

# Open Research Online

---

The Open University's repository of research publications and other research outputs

## Embodied carbon of concrete in buildings, Part 2: are the messages accurate?

### Journal Item

How to cite:

Moncaster, Alice; Malmqvist, Tove; Forman, Tim; Pomponi, Francesco and Anderson, Jane (2022). Embodied carbon of concrete in buildings, Part 2: are the messages accurate? *Buildings and Cities*, 3(1) pp. 334–355.

For guidance on citations see [FAQs](#).

© 2022 The Authors



<https://creativecommons.org/licenses/by/4.0/>

Version: Version of Record

Link(s) to article on publisher's website:  
<http://dx.doi.org/doi:10.5334/bc.199>

---

Copyright and Moral Rights for the articles on this site are retained by the individual authors and/or other copyright owners. For more information on Open Research Online's [data policy](#) on reuse of materials please consult the policies page.

---



# Embodied carbon of concrete in buildings, Part 2: are the messages accurate?

RESEARCH

**ALICE MONCASTER**

**TOVE MALMQVIST**

**TIM FORMAN**

**FRANCESCO POMPONI**

**JANE ANDERSON**

]u[ubiquity press

\*Author affiliations can be found in the back matter of this article

## ABSTRACT

This paper is the second output of a project that examines the embodied greenhouse gas emissions ('embodied carbon') from the use of concrete in buildings. In the current absence of either regulation or widespread industry practice in quantified carbon assessment, it seems likely that messaging will play a powerful role in influencing designers' perceptions and decisions. Using the UK as a case study, this paper considers the current messages about the carbon implications of concrete in buildings from professional institutions and the cement and concrete trade body. Three mechanisms through which it is claimed carbon emissions are significantly reduced are identified: thermal mass, durability, and carbonation. By assessing each of these in turn against the available scientific literature, it is shown that they are likely to have a far more limited effect on the total impacts than suggested. More accuracy is needed from trade organisations if real carbon reductions are to be achieved.

## PRACTICE RELEVANCE

In the current absence of whole life carbon assessment for buildings, messaging about the carbon impacts of different materials is likely to have a strong impact. The paper recommends that the cement and concrete industry should be more accurate with the messages it is sharing. In particular the claims that thermal mass, durability and carbonation are effective mechanisms, which suggest concrete is a low carbon option, should be reconsidered. Meanwhile designers should use the excellent advice being produced by the professional institutions and undertake whole-life carbon calculations to ensure the lowest carbon design. These should include a best estimate of future trends towards warming climates and decarbonisation of electricity, but should also recognise the importance of the immediate effects of the emissions from construction materials. There is also a key role for policymakers in legislating to make the measurement of embodied impacts of buildings mandatory.

## CORRESPONDING AUTHOR:

**Alice Moncaster**

School of Engineering & Innovation, Open University, Milton Keynes, UK

[alice.moncaster@open.ac.uk](mailto:alice.moncaster@open.ac.uk)

## KEYWORDS:

buildings; cement; concrete; construction industry; embodied carbon; greenhouse gas emissions; life cycle assessment (LCA); trade organisations; whole-life carbon

## TO CITE THIS ARTICLE:

Moncaster, A., Malmqvist, T., Forman, T., Pomponi, F., & Anderson, J. (2022). Embodied carbon of concrete in buildings, Part 2: are the messages accurate? *Buildings and Cities*, 3(1), pp. 334–355. DOI: <https://doi.org/10.5334/bc.199>

## 1. INTRODUCTION

This paper is the second output of a project that examines the embodied greenhouse gases (GHGs) ('embodied carbon')<sup>1</sup> impacts of the use of concrete in buildings. The project collates, analyses and critiques evidence from multiple sources to assess and understand the current state of knowledge, and from this starting point to develop recommendations for policymakers and industry practitioners engaged with the decarbonisation agenda. The previous paper in this series focused on the carbon impacts of different cements and concrete mixes, and reported the first comprehensive analysis of Environmental Product Declarations (EPD) (Anderson & Moncaster 2020). It concluded that 'the carbon impacts of cement and concrete remain complex and highly varied' and that (nevertheless) it is imperative to reduce them.

The present paper moves on to consider the messaging to industry decision-makers about the carbon impacts of concrete in buildings. It does not consider the specifics of how the calculations should be carried out, which is the subject of many other academic papers, including several by these authors. Nor does it consider ways in which the impacts of concrete in a building might be reduced through choice of mix and lean design, *etc.*—again others have addressed these topics, and it is included in the focus of the previous paper in this series. Instead it considers the 'headline' messages about the carbon impacts of concrete, which, if detailed calculations are not followed, could affect design decisions and material choices.

The construction of buildings is directly responsible for 10–11% of all energy-related CO<sub>2</sub> emissions through construction activities (Hertwich *et al.* 2020; UNEP 2021), and indirectly responsible for a further 27% from the heating, cooling and lighting of buildings, with non-building-related construction responsible for an additional 10% (UNEP 2021). The World Green Building Council (WGBC) has set an ambitious decarbonisation vision, which includes reducing the embodied CO<sub>2</sub> emissions of all new buildings, as well as renovation projects and infrastructure, by at least 40% by 2030, and achieving 'net zero' by 2050 (WGBC 2019: 4). In the UK, embodied carbon of new assets has been calculated to be 23% of the total GHG emissions from the construction and operation of the built environment (Giesekam & Pomponi 2017). Globally, industry engagement with calculating and reducing embodied energy and GHG emissions of buildings has surged (*e.g.* Simonen *et al.* 2017), while political interest has also grown, as demonstrated by the day dedicated to 'Cities, Regions and the Built Environment' at the United Nations' COP26 in Glasgow in November 2021.

Aligned with this there have been increasing calls for more efficient use of materials (*e.g.* Allwood *et al.* 2011; Hertwich *et al.* 2020), and of construction materials in particular (Dunant *et al.* 2021; Orr *et al.* 2019; Ramage *et al.* 2017; Ruuska & Häkkinen 2014). However, the volume of construction globally is still increasing, partly due to increasing urbanisation. Between 2015 and 2020, the urban population grew from 53% to 55% of the total global population (World Bank 2020), with 140 million additional people moving to live in cities. Zhou *et al.* (2022) report that China alone has constructed over 2 billion m<sup>2</sup> of floor area each year for the last 10 years. Their model suggests that even including predicted energy efficiencies in material production, the annual embodied energy of new construction will increase to 170 million tonnes of coal equivalent (tce), or almost  $5 \times 10^{12}$  MJ, by 2027, around 70% higher than in 2010.

One construction material, cement, is alone responsible for 7–8% of global anthropogenic emissions (Andrew 2019). The global cement industry has long been identified as a key producer of carbon emissions alongside fossil fuel producers (de Schepper *et al.* 2014), and its carbon emissions appear to be growing, although it is difficult to find harmonised figures. The US Mineral Commodity Survey (USGS 2020) reports the world production rate of cement as unchanging between 2015 and 2020 at 4100 billion tonnes/year; however, the Global Carbon Budget (Friedlingstein *et al.* 2020: 3300) found that emissions from cement grew by 3.2% between just 2018 and 2019; while the International Energy Agency (IEA) reports that the carbon intensity of cement has increased by 1.8%/year between 2015 and 2020 (IEA 2021). These later figures seem to align with the increase in urbanisation and building construction. In the UK, of the 13,000 kt of cement produced annually, 83% is used in buildings (Shanks *et al.* 2019).

In order to understand the impacts of different design choices, such as construction material, designers are encouraged to apply whole-life carbon assessment. However, there are ongoing concerns with this approach, including perceptions of a lack of reliable and comparable data, a lack of technical knowledge, and limited agreement over methodological approach (Rasmussen et al. 2020; Schlanbusch et al. 2016). A survey of 500 construction sector practitioners found a lack of quantitative life cycle assessments (LCAs) being carried out at early design stages (Jusselme et al. 2020), while detailed case studies of brownfield sites in the UK, the Netherlands and Australia showed little evidence of changing industry practice (Baker et al. 2017). Giesekam et al. (2014, 2016), while identifying the ‘moral imperative’ that many designers feel over reducing the environmental and GHG impact of their buildings, also identify multiple cultural and institutional barriers to innovation across the construction sector, including innovation in the choice of materials. In November 2021, the UK Green Building Council (UKGBC) in their ‘Net Zero Whole Life Carbon Roadmap’ stated that embodied carbon measurement is still ‘far from being mainstream practice’ (UKGBC 2021: 4).

Without mainstream uptake of detailed LCA calculations, or of regulation, it seems likely that messaging can play a powerful role in influencing designers’ perceptions and decisions. Narratives from the trade organisations for the main construction materials are not surprisingly often partisan, and are picked up by the professional institutions. In the RIBA publication *What Colour is Your building?*, Clark (2013) reports the British Steel Constructional Steelwork Association and Tata Steel claim that, ‘Steel is lower [carbon] than concrete and can also be lower than timber’; and the Forestry Commission Scotland statement, ‘Timber is by far the lowest carbon material’; as well as the Concrete Centre’s claim, ‘Differences between concrete and steel are quite small and insignificant when compared to operational CO<sub>2</sub>’.

