate is approximately 12%. Input data into the global model of Xi et al. is included for reference in Tables A2 – A7.

Hills et al.[55] provide a statistical analysis of nearly 2,000 K values and suggest two models for their calculation based on either age or strength characteristics, the latter is possibly more relevant for this study (Equation 13)

$$\ln(K) = 1.066 + 1.761I_{CEMI} + 2.062I_{GGBS} + 2.061I_{PFA} - 0.639I_{Exposed} - 0.182I_{Sheltered} - 0.648I_{Indoors} + ((0.025 - 0.053I_{CEMI} - 0.052I_{GGBS} - 0.050I_{PFA}) \cdot Strength)) \qquad \text{Equation 13}$$

Where I_x is a binary value (1 or 0) depending on its application to the concrete investigated. The national location of the concrete, the water to cement ratio, the curing length, or rainfall were omitted from the model suggesting that they had <5% impact on the outcome. A similar exercise was undertaken by Monteiro et al.,[56] with the intention of providing guidance for minimum reinforcement depths, and a similar relationship between K and concrete strength was considered, but no distinction was made between outdoor/indoor/exposed/sheltered materials.

While the national context may have been omitted from the data compilation in[55], relative humidity and temperature are important parameters in controlling cement carbonation (as described above). Presumably the omission from Equation 13 suggests that these environmental parameters are partly incorporated into parameters that consider exposed, indoors or sheltered concrete, and that the data were derived from sources with generally similar climatic conditions.

For estimation of UK cement recarbonation, Clear and De Saulles[57] provide a well-reasoned scoping study. Their summary data was used to derive ranges of K values (Table 4), although given the uncertainty in D_c, values of K are shown as integers.

Table 4: A summary of parameters for cement carbonation in the UK[57]

	Ready Mix	Precast	Blockwork	Paving	Mortar/render	Other
UK produced cement used in each market (shown as a % of the total). Based on 2005 data	55	23	9	2	6	5
Assumed average depth/thickness of concreteelements during service life (m)	0.25	0.2	0.1	0.15	0.1	0.2
Assumed average strength and environment forconcrete elements during service life	25-35	>35	<15	>35	<15	15-20
K (based on Equation 13 and CEM I)	3-4[e]	3-5[e,s,i]	6-9[i]	3[e]	6-9[e,i]	5-6[e,s]
Total cement content (kg m^{-3})	290	350	100	300	350	
CEMI (kg m^{-3})	270	315	95	270	280	
D_c	Base case of 50%, 63% used in sensitivityanalysis.					
Service life (years)	60					
Secondary life (years)	100					
e – exposed, i – indoor, s – sheltered						

Recent interest in the recarbonation of cement during its service life was promoted by Xi et al.[5] This applied the root-time based carbonation front calculation to a global database of cement/concrete characteristics. They calculate that approximately 0.25GtC (0.9Gt CO_2) are removed from the atmosphere annually due to CO_2 uptake into concrete and mortar. The study was updated by the same authors in[54], with confidence intervals 0.76-1.07Gt CO_2 yr^{-1}), and they suggest that 52% of the process emissions from the production have been recaptured. The degree of carbonation for mortars in[54] was derived from the analysis of 300 samples of concrete (data not published), with a mean D_c – 91% (range 50.2-100%). The degree of carbonation in concrete was derived from[39,58-61].

Both Renforth[15] and Cao et al.[62] used the same global model to project uptake to 2100 under a range of future scenarios. Renforth[15] uses population and economic trends associated with the shared socioeconomic pathways to suggest a cumulative potential of 120-190Gt CO_2 between 2015 and 2100. Cao et al.[62] use a set of material efficiency and technology roadmap driven scenarios to suggest a cumulative potential of 80-130Gt CO_2 for the same time period.

A7.7.3. CO_2 uptake following demolition

Following demolition, cementitious products are typically crushed, graded, stored and then partially reused as a feedstock aggregate in construction. The comminution of concrete considerably increases its surface area. For instance, a $1m^3$ block of concrete would have a surface area of $6m^2$; crushing that material to 10mm-sized particles would increase the surface area of the material to $6,000m^2$.

Stockpiling material on site could result in the relatively rapid carbonation of this material. For instance, Kikuchi and Kuroda[63] showed that, after 91 days, the CO_2 uptake in exposed crushed concrete equated to approximately 90kg CO_2/t (equivalent to rates of uptake over decades, see Table A1). Examining demolition waste on a brownfield site, Washbourne et al.[64] suggest the degree of carbonation of ~75%over four years. Thiery et al.[65] investigated the carbonation of a bed of hydrated cement under a range of CO_2 and humidity conditions. Results from the days-weeks experimental campaign were modelled to simulate the long-term fate of the material (Figure 8), to suggest >80% conversion on the order of four to five years (for material <7 mm diameter). These studies examine exclusively passive processes, in which the CO_2 uptake is possibly controlled by diffusion into the crushed material, and suggest that more active management practices may be able to promote a greater CO_2 uptake. For instance, experiments have shown that an elevated CO_2 atmosphere (3.5%, at total atmospheric pressure) can result in a degree of carbonation of 50-90% over 20-35 days for 1-8mm-sized crushed concrete[50].

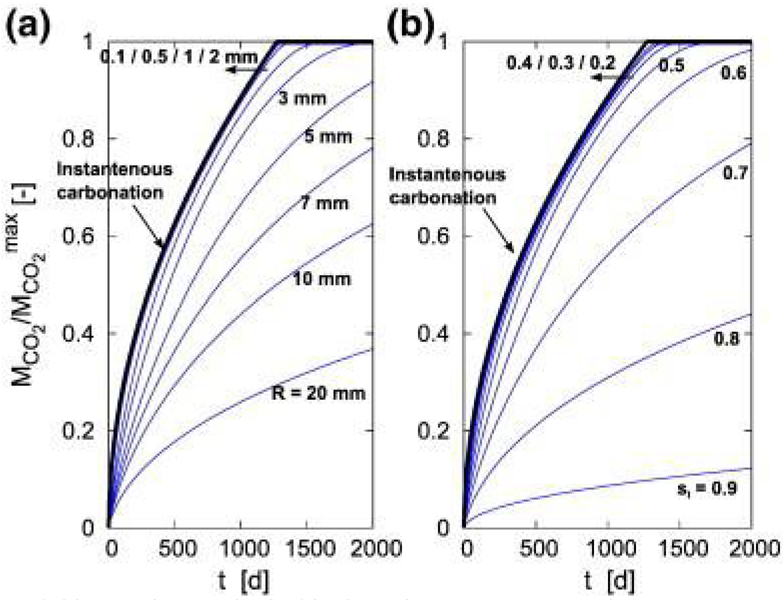


Figure 8: Time evolution of CO_2 uptake in a bed of hydrated cement paste with a) various particle sizes, and b) water content.

Crushed demolition waste is typically recycled as secondary aggregate, and carbonation would likely occur through the same mechanisms as the service life discussed above. Silva et al.[66] suggest that the introduction of recycled aggregate causes an increase in the rate of progression of the carbonation front (up to twice for complete replacement). The relationship between the degree of carbonation and the maximum uptake potential of recycled-aggregate concrete has not been explored.

A7.8. Conclusions

The model associated with Tier 2 of the hierarchy put forward in the IVL report based on EN 16757 appears to provide a robust method for calculating the progression of a carbonation front through concrete and mortar during their service life.

Not all of the material within the carbonation front fully carbonates (that is, the complete conversion of calcium silicates/oxides to calcium carbonate). A fundamental weakness of this approach is that the proportion of the total carbonation potential (or degree of carbonation) needs to be assumed. Previously, research has assumed ~70-80% but empirical evidence suggests substantial variability. There is no predictive model for calculating the degree of carbonation.

The possible uncertainty in the degree of carbonation and its apparent lack of correlation with K-values suggests that there is limited value in over-specifying K, and approximate values for a range of material uses may be more appropriate (Table 4). Research suggests that there is no statistical significance to the national context for deriving specific '*k*-values', whereas the use context (indoors/exposed/sheltered), material compressive strength and the presence of additives had a much greater influence.