Considering the UK as a bounded case study, the present paper considers the current messages that industry professionals may be receiving about the carbon implications of concrete in buildings. Having identified three prevalent claims from the concrete trade organisation the Mineral Products Association (MPA), it assesses these against the scientific literature. The final section summarises the paper and draws general conclusions, with recommendations for designers, policymakers, and the cement and concrete industry.

## 2. METHOD AND LIMITATIONS

Tracing the data and guidance accessed by industry professionals is far from easy. A paper from 2010 found that the two most frequent knowledge sources accessed by UK industry professionals were trade organisations and professional institutions, while half of engineering practitioners also browsed the web for new information at least weekly (Moncaster et al. 2010). However, this was over a decade ago; within the rapidly increasing interest in the UK around embodied impacts of buildings, this might reasonably now be expanded to include guidance from well-known organisations such as the UKGBC, and from the increasing numbers of grassroots industry and industry-academia groups such as the London Energy Transformation Initiative (LETI) and the Architects Climate Action Network (ACAN). Meanwhile, trade organisations still have an important role to play in providing advice about specific materials. This is simpler to identify, as the overarching UK trade body for cement and concrete is the MPA, which incorporates The Concrete Centre and maintains the website [sustainableconcrete.org.uk](https://sustainableconcrete.org.uk).

This type of information was originally described as ‘semi-published’ by Charles Auger (Auger 1975), who later termed it ‘grey literature’ (Auger 1989). Grey literature has long been considered in medical research (e.g. Alberani et al. 1990; Benzie et al. 2006; Pappas & Williams 2011), where it has come to mean a distinct set of sources of unpublished clinical data. Rothstein & Hopewell (2009: 105) defined it as, ‘all documents except journal articles that appear in widely known, easily accessible electronic databases’, suggesting that the grey literature is used in addition to the academic literature ‘as an attempt to lessen publication bias in research syntheses’.

However, unlike medicine, construction industry practice is often quite far removed from academic research, as Moncaster et al. (2010) demonstrated, and there are no ‘widely known,

easily accessible electronic databases' comparable with those of the medical grey literature. There is also a vast and ever-increasing quantity of such literature, spread widely across the internet with no central shared search engine, and it is difficult to assess for quality and validity. Therefore, it is generally acknowledged that a systematic review of the grey literature is difficult (e.g. Mahood *et al.* 2014), and that searching 'grey information' or 'grey data' is even more difficult (Adams *et al.* 2016).

The analysis in this paper therefore avoids attempting such a search, instead taking a pragmatic approach to reviewing some of the available guidance on embodied impacts for UK construction and design professionals from the professional institutions. In the UK there are four such institutions that have members directly involved with the specification of construction materials including concrete and cement: the Institution of Civil Engineers (ICE), the Institution of Structural Engineers (IStructE), the Royal Institute of British Architects (RIBA) and the Royal Institution of Chartered Surveyors (RICS). A further overarching institution for engineers, including those working in the built environment, is the Royal Academy of Engineering (RAEng). The websites for the institutions are highly varied, and some advice was behind a paywall, and therefore only available to institution members. This review covers only publications that are freely available (which includes the key reports), published between 2011 and 2022.

Since the MPA covers the majority of the sector in the UK, the search for this information was able to be somewhat systematic. The Concrete Centre<sup>2</sup> as of November 2021 had published 12 'Concrete Industry Sustainability Performance Reports'; the fourth was published in 2011 and the 12th in 2020 based on 2018 data. In addition, there are several advisory reports, free to download from the website. For this analysis relevant reports were identified by a systematic search of the publications library<sup>3</sup> in November 2021 in the following sequence:

- (1) An initial search for the word 'carbon' identified nine reports published between 2011 and 2021, with 'CO<sub>2</sub>' picking up one additional report during the same period. It was noted that only two of these reports included the word 'embodied' before 'carbon'.
- (2) The word 'sustainable' or 'sustainability' identified an additional six reports.
- (3) A snowball process then reviewed the short descriptions of these 10 reports to identify repeated keywords. This found the word 'thermal' (either 'thermal mass' or 'thermal performance') mentioned in four of the report descriptions, with 'overheating' (considered to be discussing the same issue) also mentioned in one.
- (4) Further concepts in the short descriptions were 'resilience' (in two publications) and 'durability' (one publication). A search for 'durable/durability' and 'resilient/resilience', however, did not reveal any further publications.
- (5) An additional phrase found in one publication was 'resource efficiency'. Used as a search term, this revealed two additional publications.
- (6) 'Circular economy' was also found in one publication, and a search under this term revealed one additional publication.
- (7) Finally, 'whole-life' was identified in four publications; a search under 'whole-life' and 'whole life' revealed one more publication.

Finally, the *Roadmap to Beyond Net Zero* (MPA 2020), although not being identified through the search terms, was referenced in several other later documents reviewed and was therefore added as a clearly significant addition.

The titles and short descriptions of the 26 identified publications are listed in Table S1 in the supplemental data online, in date and alphabetical order.

A further analysis ranked the search terms by the number of times they appeared in the titles or short descriptions of the 26 documents (note this is not the same as the number of documents that are identified by the website under this search term) (see Table S2 in the supplemental data online).

### 3. PROFESSIONAL INSTITUTION AND OTHER INDUSTRY GUIDELINES

Over 10 years ago the IStructE published *A Short Guide to Embodied Carbon in Building Structures* (2011). This focused on structural elements, but pointed out that an embodied energy/carbon assessment ‘should include all major elements’ since the form and material of the structure will have consequence elsewhere, noting, for example, that:

deeper floor construction will call for increased cladding, fair-faced concrete can eliminate the need for finishes, and some design layouts may lend themselves to reductions in applied fire protection to the structure.

(IStructE 2011: 12)

The report emphasised, for concrete in particular, the difference that careful specification can make, reporting research that showed that the embodied carbon of a particular reinforced concrete-framed building (structural elements only) could be reduced from 240 to 140 kg CO<sub>2</sub>e/m<sup>2</sup>.

A short briefing sheet by the ICE updated in 2015 (ICE 2015: 2) calls for ‘cradle to grave’ assessment of impacts, stating that:

in some buildings effective control of ventilation requirements through the use of massive building materials can outweigh the initial additional embodied energy in the building.

Later, however, it adds that savings in operational carbon might be negated through the use of high embodied energy components. A set of recommendations include better specification of steel and concrete, as well as calling for the use of alternative materials, including ‘timber, rammed earth, hempcrete etc.’ to take advantage of their low embodied impacts.

In the same year, the RICS published an Information Paper, ‘Methodology to calculate embodied carbon of materials’ (RICS 2015). Concrete is here mentioned as a carbon-intensive material, along with aluminium and steel. The report encourages a focus on calculating ‘carbon hotspots’, which it suggests are mainly sub- and superstructure elements, cladding, internal finishes and external works (10). However, while suggesting limiting spatial boundaries, it too recommends a full cradle-to-grave analysis in order to compare different materials fairly, noting that long-distance transport of materials can have a significant impact, and that:

large thermal mass materials, high in embodied carbon, may actually reduce the overall life cycle carbon footprint due to reducing the need for cooling over a building’s life. (15)

The document notes that the authors consulted with representatives from the concrete, steel and timber industries, with the first summarised as:

The concrete industry argued that ‘heavy weight’ buildings could reduce cooling and heating loads ‘in use’.

(16)

In 2017, the RICS published a professional statement on the *Whole Life Carbon Assessment of the Built Environment* (RICS 2017). This offers a comprehensive guidance that aims to provide ‘technical details of the numerous aspects influencing whole life carbon calculations for building projects’ (4). The publication identifies the minimum requirements for a whole-life carbon assessment as including substructure and superstructure, and over the whole life of the building. It also includes a section on carbonation, which it says should be accounted for during the use of the building and after demolition. However, it points out that carbonation only occurs where concrete is exposed, and is undesirable in reinforced concrete in which it is deliberately limited by mix design and reinforcement cover. The recommendations state that, as with carbon sequestration in timber, figures for carbonation in concrete should be identified separately. The methodology also requires that future decarbonisation of the electricity grid should be taken into account, and that the impact of climate change should be included in predictions of future heating and cooling demands. The methodology is currently (2022) being updated.<sup>4</sup>

ARIBA publication, also from 2017, is by the first author of the RICS Professional Statement discussed above and recommends its use (RIBA 2017). Both documents include diagrams showing ‘typical breakdowns of whole-life carbon emissions for different building types’ (RICS 2017: 3), which show whole-life-embodied emissions to be considerably over half of the whole-life emissions.

A significant recent guidance, *How to Calculate Embodied Carbon*, was published by the IStructE in 2020, and updated in 2022. This covers much of the same ground as the RICS methodology with a comprehensive explanation of the calculation process. It also offers a range of embodied carbon coefficients and waste rates for different materials. One subsection considers the use of concrete and how to reduce its carbon impact, chiefly by substituting Portland Cement with supplementary cementing materials (SCM) such as ground-granulated blast furnace slag (GGBS) and pulverised fuel ash (PFA). The updated version reports the default assumption of 25% SCM for UK concrete, noting, however, that the global availability of these SCMs is only 16% of global Portland Cement production, and likely to decrease due to decarbonisation of energy and steel. This suggests that the use of SCMs in the UK is currently reducing their use elsewhere, and not adding to general carbon reduction. Carbonation is also mentioned, and estimated to be up to 2.5% reabsorption of the carbon emitted during the product stage. For the end of life, the report adds the Concrete Centre estimate that ‘up to a further 5% of the concrete A1–A3 emissions can be reabsorbed’;<sup>5</sup> however, this is based on an assumption that crushed concrete is left on site for 26 weeks, and the report notes that this period may be much shorter.