If the IVL/EN 16757 Tier 2 model is applied to calculate CO_2 uptake during the service life of the concrete, sensitivity of outcomes to the possible variations in the degree of carbonation should also be simulated. A probability density function for a degree of carbonation between 40% and 100% coupled to a Monte Carlo simulation would be suitable.

Carbonation of concrete products at the end of the service life is poorly defined in EN 16757. The IVL suggestion for an arbitrary value of 10kg CO_2 m^{-3} (or 20kg CO_2 m^{-3} for 'enhanced handling') is insufficiently robust (as is the assumption of a fixed proportion of calcination emissions). Instead, the approach adopted in global models considers applying a diffusion model (like that applied to CO_2 uptake during service life) to crushed and stockpiled material of known particle size assuming that it is exposed for ~140 days. Advanced treatment methods (for example, further crushing, longer weathering of stockpiled material, or the injection of CO_2 into the heap) may promote high degrees of carbonation. While this may not be economical in current waste management practices, it may be incentivised by a value for atmospheric CO_2 removal. This may be required to maximise net negative CO_2 emissions in the life cycle of cement.

A7.9. References

1. Committee on Climate Change. Net Zero: The UK's contribution to stopping global warming.

Comm. Clim. Chang. 275 (2019).

2. Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. [eds. . *2006 IPCC Guidelines for National Greenhouse Gas Inventories*. (2006) doi:https://doi.org/.

3. Friedlingstein, P. *et al*. Global carbon budget 2020. *Earth Syst. Sci. Data* **12**, 3269–3340(2020).

4. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I tothe Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (2021).

5. Wang, J. *et al*. Substantial global carbon uptake by cement carbonation. *Nat. Geosci.* **9**, 880–883 (2016).

6. Agency, S. E. P. *National Inventory Report Sweden 2021*. (2021).

7. Sacchi, R. & Bauer, C. Should we neglect cement carbonation in life cycle inventorydatabases? *Int. J. Life Cycle Assess.* **25**, 1532–1544 (2020).

8. Hartmann, J., Jansen, N., Dürr, H. H., Kempe, S. & Köhler, P. Global CO2-consumption bychemical weathering: What is the contribution of highly active weathering regions? *Glob. Planet. Change* **69**, 185–194 (2009).

9. Seifritz, W. CO2 disposal by means of silicates. *Nature* **345**, 486 (1990).

10. Dunsmore, H. E. A geological perspective on global warming and the possibility of carbon dioxide removal as calcium carbonate mineral. *Energy Convers. Mgmt* **33**, 565–572 (1992).

11. Lackner, K. S., Wendy, C. H., Butt, D. P., Joyce, C. L. & Sharp, D. H. Carbon-dioxide disposal in carbonate minerals. *Energy* **20**, 1153–1170 (1995).

12. Sanna, A., Uibu, M., Caramanna, G., Kuusik, R. & Maroto-Valer, M. M. A review of mineral carbonation technologies to sequester CO2. *Chem. Soc. Rev.* **43**, 8049–8080 (2014).

13. Renforth, P., Washbourne, C.-L., Taylder, J. & Manning, D. A. C. Silicate production andavailability for mineral carbonation. *Environ. Sci. Technol.* **45**, 2035–2041 (2011).

14. U.S. Geological Survey. Mineral Commodity Summaries 2015 Mineral Commodity Summaries 2015. *US Geol. Surv.* 196 (2015).

15. Renforth, P. The negative emission potential of alkaline materials. *Nat. Commun.* **10**, 1401(2019).

16. IPCC. *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,. Aromar Revi* (2018).

17. MPA. UK Concrete and Cement Industry Roadmap to Beyond Net Zero. *Concr. Cent.* 1-9(2020).

18. Intergovernmental Panel on Climate Change. *Climate Change 2014 Mitigation of Climate Change. Climate Change 2014 Mitigation of Climate Change* (2014). doi:10.1017/cbo9781107415416.

19. Capita Symonds Ltd & WRc plc. *Survey of arisings and use of alternatives to primary aggregates in England, 2005: construction, demolition and excavation waste.* (2007).