In 2021 the RAEng & National Engineering Policy Centre (NEPC) (2021) published a report on *Decarbonising Construction*. This proposed four ‘missions’ across different areas—product outcomes, design and specification, construction and reuse, and changes to procurement (5). Section 1 states that the cement and concrete industry have ‘already delivered a 53% reduction in absolute CO<sub>2</sub> emissions since 1990, faster than the UK economy as a whole’ (4), referencing the UK Concrete and Cement Industry Roadmap. Nevertheless for the design phase, the first enabler for decarbonisation is identified as the development and use of low carbon materials (15). The importance of information and an accreditation scheme for embodied carbon of materials is emphasised in several places, as well as general advice on design and specification.

Most recently (and during the revision of this paper), the ICE has published the *Low Carbon Concrete Routemap* (2022). This offers detailed guidance on how to reduce carbon emissions from concrete, noting the extent of the challenge when ‘the active ingredient is such a significant source of greenhouse gas emissions’ (8). It identifies knowledge transfer, clear guidance, and coordination between institutions and trade bodies as key. Perhaps surprisingly for a document focused on concrete, the section on design and specification starts by suggesting that avoiding the use of concrete altogether should be the initial presumption:

If it has been established that it is not possible to ‘do nothing’ or to re-use an existing structure or element, and that an alternative material would not provide a lower-carbon solution, then concrete may be an appropriate choice.

(31)

Meanwhile, other UK industry bodies with a particular remit for advising on sustainability issues have published a significant set of recent reports. The UKGBC launched their ‘Net Zero Whole Life Carbon Roadmap’ in 2021 at COP26 (UKGBC 2021). LETI published their Embodied Carbon Primer in 2020 (LETI 2020), followed by several related reports in 2021; while ACAN published *The Carbon Footprint of Construction* in 2021. These reports are not reviewed in any detail in this paper, but are bold in their calls for radical change to the construction sector and to the choice of construction materials, with ACAN in particular stressing the environmental impacts of concrete and calling for its use to be reduced as well as its carbon intensity.

The professional institutions, while mentioning and sometimes evaluating the embodied carbon of buildings and individual materials including concrete, are therefore particularly focused on calculation methodologies and advising their members on how to carry these out. Requirements to measure embodied impacts have been missing so far from UK building regulations, and so these fill a necessary gap. Most of the professional institutions recommend that embodied

impacts are calculated over the whole life of the building, including not just the carbon impact of the construction materials but also of their transport and construction, their maintenance and replacement, and the end-of-life processes. This aligns with the BS EN 15978 standard (BSI 2011). Where concrete is specifically mentioned, its potential for (limited) carbonation and its high thermal mass (particularly in earlier publications) are both stated. However, more recent reports from professional institutions call for reducing both the use and the embodied carbon of concrete.

#### 4. CEMENT AND CONCRETE TRADE BODY PUBLICATIONS

The most prominent search term within the MPA documents identified through the systematic review was *'thermal mass'*. The first captured document that includes this term is *Zero Carbon Performance* (MPA 2012). This report considers designing a brick and block house to meet the proposed 2016 Building Regulations Part L Target Emissions Rate of 11 kgCO<sub>2</sub>/m<sup>2</sup>/year (which never came into force). The report states that the high thermal mass helps summer comfort and 'reduces annual CO<sub>2</sub> emissions by around 3% compared to an equivalent lightweight home' (2). However, the document does not include any consideration of embodied carbon.

Meanwhile, in the 2015 *Ahead of the Game* magazine (MPA 2015a), the opening article discusses extreme weather conditions expected due to climate change. A call out box on thermal mass states:

Overheating is a key climate resilience issue that we are already having to contend with and suggests that:

thermal mass provided by the building fabric helps to address excessive gains through its ability to absorb unwanted heat.

However, it also notes that highly insulated new buildings can overheat more due to lack of night-time ventilation, and that 'the case for thermal mass in the commercial sector is more fully established'. A further article suggests:

Over-heating is set to be an increasing problem in well-insulated, low-carbon homes, but thermal mass can provide a solution.

This is also the first publication in which the search term *'whole life'* was identified by the systematic analysis, and here it is related to thermal mass and durability. A call-out box titled 'Whole-life performance' (p. 11) welcomes the development of EPD as a 'much better alternative to the often-misused cradle-to-gate data'. The 'numerous whole-life CO<sub>2</sub> merits of heavyweight materials' are described in this box as 'increased durability, lower maintenance requirements and enhanced thermal performance' as well as 'the ability to design-out internal finishes and rationalise air conditioning installations'. Another search term, *'durability'*, is mentioned again on p. 4 with large text stating '100+ years Concrete has a lifecycle of over a century'. A further large text claim on p. 13 is 'Masonry construction offers the lowest carbon solution over the lifetime of a home'. Thermal mass and durability are once again identified as two of the reasons for specifying concrete on the final page.

In *Thermal Mass Explained* (MPA 2019), the distinction between the use of energy for heating and cooling is conflated. The opening sentences (3) read:

The energy used for space heating accounts for around 20 to 50 per cent of a building's energy consumption depending on type [1], and around 37% of the carbon emissions from all UK buildings [2].

It continues:

In offices and similar building types, the use of thermal mass was, until recently, largely ignored in favour of an entirely air-conditioned approach to cooling. However, with increasing energy costs and concern over CO<sub>2</sub> emissions, its ability to provide passive cooling is being rediscovered and applied in both new and refurbished buildings.



Therefore, while the first sentence is used to stress the carbon impact of heating buildings, the second follows straight on with a claim about the use of thermal mass in reducing cooling. No explicit link is provided, but the casual reader might assume that the second sentence was describing a way of mitigating the high carbon emissions described in the first.

The MPA webpage *Thermal Mass Explained* (MPA 2019), which signposts to this report, does acknowledge that thermal mass is mainly useful for combating overheating in summer, and that this only works if night-time purging of heat is used. They also acknowledge that heavyweight buildings may in fact require *more* heating than lightweight buildings due to the need to warm the fabric, although this should be reduced in well-insulated buildings where the fabric retains its warmth even when heating is off.

The introduction to the 2016 report on *Whole Life Carbon and Buildings* states that:

Concrete-frame construction will of course provide a durable structure, which is a fundamental aspect of whole-life performance. But less understood is its compelling whole-life CO<sub>2</sub> performance, resulting from several attributes largely unique to concrete buildings.

(MPA 2016: 3)

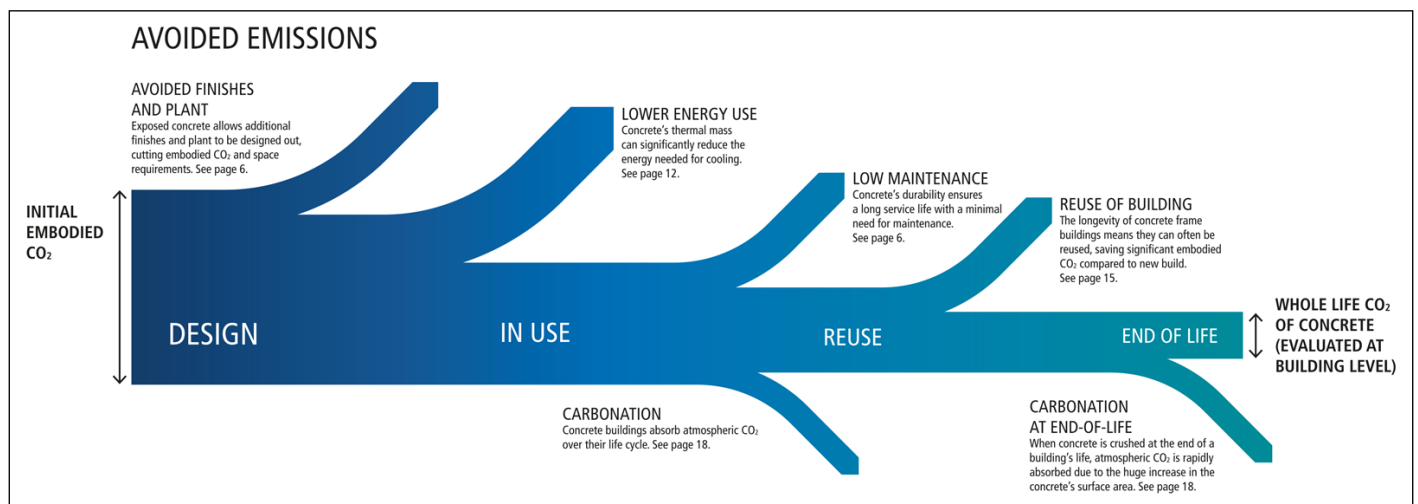
The ‘attributes’ are portrayed in their ‘Figure 1: Overview of opportunities to reduce lifecycle CO<sub>2</sub> in concrete and masonry buildings’ (MPA 2016: 1) (and reproduced here as Figure 1). It is of note that this figure heading includes masonry as well as concrete, although masonry is not discussed further. The figure suggests that the final ‘whole life CO<sub>2</sub> of concrete (evaluated at building level)’ is around one-quarter of the ‘initial embodied CO<sub>2</sub>’ based on the relative thickness at start and finish. The carbon is shown as reducing (by peeling off arrows from the main stream) over the ‘design’, ‘in use’, ‘reuse’ and ‘end-of-life’ stages, due to:

- ‘*Avoided finishes and plant*: Exposed concrete allows additional finishes and plant to be designed out, cutting embodied CO<sub>2</sub> and space requirements.
- ‘*Lower energy use*: Concrete’s thermal mass can significantly reduce the energy needed for cooling.
- ‘*Carbonation*: Concrete buildings absorb atmospheric CO<sub>2</sub> over the life cycle due to a natural process called carbonation.
- ‘*Low maintenance*: Concrete’s durability ensures a long service life with a minimal need for maintenance.
- ‘*Reuse of building*: The longevity of concrete frames means they can often be reused, saving significant embodied CO<sub>2</sub> compared to new build.
- ‘*Carbonation at end-of-life*: When concrete is crushed at the end of a building’s life, atmospheric CO<sub>2</sub> is rapidly absorbed due to the huge increase in the concrete’s surface area.’

As well as thermal mass (the thickest arrow, suggesting the largest reduction), and durability (included in both ‘low maintenance’ and reuse’), this introduces a further concept, ‘carbonation’, shown as occurring both during the life of the building and after the end of life.

**Figure 1:** Overview of the opportunities to reduce life-cycle CO<sub>2</sub> in concrete and masonry buildings.

Source: MPA (2016: 2–3).



Carbonation and thermal mass are also given significant focus in the 2020 Roadmap (MPA 2020). This starts by offering six bullet points in response to 'UK concrete is ...'. Two of these are 'Sustainable, local and responsibly sourced' and 'Tackling climate change and key to a net zero carbon economy'. The roadmap proposes a set of seven 'technology levers', which it claims will lead to 'net zero' and 'beyond net zero'. These include indirect savings from decarbonised electricity (4% CO<sub>2</sub> reduction) and decarbonised transport (7% CO<sub>2</sub> reduction), fuel switching to biomass and hydrogen (16% CO<sub>2</sub> reduction), and innovations in low carbon cements and concretes (12% CO<sub>2</sub> reduction). 'Carbon capture and storage' (61%) takes the total to over 100%, with carbonation (12%) and thermal mass (44%) as two 'technology levers' that will support the further reduction of carbon impacts from concrete to 'beyond net zero' by 2050. The predominant reduction is therefore through carbon capture and storage, a technology independent of the concrete industry and long discussed (e.g. Anderson & Newell 2004), but remaining stubbornly in its infancy and facing increased scrutiny of its real technical potential (e.g. Lane et al. 2021; Warszawski et al. 2021; Haikola et al. 2021). The word 'Carbonation' appears 19 times in the document and 'thermal mass' 13 times. The latter is explained further as:

The [...] deployment of concrete's thermal mass produces a building stock which has an estimated 14% saving of 2050 UK electricity consumption from avoided heating and cooling. This equates to 44% of 2018 concrete and cement emissions levels.

Carbonation is further explained as 'This roadmap assumes the global average rate of natural carbonation of 23%.'

The cement and concrete industry, therefore, as typified by these publications from the MPA, have long been aware of the carbon impact of their material and of its choice as a building material. However, while they are bullish about the potential to reduce their carbon emissions to 'beyond net zero', their main message to industry for the last 10 years is that using concrete in buildings will increase thermal mass and thus reduce operational energy emissions. This has led them to strongly emphasise the importance of whole-life carbon calculations instead of calculating the initial embodied carbon separately. Another (related) message repeatedly stressed has been the durability of concrete. And the third, which has been a growing focus since at least 2015, is the inclusion of the carbonation of cement over the lifetime and after the end of life of the building. Both thermal mass and carbonation are also described as part of the roadmap to decarbonisation. They are therefore claimed both to be routes through which concrete will reduce its impact in the future, and to be evidence that concrete is already a low carbon solution. The roadmap even introduces a phrase, which has started to be repeated elsewhere, that concrete is 'a carbon sink'.

In their written evidence to the Environmental Audit Committee Inquiry on Sustainability of the Built Environment (EAC 2021) the MPA repeat their claims, of durability, thermal mass and carbonation as carbon benefits of concrete, adding recyclability, local production and responsible sourcing. They add that concrete has a sector roadmap 'to achieve beyond net zero by 2050'.

## 5. DISCUSSION

Within the trade publications, and reiterated in some of the professional institution reports, there are three particularly recurring messages made about the use of concrete in buildings in relation to whole-life carbon emissions.

These three claims are examined in turn.

### 5.1 THERMAL MASS EXAMINED

The most prominent claim of the trade publications is that using concrete in buildings will reduce the operational energy demands over the life of a building, due to their thermal mass. The report *Whole Life Carbon and Buildings* (MPA 2016) suggests that this is the major reduction over the life of the building, equivalent (it would appear from Figure 1 in that report) to over one-quarter of the initial embodied carbon. This figure therefore shows the 'initial embodied carbon' itself as being reduced over the life of the building by the lowered (operational) energy use due to thermal

mass. However, this is nonsensical, since the embodied carbon of construction materials and the operational carbon of a building from heating, cooling and lighting are two separate impacts, and this figure is only showing embodied.

Assuming that [Figure 1](#) is really considering whole-life (embodied plus operational) carbon, does the claim that thermal mass will significantly reduce this total stand up? There is a shortage of empirical evidence for how much this effect might be in reality. The detailed report *Thermal Mass Explained* (MPA 2019) references a single paper from a decade before, written by authors from Arup and the Concrete Centre ([Hacker et al. 2008](#)). This paper compares the life-cycle carbon of a small house built of different constructions, including timber frame, lightweight concrete block and dense concrete block. There are several assumptions embedded in this paper. First, the figure for embodied carbon of timber is estimated at about 400 kg CO<sub>2</sub>e/tonne, while that for embodied carbon of high-density block is 75 kg CO<sub>2</sub>e/tonne. Second, the carbon impact of electricity (used for cooling) is taken as 0.422 kg CO<sub>2</sub>/kWh, with no assumptions that this will change. Third, the paper, on the other hand, does assume that external temperatures will increase significantly, based on a medium-high emissions scenario. Finally, in addition to these choices of technical data, there are also social assumptions embedded in the calculations. This two-bedroom house in Outer London is assumed to be kept at a constant temperature of between 19 and 22°C (depending on the room) for 24 h/day, with heating only turned off for three months in the summer, with cooling (seldom currently used in UK residential buildings) considered to be needed if the house reaches 2°C above the maximum temperatures.

Each of these assumptions lead towards the conclusion of the paper that the heaviest weight construction will ‘pay back’ the reduced need for cooling between 23 and 25 years, and that although the heaviest weight construction is 4% higher in embodied carbon compared with timber frame (from the authors’ calculations), it will save between 11% and 17% of CO<sub>2</sub> emissions over the 100-year assumed lifetime. However, the assumptions that these conclusions are based on are clearly problematic. For the materials, the embodied carbon figure used for timber was too high, although there is a wide range of data: [Moncaster et al. \(2021\)](#) suggest between 145 and 196 kg CO<sub>2</sub>e/tonne, while the ICEv.3 database ([Circular Ecology 2019](#)) offers 263 kg CO<sub>2</sub>e/tonne for softwood timber, all excluding sequestration. The figure given for high-density concrete block, on the other hand, was too low, with the ICEv.3 database giving high-density block as around 93 kg CO<sub>2</sub>e/tonne. Therefore, the difference in embodied impacts between the timber and the dense block designs is likely to be much higher than calculated. The second assumption is the carbon intensity of electricity, which is assumed to be constant for the full 100-year lifetime of the building. In the UK electricity has been decarbonised considerably since 2008, reaching around 0.25 kg CO<sub>2</sub>e/kWh in 2020, and it is predicted to fall to less than 0.05 kg CO<sub>2</sub>e/kWh in the next 10 years ([BEIS 2019](#)). The third assumption, of increased average temperatures due to climate change, is the only one that is unfortunately likely to be accurate. Finally, a survey of 405 homes for the Cambridge Housing Model found that an average heated temperature across all houses was 19.8°C; that heating was on for only 10 h/day; and that 80% of houses had their heating off for six months a year, between April and September ([Hughes et al. 2016](#)). Cooling is almost negligible at present in UK residential homes. The amount of operational energy used in the house, and therefore any savings calculated in the heavyweight house, are likely to be very different to the real-world scenario suggested by [Hughes et al. \(2016\)](#).