20. Taylor, H. F. W. *Cement chemistry*. vol. 2 (Thomas Telford London, 1997).

21. Proctor, D. *et al.* Physical and Chemical Characteristics of Blast Furnace, Basic Oxygen Funace and Electric Arc Furnace Steel Industry Slags. *Environ. Sci. Technol.* **34**, 1576–1582 (2000).

22. Pullin, H. *et al.* Atmospheric Carbon Capture Performance of Legacy Iron and Steel Waste. *Environ. Sci. Technol.* **53**, 9502–9511 (2019).

23. Shaw, S., Clark, S. M. & Henderson, C. M. B. Hydrothermal formation of the calcium silicate hydrates, tobermorite ($Ca_5Si_6O_{16}(OH)_2 \cdot 4H_2O$) and xonotlite ($Ca_6Si_6O_{17}(OH)_2$): An in situ synchrotron study. *Chem. Geol.* **167**, 129–140 (2000).

24. Matschei, T., Lothenbach, B. & Glasser, F. P. Thermodynamic properties of Portland cement hydrates in the system CaO-Al2O3-SiO2-CaSO4-CaCO3-H2O. *Cem. Concr. Res.* **37**, 1379–1410 (2007).

25. Steinour, H. H. Some effects of carbon dioxide on mortars and concrete-discussion. *J. Am. Concr. Inst.* **50**, 905–907 (1959).

26. Robie, R. A. & Hemingway, B. S. *Thermodynamic properties of minerals and related substances at 298.15 K and 1 bar (10^5 pascals) pressure and at higher temperatures.* https://pubs.er.usgs.gov/publication/b2131 (1995) doi:10.3133/b2131.

27. Renforth, P. & Henderson, G. Assessing ocean alkalinity for carbon sequestration. *Rev. Geophys.* **55**, 636–674 (2017).

28. Renforth, P., Manning, D. A. C. & Lopez-Capel, E. Carbonate precipitation in artificial soilsas a sink for atmospheric carbon dioxide. *Appl. Geochemistry* **24**, 1757–1764 (2009).

29. Dietzel, M., Usdowski, E. & Hoefs, J. Chemical and13C/12C-and18O/16O-isotope evolution of alkaline drainage waters and the precipitation of calcite. *Appl. Geochemistry* **7**, 177–184(1992).

30. Papadakis, V. G., Vayenas, C. G. & Fardis, M. N. Fundamental modeling and experimental investigation of concrete carbonation. *Mater. J.* **88**, 363–373 (1991).

31. You, X., Hu, X., He, P., Liu, J. & Shi, C. A review on the modelling of carbonation of hardened and fresh cement-based materials. *Cem. Concr. Compos.* **125**, 104315 (2022).

32. Bird, R. B., Stewart, W. E. & Lightfoot, E. N. *Transport phenomena*. vol. 1 (John Wiley &Sons, 2006).

33. Gustafsson, H. S. C. L. T. & Andersson, R. CO2 uptake in cement-containing products.(2021).

34. British Standards Institution. *BS EN 16757:2017 Sustainability of construction works. Environmental product declarations. Product Category Rules for concrete and concrete elements*. https://shop.bsigroup.com/products/sustainability-of-construction-works-environmental-product-declarations-product-category-rules-for-concrete-and-concrete-elements/standard/details.

35. Lagerblad, B. *Carbon dioxide uptake during concrete life cycle: State of the art*. (SwedishCement and Concrete Research Institute Stockholm, 2005).

36. Shi, Z. *et al*. Experimental studies and thermodynamic modeling of the carbonation of Portlandcement, metakaolin and limestone mortars. *Cem. Concr. Res.* **88**, 60–72 (2016).

37. Possan, E., Felix, E. F. & Thomaz, W. A. CO 2 uptake by carbonation of concrete during lifecycle of building structures. *J. Build. Pathol. Rehabil.* **1**, 1–9 (2016).

38. Pommer, K. & Pade, C. *Guidelines: uptake of carbon dioxide in the life cycle inventory ofconcrete*. (Nordic Innovation Centre, 2006).

39. Andersson, R., Fridh, K., Stripple, H. & Häglund, M. Calculating CO2 uptake for existingconcrete structures during and after service life. *Environ. Sci. Technol.* **47**, 11625-11633 (2013).