The comparative embodied carbon of the very heavyweight (concrete structure) house compared with timber frame also seems unlikely when compared with other findings. A review of the IEA’s Annex 57 case studies ([Birgisdottir et al. 2017](#)) showed that the replacement of concrete structures with timber resulted in reductions in embodied carbon of between 28% and 77% for these particular buildings ([Malmqvist et al. 2018](#)), excluding the additional benefits of sequestration of carbon in growing timber. A probabilistic study by [Hart et al. \(2021\)](#) modelled 127 different building superstructure frames of between two and 19 stories and found that the median values for the timber, concrete and steel frames were 119, 185 and 228 kgCO<sub>2</sub>e/m<sup>2</sup>, respectively. A further study conducted a detailed analysis of a medium-rise building using dynamic LCA and found that concrete had the highest initial impact, being somewhat higher than steel and about twice that of timber ([Hawkins et al. 2021](#)).

There is very clear evidence, therefore, that the conclusions from Hacker *et al.* (2008), the apparent basis for the claims of the benefits of thermal mass, are unsound. The majority of recent studies instead suggest that while exposed concrete in high thermal mass buildings is one method to reduce energy use in cooling for buildings in hot climates, it has a limited effect on reducing energy used in heating buildings in cooler climates such as the UK (e.g. Sharston & Murray 2020). A review of academic research by Reilly & Kinnane (2017) concludes that thermal mass only reduces energy demand associated with cooling (not heating), and furthermore, this is only the case if mass is coupled to conditioned spaces by employing external insulation, which is not a common design approach in the UK. In the UK the rapid decarbonisation of energy supply means that any reductions in future cooling loads will save decreasing levels of carbon emissions. Reilly and Kinnane developed accurate models incorporating modern layered wall assemblies and intermittent heating regimes—as opposed to a fixed internal temperature—for both residential and non-residential buildings. They found that while buildings in hot climates with high thermal mass require less energy for cooling, in cooler climates these buildings will require more energy for heating compared with low thermal mass buildings due to the additional requirement of heating the structural elements as well as the internal space.

Indeed, the MPA also acknowledges that buildings with higher thermal mass will take longer to heat up (MPA 2019) unless they are highly insulated and retain rather than lose the stored heat, and it notes that reduction in cooling load is only realised if night-time ventilation and purging is possible.

These conclusions do not, however, appear to have fed in to their Roadmap in 2020, which claims 44% of its carbon reduction as coming from reducing the operational energy in buildings (specifically ‘an estimated 14% of 2050 UK electricity consumption from avoided heating and cooling’), although this is identified as a ‘contribution to beyond net zero’, perhaps in recognition that it does not fit within the boundaries of the assessment.

In the UK, as with other North European countries, by far the major part of energy use is currently in heating rather than cooling. A government analysis of UK energy use in buildings (BEIS 2018) found that across the building stock, 1582 PJ (62% of the total energy used in residential and non-residential buildings) was used for space heating, with the majority of this in residential buildings. Cooling and ventilation accounted for just 91 PJ, or just 3.5%, and almost entirely in non-residential buildings. Average temperatures in the UK are predicted to increase, as are extreme weather events, including heatwaves, and therefore the use of energy in cooling in the UK is likely to increase, and overheating is likely to become a concern. Meanwhile, heating requirements in warmer winters are likely to decrease. However, cooling energy requirements are unlikely to overtake heating energy requirements for several decades.

Thermal mass is one method by which cooling energy loads can be reduced in buildings in hot climates, and possibly for deep-plan office buildings in temperate climates such as the UK where air-conditioning is used, so long as they are designed with internally exposed concrete (or brick), and both adequate insulation (external to the concrete) and night-time purging are provided. It is possible that the whole-life energy could be reduced by this approach, under these specific (and currently non-standard) designs; however, whole-life carbon is a different matter. In the UK where the carbon intensity of electricity has reduced by over 50% over the last 10 years and is predicted to drop further, the carbon cost of cooling the building in future is likely to be too low ever to ‘repay’ the substantially higher initial embodied carbon cost of the concrete. In countries where there is already a majority of renewable energy in the national grid mix, such as Sweden, this is already the case. It is important to reduce even low carbon energy use. But this is at most a dubious long-term carbon saving for a very high short-term carbon cost. In the UK, the new Building Regulations coming into force in June 2022 already have a requirement for limiting overheating. As with the regulations for increasing thermal efficiency, this will have the impact of ensuring all buildings are designed for low cooling loads, whether built of concrete or other materials.

In summary, for housing and the majority of other buildings there is little evidence that using more concrete will reduce the operational energy, let alone the operational carbon, and considerable evidence that using concrete rather than say timber is likely to substantially increase the embodied carbon.

## 5.2 DURABILITY

The second claim made throughout the MPA publications identified is that concrete structures are more durable. This includes two arguments: that the building will last longer, and that less maintenance is required over the lifetime. However, while poor physical condition may often be stated as a reason to demolish buildings, the real reasons are usually found to be social or financial (Thomsen & van der Flier 2011). One of the most thorough studies in this area was by Huuhka & Lahdensivu (2016), who conducted a statistical analysis of all 50,818 buildings demolished in Finland between 2000 and 2012. During the same period, over four times this number of buildings were constructed, with a greater average floor area than the demolished buildings. The majority of demolition occurred in growing communities and in the most urban areas, with the most significant relationships shown between the demolished floor area, the numbers of inhabitants in the municipality, and the rate of growth—in other words, the denser the population and the quicker growing an area is, the greater the demolition. This is not to do with structural obsolescence, but with densification and economic growth. The reason given for the majority of inner-city demolition was to make way for new construction. Over three-quarters of the floor area demolished was from non-residential buildings, and these were demolished at four times the rate of residential buildings, and at a younger age (around 40 years). The most common known construction type of these demolished non-residential buildings was concrete. Therefore, this evidence suggests that non-residential concrete buildings are often demolished well before the end of their life.

The same appears to be true in other countries, too. A survey of 227 buildings in North America (O'Connor 2004) found similar reasons for demolition, with 'no significant relationship' between the structural material and the age of demolition. The majority of concrete and steel buildings in the survey were demolished before they were 50 years old. Zhou et al. (2019) found that in China, where the majority of buildings are concrete, the average age of the residential building stock was 34 years. In a further study of why some buildings were retained while others were demolished, looking at master plan developments in the UK, the Netherlands and Australia, Baker et al. (2021) found that 'fitness-for-purpose, target markets, heritage listings and the desire to create a density uplift' were the main factors considered, rather than structural integrity.

The second cited aspect of durability, low maintenance, is unlikely to reduce carbon emissions since any need for maintenance of structural components is highly unusual.

The durability arguments for concrete, therefore, whether or not factually accurate, are of little relevance where changes in use and market demand commonly lead to demolition long before a structure's usable lifespan. None of the studies of demolition of buildings suggested that concrete buildings were more likely to be retained and reused, with those studied not even reaching their expected design life before being demolished. Whether concrete buildings have the capacity to last longer than buildings of other materials is also not proven; within the UK there are around five million residential homes—about one fifth of the total building stock—which are over 100 years old (MHCLG 2020), and these are of brick, timber frame and stone, not concrete.

## 5.3 CARBONATION

An additional message made throughout the MPA documents, and reiterated elsewhere, too, is that concrete absorbs CO<sub>2</sub> through carbonation, both during the building life and 'at' end of life. The *Whole Life Carbon and Buildings* (MPA 2016: fig. 1) report suggests that the initial embodied emissions are reduced by almost one-quarter through this mechanism. In the Roadmap (MPA 2020) the contribution of carbonation to 'further CO<sub>2</sub> reduction' is defined as 12%.

While intentional carbonation of natural mineral deposits has long been proposed as an approach for carbon capture and storage (Matter & Kelemen 2009), the majority of papers discussing carbonation of concrete in buildings consider it as a negative impact, and consider how it can be avoided in reinforced concrete (e.g. Zheng *et al.* 2021; Sáez del Bosque *et al.* 2020). This is because carbonation reduces the pH of concrete, leading to the risk of corrosion of any reinforcement and loss of structural integrity (Monteiro *et al.* 2012).

However, an influential paper by an extensive group of authors (Xi *et al.* 2016) has suggested that, globally, long-term carbonation of concrete between 1930 and 2013 offset 43% of the emissions from the original calcination process during manufacture (in which limestone—calcium carbonate (CaCO<sub>3</sub>)—is converted to calcium oxide (CaO) and CO<sub>2</sub>). Calcination is responsible for around half of the total CO<sub>2</sub> emissions from the manufacture of CEM I and CEM II cement (e.g. Anderson & Moncaster 2020: figs 9–10); for other classes of cement, calcination can be a lower proportion of the total. The remainder of GHG emissions are due to the use of non-renewable (fossil fuel) energy use in the manufacturing process (Anderson & Moncaster 2020).

Carbonation occurs mostly at exposed surfaces, and Xi *et al.* (2016) suggest that the majority of carbonation is due to external cement renders and mortars, with further carbonation after the end of life occurring when surface area is increased by crushing. This mostly stops again once the crushed concrete is no longer exposed to open air such as when it is re-incorporated as recycled aggregate into other construction.

The annual Global Carbon Budgets in 2018 and 2019 cited Xi *et al.* (2016), but noted that there was insufficient evidence to support the inclusion of carbonation in the fossil fuel and cement part of the global budget (Quéré *et al.* 2018; Friedlingstein *et al.* 2019), concluding that:

The balance of these two processes (calcination during production and subsequent carbonation) is not clear.

However, in 2020, a cement carbonation sink of 0.2 Gt/year was included as part of the total estimate of 9.6 Gt/year (Friedlingstein *et al.* 2020); this was based on two papers (Cao *et al.* 2020; Guo *et al.* 2021), which built on the modelling of Xi *et al.* (2016).

The approach for products and activities that use cement and concrete is somewhat different to that for the Global Carbon Budget. Sacchi & Bauer (2020) discuss whether carbonation should be included in life cycle inventory (LCI) databases. To answer this question, they conduct a detailed statistical analysis of carbonation in 978 different cement-consuming ‘activities’. They note that the surface-to-volume ratio, and the amount of the surface exposed to weather conditions, are the two most significant factors affecting the extent and speed of carbonation. Using a method for including carbonation in LCA studies standardised in EN 16757 (BSI 2017), they identify the resultant reduction in global warming potential (GWP) over the life of each ‘activity’. They conclude that including carbonation can reduce GWP impacts by up to 35%, in a very few activities, with one such example given as the use of cement for soil stabilisation, where it is exposed to the air. They also note that comparative LCA studies might result in marginally different answers where carbonation is included, but only in a very few cases. In 90% of the cases studied, including carbonation in the calculations reduces the GWP over the lifetime by less than 5%, and in 65% of cases by less than 1%. The authors conclude that the inclusion of carbonation in LCI data is unlikely to make a statistically important difference to the majority of comparative LCAs.

Monteiro *et al.* (2012) tested actual depths of carbonation activity in exposed concrete structures of between four and 99 years old as part of an investigation to inform cover depth to steel reinforcement. They found a non-linear relationship between carbonation depth and age, with the most rapid carbonation occurring during the first 10 years up to a depth of around 15 mm and the oldest structure showing carbonation up to 45 mm from the surface. Andersson *et al.* (2013, 2019) meanwhile set out a detailed method by which to calculate this depth of carbonation under different exposure conditions and for different strengths of concrete, over time. They propose that low strength, internal, exposed concrete starts to carbonate at the greatest rate, with the depth of carbonation proportional to the square root of time in years. Higher strength concretes, such as those likely to be used in internally exposed floor soffits (MPA 2015b), and reduced levels of

exposure even with very thin coverings, such as paint or wallpaper, both significantly reduced the initial rate of carbonation. For foundations the maximum initial carbonation rate is just 1.1 mm/year. The main author, Andersson, is the head of research at Sweden's dominant cement producer, Cementa.

Shanks et al. (2019: fig. 4) show the distribution of cement by application in the UK. They calculate that 22% of cement is used in building frames, and 5% in foundations (which tend to be lower strength concrete and therefore have lower cement proportions). Uses that are likely to be exposed include screed, render and mortar, which together make up around 20% of all cement use.

There are therefore two considerations. The global impact of carbonation of existing concrete appears to be significant. However, the effect of carbonation on LCAs of concrete in buildings, particularly where surfaces are not exposed, would seem to be very low. The estimate of 2.5% of the initial embodied carbon over a 60-year lifetime suggested by IStructE (2020) is perhaps still higher than the figures suggested in the academic literature (Andersson et al. 2019; Monteiro et al. 2012; Sacchi & Bauer 2020). The majority of total carbonation is likely to occur after the end of life of the building, and will then depend on the treatment of the waste; the MPA suggest 5%, where crushed and left exposed to the air for 26 weeks on-site, but the IStructE point out that this is often a much shorter period.

## 5.4 AVOIDED EMISSIONS

The above analysis allows one to return to and reassess Figure 1 (MPA 2016: fig. 1). First it is apparent that the labelling of the left-hand side as 'initial embodied CO<sub>2</sub>' is missing major elements of the whole-life carbon which the rest of the figure (and title) relates to. If this embodied carbon is taken to be 100 units, in a conservative estimate where initial embodied carbon is 50% of whole-life carbon, the addition of operational carbon would increase this 'lifecycle CO<sub>2</sub>' to 200 units. In-use and end-of-life embodied impacts, such as those of replacements and demolition, will be ignored for simplicity, but would only strengthen the following arguments.

First, the total reduction due to reduced cooling emissions will be 0% for the majority of buildings in the UK at present, as has been shown. Predictions of future climates and cooling requirements do not suggest that this will change significantly. However, for buildings with a specific design, assuming that the UK is warming, but that at the same time the electricity grid is decarbonising, the carbon from cooling energy over the life of a building with exposed concrete might be reduced. Heating energy and carbon are also likely to reduce due to warming winters, but remain likely to continue to account for the great majority of the operational emissions of the building. A reasonable estimate can be made that the reduction in total operational carbon due to the effect of thermal mass will therefore be not more than 10%, or 10 of our units. This is therefore 5% of the initial 200 units of whole-life carbon.

The durability claims have been discussed above, and they seem to have little basis; it is proposed therefore that this figure should be 0%.

The third claim is of carbonation. Over the life of the building this may be up to around 2.5% of the initial carbon emissions from the manufacture of cement, according to the IStructE (2022). At the end of life it could be up to 5%. Therefore, the maximum possible reduction is 7.5% of the embodied carbon, or 7.5 units. This is, therefore, 3.75% of the initial 200 units.

The absolute maximum reduction in whole-life carbon emissions from these three mechanisms appears likely to be under 9% , and for the majority of buildings under 4%. The carbon impact of these mechanisms will therefore be a fraction of what this figure suggests. The figures for carbonation and thermal mass suggested in the roadmap (MPA 2020) offering 12% and 44% carbon reduction, respectively, seem similarly unjustified.

## 6. CONCLUSIONS

The world is in an increasingly grave situation as a result of anthropogenic emissions of greenhouse gases (GHGs). The Intergovernmental Panel on Climate Change's (IPCC) *Sixth Assessment Report*

(published in August 2021) was clear that ‘at least net zero CO<sub>2</sub> emissions’ needs to be reached in order to limit human-induced global warming. Without rapid decarbonisation of all human activities, many areas of the world will soon become uninhabitable by humans and existing ecosystems. This is no longer a time to make incremental changes. Radical reassessment of what we do is needed, and this applies to the construction sector more than most. Globally buildings are responsible for 39% of GHG emissions, including 28% from the operation (heat and light) of existing buildings, and 10–11% embodied in the construction materials of new buildings each year.

As much as 7–8% of anthropogenic GHG emissions is due to cement production (Andrew 2019). The production of cement releases carbon, ‘previously stored as limestone for hundreds of millions of years’ (Sacchi & Bauer 2020: 1533), in the form of CO<sub>2</sub>. The immediate impact of cement manufacture is to release this ancient store of carbon to the atmosphere through calcination, just as with the burning of fossil fuels. Limestone is also a fossil reserve, and the Global Carbon Budget calculates emissions from fossil fuels and cement together as ‘EFF’ (emissions from fossil fuels) (Friedlingstein et al. 2020). However, despite overwhelming evidence that emissions must be reduced rapidly and radically, cement production is increasing (Andrew 2019; Friedlingstein et al. 2020).

The professional institutions mainly offer advice on methodology. Most agree with the European and British Standard BS EN 15978 (BSI 2011) that whole-life calculations are important for adequate comparisons of impacts of different materials, and that the principal building elements of structure and superstructure should be included as a minimum. The two most thorough recent publications define these boundaries most clearly and are in broad agreement (IStructE 2020; RICS 2017) with the three factors—thermal mass, durability and carbonation—identified by the MPA as having a significant reduction on the whole-life carbon emissions of concrete buildings not given much weight in either of these publications.

The MPA, the main trade body for the cement and concrete industry in the UK, also strongly promotes whole-life calculations. It also supports approaches to reducing carbon impacts from cement and concrete through, for example, increasing the use of supplementary cementing materials (SCM), using different fuels, and lean design. However, as this analysis has shown, it repeatedly promotes three mechanisms through which it claims carbon emissions are reduced or even reabsorbed during the in use, end of life and after the end of life of the building. These mechanisms—thermal mass, durability and carbonation—it suggests are sufficient to reduce the whole-life impacts of concrete by a very significant amount.

This paper shows that, in reality, each of these mechanisms has at best a very limited effect on the whole-life carbon of UK buildings. For the vast majority of UK buildings, there is slim evidence to support the idea that the thermal mass of concrete will significantly reduce operational carbon emissions. While it is to be hoped that demolition of structurally sound buildings will stop, under the current circumstances any potential additional durability of new buildings constructed of concrete (itself unproved) is an irrelevance. The third mechanism discussed is carbonation. While the global impact of the carbonation of existing, exposed, concrete has been calculated to be significant, in buildings carbonation is very little, and the majority happens after the building is demolished. This might be better termed ‘re-carbonation’, as it is the partial reabsorption of CO<sub>2</sub> originally released due to calcination during manufacture of cement. It seems rather obvious that avoiding this initial release of CO<sub>2</sub> is a better approach to reducing carbon emissions than hoping that some of it will be reabsorbed after the end of life of the building.

Since industry publications do not tend to reference their sources of information, their assumptions and methods are often difficult to check. They are seldom peer-reviewed, and understandably are written at least in part to support the economic goals of the organisation. There is therefore a particularly strong argument for a stringent critique of such publications. However, such a critique is seldom carried out allowing the messages being promoted by such publications to continue unchecked. The impact of these messages on both policy and practice is also difficult to ascertain,



but it is potentially very significant. This paper has therefore carried out such a critique, focusing here on the cement and concrete industry, while accepting that other trade organisations are likely to be making similarly unfounded claims.