40. British Standards Institution. *CEN-TR 17310-2019 Carbonation and CO2 uptake in concrete*.

41. Leemann, A., Nygaard, P., Kaufmann, J. & Loser, R. Relation between carbonation resistance,mix design and exposure of mortar and concrete. *Cem. Concr. Compos.* **62**, 33–43 (2015).

42. Andrade, C. Evaluation of the degree of carbonation of concretes in three environments.

Constr. Build. Mater. **230**, 116804 (2020).

43. Houst, Y. F. & Wittmann, F. H. Influence of porosity and water content on the diffusivity ofCO2 and O2 through hydrated cement paste. *Cem. Concr. Res.* **24**, 1165–1176 (1994).

44. Galan, I., Andrade, C., Mora, P. & Sanjuan, M. A. Sequestration of CO2 by concretecarbonation. *Environ. Sci. Technol.* **44**, 3181–3186 (2010).

45. Liu, Z. & Meng, W. Fundamental understanding of carbonation curing and durability ofcarbonation-cured cement-based composites: A review. *J. CO2 Util.* **44**, 101428 (2021).

46. Pu, Y. *et al*. Accelerated carbonation technology for enhanced treatment of recycled concreteaggregates: A state-of-the-art review. *Constr. Build. Mater.* **282**, 122671 (2021).

47. Ravikumar, D. *et al*. Carbon dioxide utilization in concrete curing or mixing might not produce a net climate benefit. *Nat. Commun.* **12**, 1–13 (2021).

48. Vermeulen, E. BalansTussenEmissieenOpname CO2. *Hoe Zit Het nu Werkelijk Met CO2- Emissie en—OpnameDoor Bet*. (2017).

49. Jacobson, R. & Sanchez, D. L. Opportunities for Carbon Dioxide Removal Within the UnitedStates Department of Agriculture . *Frontiers in Climate* vol. 1 2 (2019).

50. Engelsen, C. J. & Justnes, H. CO2-binding by concrete structures during life cycle. in *Conference paper: 2nd International Congress on Durability of Concrete, 2nd ICDC, at NewDelhi, India* vol. 1 (2014).

51. Fitzpatrick, D., Nolan, E. & Richardson, M. G. Sequestration of carbon dioxide by concrete Infrastructure: A preliminary Investigation in Ireland. *J. Sustain. Archit. Civ. Eng.* **10**, 66–77(2015).

52. Nygaard, P. V & Leemann, A. Carbon dioxide uptake of reinforced concrete structures due tocarbonation. *EMPA, Cemsuisse Proj.* **201106**, (2012).

53. García, I. G., Rábade, M. P., PeriS, P. M., AgÜÍ, J. C. L. & Barbudo, M. Á. S. *Estudio del efecto sumidero de CO2 de los materiales de base cemento*. (Agrupación de Fabricantes deCemento de España, 2010).

54. Guo, R. *et al.* Global CO 2 uptake of cement in 1930–2019. *Earth Syst. Sci. Data Discuss.* **2020**, 1–28 (2020).

55. Hills, T. P., Gordon, F., Florin, N. H. & Fennell, P. S. Statistical analysis of the carbonationrate of concrete. *Cem. Concr. Res.* **72**, 98–107 (2015).

56. Monteiro, I., Branco, F. A., de Brito, J. & Neves, R. Statistical analysis of the carbonationcoefficient in open air concrete structures. *Constr. Build. Mater.* **29**, 263–269 (2012).

57. Clear, C. A. & De Saulles, T. BCA Recarbonation Scoping Study. *Br. Cem. Assoc. Camberly, UK* (2007).

58. Gajda, J. Absorption of atmospheric carbon dioxide by portland cement concrete. *Portl. Cem.Assoc.* (2001).

59. Pade, C. & Guimaraes, M. The CO2 uptake of concrete in a 100 year perspective. *Cem. Concr.Res.* **37**, 1348–1356 (2007).

60. Guimaraes, M. S., Valdes, J. R., Palomino, A. M. & Santamarina, J. C. Aggregate production:Fines generation during rock crushing. *Int. J. Miner. Process.* **81**, 237–247 (2007).

61. Chang, C.-F. & Chen, J.-W. The experimental investigation of concrete carbonation depth. *Cem. Concr. Res.* **36**, 1760–1767 (2006).

62. Cao, Z. *et al.* The sponge effect and carbon emission mitigation potentials of the global cementcycle. *Nat. Commun.* **11**, 1–9 (2020).

63. Kikuchi, T. & Kuroda, Y. Carbon dioxide uptake in demolished and crushed concrete. *J. Adv.Concr. Technol.* **9**, 115–124 (2011).

64. Washbourne, C.-L. L., Lopez-Capel, E., Renforth, P., Ascough, P. L. & Manning, D. A. C. Rapid Removal of Atmospheric CO 2 by Urban Soils. *Environ. Sci. Technol.* **49**, 5434–5440(2015).

65. Thiery, M., Dangla, P., Belin, P., Habert, G. & Roussel, N. Carbonation kinetics of a bed of recycled concrete aggregates: a laboratory study on model materials. *Cem. Concr. Res.* **46**, 50–65 (2013).

66. Silva, R. V, Neves, R., De Brito, J. & Dhir, R. K. Carbonation behaviour of recycled aggregateconcrete. *Cem. Concr. Compos.* **62**, 22–32 (2015).

A7.10. Appendix – literature review tables

Table A1: A summary of national and global studies that consider CO_2 uptake into concrete and mortar

Context	National ‘Sweden’	National ‘Norway’	National ‘Netherlands’	National ‘Ireland’	National ‘Switzerland’	National ‘Spain’	Global
Reference	39	50	48	51	52	53	5
Material production	Clinker consumption, historical 100 years	Present cement consumption, 100 years future uptake	Cement consumption	Clinker consumption, historical, 40 years	Clinker consumption, 2010	Cement production	Cement consumption, historical 1930-2013, in four regions: China, US, Europe, rest of the world
Fly ash/slag additives	no	yes	yes	no	no	yes	no
Model	Carbonation depth from the product of *k*-value and root time						
Degree of carbonation (%)	50-90	70	40-85	30-100 (‘as modification factors’)	50-75		80-92
Demolition wastes included	yes (8%)	yes (10%)	yes (35%)	no	yes (0 -100%)	no	yes (3 – 61%)
Time horizon (years)	100	100	60	100	50		83
Result (kg CO_2 t^{-1})	125	70-83	21-90	75			250
Result (% calcination emissions)	17%	15-18%	19-23%	16%	16%	3%	43%

Table A2: Distribution of concrete by strength class and region (SI Data 7 in Xi et al.[5])

Country/region	Strength	Distribution Pattern	a	b	max	min	Mean
USA*	≤C15 (%)	Weibull	22.20%	12	40.00%	0.00%	21.20%
	C16-C23 (%)	Weibull	40.50%	12	60.00%	5.00%	38.80%
	C24-C35 (%)	Weibull	29.50%	8	80.00%	20.00%	27.70%
	>C35 (%)	Weibull	12.70%	16	15.00%	10.00%	12.30%
China**	≤C15 (%)	Weibull	16.50%	3.5	33.50%	0.00%	14.90%
	C16-C23 (%)	Weibull	13.70%	3	25.80%	0.00%	12.50%
	C24-C35 (%)	Weibull	66.00%	7	82.80%	41.60%	66.20%
	>C35 (%)	Weibull	11.60%	3.5	23.40%	0.00%	10.40%
Europe***	≤C15 (%)	Weibull	5.50%	12	8.00%	2.90%	5.30%
	C16-C23 (%)	Weibull	40.70%	12	54.00%	18.90%	39.00%
	C24-C35 (%)	Weibull	46.80%	16	62.90%	32.00%	45.30%
	>C35 (%)	Weibull	10.90%	12	13.50%	8.00%	10.40%
Indian ****	≤C15 (%)	Weibull	5.50%	12	8.00%	2.90%	5.30%
	C16-C23 (%)	Weibull	40.70%	12	54.00%	18.90%	39.00%
	C24-C35 (%)	Weibull	46.80%	16	62.90%	32.00%	45.30%
	>C35 (%)	Weibull	10.90%	12	13.50%	8.00%	10.40%
the rest of the world ****	≤C15 (%)	Weibull	5.50%	12	8.00%	2.90%	5.30%
	C16-C23 (%)	Weibull	40.70%	12	54.00%	18.90%	39.00%
	C24-C35 (%)	Weibull	46.80%	16	62.90%	32.00%	45.30%
	>C35 (%)	Weibull	10.90%	12	13.50%	8.00%	10.40%