The paper has focused on a case study of the UK. However, similar claims are made in other countries. For example, in the Swedish context the cement industry highlights existing concrete structures as a carbon sink, stating in their *Road-Map for a Climate-Neutral Concrete Construction* (Fossilfritt Sverige/Fossil Free Sweden 2021) that 15–20% of the calcination process emissions in the cement production is reabsorbed in existing concrete structures, and that this:

can nearly double through improving crushing and handling of demolished concrete structures to create larger exposed concrete surfaces.

(12)

The concrete federation (Svensk Betong 2021) as well as the dominant cement producer in Sweden (Cementa 2021) also argue for the inclusion of carbonation in the calculations and make claims about durability. Thermal mass has not been brought up in Sweden recently, but the durability and carbonation of concrete are used to support the argument that climate declarations should be performed over longer time horizons.

The findings in this paper point towards clear recommendations for designers and specifiers, policymakers, and the cement and concrete industry. For the first group it is clear that only an independent life cycle assessment (LCA) will provide any accuracy in assessing the whole-life impacts of buildings. However, these can be complex at an early design stage. There needs to be a clear understanding of the impact on calculations of future trends towards both warming climates and decarbonisation of electricity supplies, but also of the critical importance of reducing initial emissions of GHGs. Furthermore professionals and students need to be educated in concepts new to most of them such as carbonation, and in critical analysis, to give them the skills to interrogate messages from trade organisations. Policy makers can help by legislating to make the measurement of whole-life embodied impacts of buildings mandatory, as they have very recently in Sweden and other Nordic countries. In order for these measurements to be meaningful at the preliminary design stage, when construction materials are being decided, it is proposed that independent benchmarks are calculated and published as they have been in Sweden in order to give an overview of the range of likely values for different buildings in different materials. Finally the cement and concrete industry needs to be more honest with the messages it is sharing. Concrete is cheap, readily available and extremely versatile, and there is always likely to be a market for its use. But its continued use is also contributing significantly to climate change, and organisations such as the MPA have a duty to provide honest messaging to reflect realistic approaches to reduce this contribution.

The concluding remarks in the IStructE report note that there are many sources of uncertainty, but that:

widespread measurement and open reporting ... [will] reduce this uncertainty and reduce our climate impact.

(IStructE 2022: 43)

Gieseckam & Pomponi (2017) also suggest that:

By the end of 2017, there will be sufficient guidance and evidence to support widespread assessment; the industry must now demonstrate its commitment to tackling climate change by using this guidance to drive carbon reduction.

(339)

However, while accurate assessment is still unregulated and unpracticed, if the guidance is unclear or inaccurate, there is little hope that real carbon reduction will follow.

## NOTES

- 1 In many cases, what is measured and reported is CO<sub>2</sub>, rather than all GHGs. Since CO<sub>2</sub> is by far the major component of GHG emissions from construction materials, this makes rather little difference in practice. The term ‘carbon’ (which can be used either for just CO<sub>2</sub> or for all GHG emissions) is widely used across UK industry as well as, for example, major sector bodies such as the World Green Building Council (WGBC). Since the present paper is focused on the concept rather than on specific quantities, ‘embodied carbon’ as a generic term is considered appropriate.
- 2 See <https://www.concretecentre.com/>.
- 3 See <https://www.concretecentre.com/Resources/Publications.aspx/>.
- 4 For the survey, see <https://globalabc.org/resources/calls-for-proposals/rics-needs-you-development-its-whole-life-carbon-assessment-built/>.
- 5 ‘Stages A1–A3 cover the extraction, transport, and processing of materials and components up to the point at which they leave the manufacturer; this is also known as the ‘cradle to gate’ stage.

## ACKNOWLEDGEMENTS

The authors acknowledge their colleagues who worked with them on the wider project. In alphabetical order: Harpa Birgisdottir (Aalborg University, Denmark), Peter Guthrie (University of Cambridge, UK), Freja Nygaard Rasmussen (Aalborg University, Denmark) and Anne Rønning (Ostfoldforskning, Norway).

## AUTHOR AFFILIATIONS

**Alice Moncaster**  0000-0002-6092-2686

School of Engineering & Innovation, Open University, Milton Keynes, UK

**Tove Malmqvist**  0000-0003-2949-422X

School of Architecture and the Built Environment, KTH Royal Institute of Technology, Stockholm, SE

**Tim Forman**  0000-0002-2333-9416

Cambridge Institute for Sustainability Leadership, University of Cambridge, Cambridge, UK

**Francesco Pomponi**  0000-0003-3132-2523

Resource Efficient Built Environment Lab (REBEL), Edinburgh Napier University, Edinburgh, UK

**Jane Anderson**  0000-0002-9161-6913

School of Engineering & Innovation, Open University, Milton Keynes, UK  
Construction LCA Ltd, Lincolnshire, UK

## AUTHOR CONTRIBUTIONS

The majority of the text was written by A.M., with additional sections by T.M., F.P., T.F. and J.A. All authors were involved in discussions on the content of this paper, and reviewed and proposed changes to the script. J.A. also provided a thorough final review.

## COMPETING INTERESTS

The authors have no competing interests to declare.

## FUNDING

A.M. was funded by the School of Engineering and Innovation at the Open University. Funding for J.A. came from the Arts and Humanities Research Council (AHRC) (grant number AH/R012709/1) Open-Oxford-Cambridge Doctoral Training Partnership.

Supplemental data for this article can be accessed at: <https://doi.org/10.5334/bc.199.s1>

## REFERENCES

- ACAN.** (2021). *The carbon footprint of construction*. Architects Climate Action Network (ACAN). [www.architectscan.org](http://www.architectscan.org)
- Adams, J., Hillier-Brown, F. C., Moore, H. J., Lake, A. A., Araujo-Soares, V., White, M., & Summerbell, C.** (2016). Searching and synthesising 'grey literature' and 'grey information' in public health: Critical reflections on three case studies. *Systematic Reviews*, 5(1), art. 164. DOI: <https://doi.org/10.1186/s13643-016-0337-y>
- Alberani, V., Pietrangeli, P. D. C., & Mazza, A. M.** (1990). The use of grey literature in health sciences: A preliminary survey. *Bulletin of the Medical Library Association*, 78(4), 358. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC225438/>
- Allwood, J. M., Ashby, M. F., Gutowski, T. G., & Worrell, E.** (2011). Material efficiency: A white paper. *Resources, Conservation and Recycling*, 55(3), 362–381. DOI: <https://doi.org/10.1016/j.resconrec.2010.11.002>
- Anderson, J., & Moncaster, A.** (2020). Embodied carbon of concrete in buildings, Part 1: Analysis of published EPD. *Buildings and Cities*, 1(1). DOI: <https://doi.org/10.5334/bc.59>
- Anderson, S., & Newell, R.** (2004). Prospects for carbon capture and storage technologies. *Annual Review of Environment and Resources*, 29(1), 109–142. DOI: <https://doi.org/10.1146/annurev.energy.29.082703.145619>
- Andersson, R., Fridh, K., Stripple, H., & Häglund, M.** (2013). Calculating CO<sub>2</sub> uptake for existing concrete structures during and after service life. *Environmental Science & Technology*, 47(20), 11625–11633. DOI: <https://doi.org/10.1021/es401775w>
- Andersson, R., Stripple, H., Gustafsson, T., & Ljungkrantz, C.** (2019). Carbonation as a method to improve climate performance for cement based material. *Cement and Concrete Research*, 124, 105819. DOI: <https://doi.org/10.1016/j.cemconres.2019.105819>
- Andrew, R. M.** (2019). Global CO<sub>2</sub> emissions from cement production, 1928–2018. *Earth System Science Data*, 11(4), 1675–1710. DOI: <https://doi.org/10.5194/essd-11-1675-2019>
- Auger, C. P.** (1975). *Use of reports literature*. Butterworth.
- Auger, C. P.** (Ed.). (1989). *Information sources in grey literature*, 2nd ed. Bowker-Saur.
- Baker, H., Moncaster, A., Remøy, H., & Wilkinson, S.** (2021). Retention not demolition: How heritage thinking can inform carbon reduction. *Journal of Architectural Conservation*, 27(3), 176–194. DOI: <https://doi.org/10.1080/13556207.2021.1948239>
- Baker, H. E., Moncaster, A. M., & Al Tabbaa, A.** (2017). The decision to demolish or adapt on brownfield sites. *Proceeding of the Institute of Civil Engineers—Forensic Engineering*, 170 FE3, 144–156. DOI: <https://doi.org/10.1680/jfoen.16.00026>
- BEIS.** (2018). *2018 UK greenhouse gas emissions, final figures*. Department for Business, Energy and Industrial Strategy (BEIS). <https://webarchive.nationalarchives.gov.uk/ukgwa/20190509005513/https://www.gov.uk/government/statistics/energy-consumption-in-the-uk>
- BEIS.** (2019). *Updated energy and emissions projections*. Department for Business, Energy and Industrial Strategy (BEIS). <https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019>
- Benzies, K. M., Premji, S., Hayden, K. A., & Serrett, K.** (2006). State-of-the-evidence reviews: Advantages and challenges of including grey literature. *Worldviews on Evidence-Based Nursing*, 3(2), 55–61. DOI: <https://doi.org/10.1111/j.1741-6787.2006.00051.x>
- Birgisdottir, H., Moncaster, A. M., Wiberg, A. H., Chae, C.-U., Yokoyama, K., Balouktsi, M., Seo, S., Oka, T., Luetzkendorf, T., & Malmqvist, T.** (2017). IEA EBC Annex 57 'Evaluation of Embodied Energy and CO<sub>2</sub>eq for Building Construction'. *Energy and Buildings*, 154, 72–80. DOI: <https://doi.org/10.1016/j.enbuild.2017.08.030>
- BSI.** (2011). *BS EN 15978:2011: Incorporating corrigendum November 2011. Sustainability of construction works: Assessment of environmental performance—Calculation method*. British Standards Institution (BSI). <https://shop.bsigroup.com/products/sustainability-of-construction-works-assessment-of-environmental-performance-of-buildings-calculation-method/standard>
- BSI.** (2017). *BS EN 16757:2017 Sustainability of construction works—Environmental product declarations—Product category rules for concrete and concrete elements*. British Standards Institution (BSI).