* data is from ERMCO. (European Ready Mixed Concrete Organization) Ready-Mixed Concrete Industry Statistics 2001-2013, Available at (http://www.ermco.eu).Low M S. Material flow analysis of concrete in the United States, Massachusetts Institute of Technology,2005.

**data is from 1144 survey projects.Xi, F., Davis, S. J., Ciais, P., Crawford-Brown, D., Guan, D., Pade, C., Shi, T., Syddall, M., Lv, J., Ji, L., Bing, L., Wang, J., Wei, W., Yang, K. H., Lagerblad, B., Galan, I., Andrade, C., Zhang, Y. and Liu, Z.: Substantial global carbon uptake by cement carbonation, Nat. Geosci., 9(12), 880-883, doi:10.1038/ngeo2840, 2016..

*** ERMCO. (European Ready Mixed Concrete Organization) Ready-Mixed Concrete Industry Statistics 2001-2013, Available at (http://www.ermco.eu).

****The strength class distribution in the rest of world refer to situation of Europe

Table A3: Distribution of cement content of concrete by strength class (Average form data sourcesbelow) SI Data Table 8 in Xi et al.[5])			
Strength	Distribution Pattern	Cement content(kg/m^3)	
		max	min
≤C15	uniform	288	165
C16-C23	uniform	390	240
C24-C35	uniform	400	280
>C35	uniform	670	300

Low, M.S.: Material flow analysis of concrete in the United States, Massachusetts Institute of Technology, http://dspace.mit.edu/bitstream/1721.1/33030/2/62096322-MIT.pdf,2005.
ERMCO (European Ready Mixed Concrete Organization) Ready-Mixed Concrete Industry Statistics 2001-2013, Available at (http://www.ermco.eu).
Pade, C. and Guimaraes, M.: The CO2 uptake of concrete in a 100 year perspective, Cem. Concr. Res., 37(9), 1348-1356, doi:10.1016/j.cemconres.2007.06.009, 2007.
Construction and Installation Engineering Budget Manual and Concrete Mix Proportion Quick Manual

Table A4: Concrete carbonation rate coefficients by region for various concrete strengths and exposure conditions in Europe (SI Data Table 9 in Xi et al. [5])					
Region	Exposure condition	Compressive strength (mm/(year)$^{0.5}$)			
		≤15MPa	16-20Mpa	23-35Mpa	>35MPa
Europe (Plain concrete)*	Exposed outdoor	5	2.5	1.5	1
	Sheltered	10	6	4	2.5
	Indoors	15	9	6	3.5
	Wet	2	1	0.75	0.5
	Buried	3	1.5	1	0.75
China (Plain concrete)**	Exposed outdoor	6.1	3.9	2.4	1.3
	Sheltered	9.9	7.1	4.8	2.5
	Indoors	13.9	9.8	7.0	4
	Buried	3.8	1.9	1.0	0.5
	Wet	1.9	1.0	0.7	0.3
USA***	uncoated	7.1	6.9	3.8-5.4	2.5
	Coated	n/a	3.5	1.9-2.7	n/a

*The parameter is for plain concrete in Nordic countries. Pade, C. and M. Guimaraes (2007). "The CO2 uptake of concrete in a 100-year perspective." Cement and concrete research 37(9):1348-1356.
** Cement concrete carbonation coefficients in China are derived from more than 1300 concrete samples all over China.
***Gajda, John, Absorption of Atmospheric Carbon Dioxide by Portland Cement Concrete, R&D Serial No. 2255a, Portland Cement Association, Skokie, Illinois, USA, 2001, 22 pages.

Table A5: Concrete carbonation rate coefficients (K) for different powder additions to be multiplied by the carbonation rate coefficients provided for concrete (SI Data Table 9 in Xiet al.[5])

Type of addition	Amount of addition(wt.%)*					
	0-10%	10-20%	20-30%	30-40%	40-50%	60-80%
Limestone		1.05	1.1			
Fly-ash		1.05		1.1		
Silica-fume	1.05	1.1				
GGBF-Slag	1.05	1.1	1.15	1.2	1.25	1.3

*wt.% is the weight percentage of addition in cement.

data from Pade, C. & Guimaraes, M. The CO2 uptake of concrete in a 100-year perspective. Cement and concrete research37, 1348-1356, doi:DOI 10.1016/j.cemconres.2007.06.009 (2007).

Papadakis, V. G. Effect of supplementary cementing materials on concrete resistance againstcarbonation and chloride ingress. *Cement and Concrete Research***30**, 291-299 (2000).

Table A6: Exposure times of cement materials in life cycle by region (SI Data Table 10 in Xiet al.[5])

The average service life, demolition stage, and secondary use stage (years)in different countries

Countries andregions	average servicelife (range)	average demolition stage (range)	average secondary use stage	assessment time
USA (years)*	65 (56-82)	0.4 (0.1-0.7)	34.6	100
China(years)**	35 (4-73)	0.4 (0.1-0.8)	64.6	100
Europe(years)***	70 (50-90)	0.4 (0.1-0.7)	29.6	100
Indian(years)****	40 (10-90)	0.4 (0.1-1.0)	59.6	100
The rest of world(years)****	40 (10-90)	0.4 (0.1-1.0)	59.6	100

* Kapur, A., Keoleian, G., Kendall, A. & Kesler, S. E. Dynamic Modeling of In-Use Cement Stocks in the United States. Journal of Industrial Ecology 12, 539-556 (2008).

** data in China is estimated based on the Chinese studies and field survey data

***Pommer, K., Pade, C., Institut, D. T. & Centre, N. I. Guidelines: Uptake of Carbon Dioxide in the Life Cycle Inventory of Concrete. (Nordic Innovation Centre, 2006);

Mequignon, M., Ait Haddou, H., Thellier, F., Bonhomme, M.: Greenhouse gases and building lifetimes. Build.Environ., 68, 77-86, doi:http://dx.doi.org/10.1016/j.buildenv.2013.05.017, 2013.

**** Yang, K.-H., Seo, E.-A.,Tae, S.-H.: Carbonation and CO2 uptake of concrete. Environ.Impact Assess.Rev., 46, 43-52, doi:http://dx.doi.org/10.1016/j.eiar.2014.01.004, 2014.

Table A7: Mortar carbonation rate coefficients and CaO converted to $CaCO_3$ in China (SIData Table 14 in Xi et al. [5])

Mortar carbonation rate coefficients measured in China*

	Strength class	Exposure conditions	Experiment exposure time (year)	Average ($mm/yr^{0.5}$)	Max ($mm/yr^{0.5}$)	Min ($mm/yr^{0.5}$)
Portland cement	M15	Outdoor	1	11.1	22.1	4.2
		Indoor		25.5	36.5	15.4
	M20	Outdoor		10.4	19.2	4.3
		Indoor		23.9	36.5	13.9
	M25	Outdoor		10.5	17.9	5.2
		Indoor		23.9	37.8	15.2
	M30	Outdoor		10.8	21.6	4.8
		Indoor		23.5	32.5	16.3
Fly ash cement orslag cement	M15	Outdoor	0.5	13.6	19.9	7.1
		Indoor		29.1	35.4	23.3
	M20	Outdoor		14.2	21.2	7.1
		Indoor		29.9	37.1	22.3
	M25	Outdoor		14.3	20.8	9.0
		Indoor		28.8	38.8	20.8
	M30	Outdoor		13.4	21.6	7.1
		Indoor		30.2	39.4	22.6
	Average	Indoor		26.8	36.8	18.7
	Average	Outdoor		12.3	20.5	6.1

*The mortar carbonation rate coefficients in China is derived from 100 experiment data

The other countries of world refer to the situations of China.

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