- Cao, Z., Myers, R. J., Lupton, R. C., Duan, H., Sacchi, R., Zhou, N., Reed Miller, T., Cullen, J. M., Ge, Q., & Liu, G.** (2020). The sponge effect and carbon emission mitigation potentials of the global cement cycle. *Nature Communications*, 11(1), art. 3777. DOI: <https://doi.org/10.1038/s41467-020-17583-w>
- Cementa.** (2021). *Synpunkter på Boverkets rapport 2020:13 'Utveckling av regler om klimatdeklaration av byggnader'* [Comments on the National Board of Housing, Building and Planning's report 2020: 13 'Development of rules on climate declaration of buildings']. <https://www.regeringen.se/49befc/contentassets/eee4559302dc4ac5a904c92df5e836de/cementa.pdf>
- Circular Ecology.** (2019). *Embodied carbon: The ICE database*. <https://circularecology.com/embodied-carbon-footprint-database.html>
- Clark, D.** (2013). *What colour is your building? Measuring and reducing the energy and carbon footprint of buildings*. RIBA Publ.
- de Schepper, M., van den Heede, P., van Driessche, I., & de Belie, N.** (2014). Life cycle assessment of completely recyclable concrete. *Materials*, 7(8), 6010–6027. DOI: <https://doi.org/10.3390/ma7086010>
- Dunant, C. F., Drewniok, M. P., Orr, J. J., & Allwood, J. M.** (2021). Good early stage design decisions can halve embodied CO<sub>2</sub> and lower structural frames' cost. *Structures*, 33, 343–354. DOI: <https://doi.org/10.1016/j.istruc.2021.04.033>
- EAC.** (2021). *Inquiry into sustainability of the built environment: Written evidence*. MPA UK Concrete. Environmental Audit Committee (EAC). <https://committees.parliament.uk/work/1147/sustainability-of-the-built-environment/publications/written-evidence/>
- Fossilfritt Sverige/Fossil Free Sweden.** (2021). *Road-map for a climate-neutral concrete construction*. <https://fossilfrittverige.se/en/roadmap/the-cement-industry/>
- Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., le Quéré, C., DBakker, O. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Anthoni, P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., ... Zaehle, S.** (2019). Global carbon budget 2019. *Earth System Science Data*, 11(4), 1783–1838. DOI: <https://doi.org/10.5194/essd-11-1783-2019>
- Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., le Quéré, C., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S., Aragão, L. E. O. C., Arneeth, A., Arora, V., Bates, N. R., ... Zaehle, S.** (2020). Global carbon budget 2020. *Earth System Science Data*, 12(4), 3269–3340. DOI: <https://doi.org/10.5194/essd-12-3269-2020>
- Gieseckam, J., Barrett, J. R., & Taylor, P.** (2016). Construction sector views on low carbon building materials. *Building Research & Information*, 44(4), 423–444. DOI: <https://doi.org/10.1080/09613218.2016.1086872>
- Gieseckam, J., Barrett, J., Taylor, P., & Owen, A.** (2014). The greenhouse gas emissions and mitigation options for materials used in UK construction. *Energy and Buildings*, 78, 202–214. DOI: <https://doi.org/10.1016/j.enbuild.2014.04.035>
- Gieseckam, J., & Pomponi, F.** (2017). Briefing: Embodied carbon dioxide assessment in buildings: guidance and gaps. *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 171(7), 334–341. DOI: <https://doi.org/10.1680/jensu.17.00032>
- Guo, R., Wang, J., Bing, L., Tong, D., Ciais, P., Davis, S. J., Andrew, M., Xi, F., & Liu, Z.** (2021). Global CO<sub>2</sub> uptake of cement in 1930–2019. *Earth System Science Data*, 2(October). DOI: <https://doi.org/10.5194/essd-13-1791-2021>
- Hacker, J. N., de Saullés, T. P., Minson, A. J., & Holmes, M. J.** (2008). Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings*, 40(3), 375–384. DOI: <https://doi.org/10.1016/j.enbuild.2007.03.005>
- Haikola, S., Anshelm, J., & Hansson, A.** (2021). Limits to climate action—Narratives of bioenergy with carbon capture and storage. *Political Geography*, 88, 102416. DOI: <https://doi.org/10.1016/j.polgeo.2021.102416>
- Hart, J., D'Amico, B., & Pomponi, F.** (2021). Whole-life embodied carbon in multistory buildings: Steel, concrete and timber structures. *Journal of Industrial Ecology*, 25(2), 403–418. DOI: <https://doi.org/10.1111/jiec.13139>
- Hawkins, W., Cooper, S., Allen, S., Royon, J., & Ibelt, T.** (2021). Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure. *Structures*, 33, 90–98. DOI: <https://doi.org/10.1016/j.istruc.2020.12.013>
- Hertwich, E., Lifset, R., Pauliuk, S., & Heeren, N.** (2020). *Resource efficiency and climate change: Material efficiency strategies for a low-carbon future. A report of the International Resource Panel (IRP)*. <http://hdl.handle.net/20.500.11822/34351>
- Hughes, M., Pope, P., Palmer, J., & Armitage, P.** (2016). UK housing stock models using SAP: The case for heating regime change. *Science Journal of Energy Engineering*, 4(2), 12–22. DOI: <https://doi.org/10.11648/j.sjee.20160402.11>
- Huuhka, S., & Lahdensivu, J.** (2016). Statistical and geographical study on demolished buildings. *Building Research & Information*, 44(1), 73–96. DOI: <https://doi.org/10.1080/09613218.2014.980101>

- ICE.** (2015). *Embodied energy and carbon*. Institution of Civil Engineers (ICE). <https://www.ice.org.uk/knowledge-and-resources/briefing-sheet/embodied-energy-and-carbon>
- ICE.** (2022). *Low carbon concrete routemap*. Institution of Civil Engineers (ICE). [https://www.ice.org.uk/media/200i0yqd/2022-04-26-low-carbon-concrete-routemap-final\\_rev.pdf](https://www.ice.org.uk/media/200i0yqd/2022-04-26-low-carbon-concrete-routemap-final_rev.pdf)
- IEA.** (2021). *Cement*. International Energy Agency (IEA). <https://www.iea.org/reports/cement>
- IPCC.** (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R., & Zhou, B. (Eds.)). Cambridge University Press. <https://www.ipcc.ch/report/ar6/wg1/>
- IStructE.** (2011). *A short guide to embodied carbon in building structures*. Institution of Structural Engineers (IStructE). <https://www.istructe.org/IStructE/media/Public/Resources/a-short-guide-to-embodied-carbon-in-building-structures.pdf>
- IStructE.** (2020). *How to calculate embodied carbon*. Institution of Structural Engineers (IStructE). <https://www.istructe.org/IStructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf>
- IStructE.** (2022). *How to calculate embodied carbon*. Institution of Structural Engineers (IStructE). <https://www.istructe.org/resources/guidance/how-to-calculate-embodied-carbon/>
- Jusselme, T., Rey, E., & Andersen, M.** (2020). Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. *Sustainable Cities and Society*, 52, 101879. DOI: <https://doi.org/10.1016/j.scs.2019.101879>
- Lane, J., Greig, C., & Garnett, A.** (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nature Climate Change*, 11, 925–936. DOI: <https://doi.org/10.1038/s41558-021-01175-7>
- LETI.** (2020). *Embodied carbon primer*. London Energy Transformation Initiative (LETI). <https://www.leti.london/ecp>
- Mahood, Q., van Eerd, D., & Irvin, E.** (2014). Searching for grey literature for systematic reviews: Challenges and benefits. *Research Synthesis Methods*, 5(3), 221–234. DOI: <https://doi.org/10.1002/jrsm.1106>
- Malmqvist, T., Nehasilova, M., Moncaster, A., Birgisdottir, H., Nygaard Rasmussen, F., Houlihan Wiberg, A., & Potting, J.** (2018). Design and construction strategies for reducing embodied impacts from buildings—Case study analysis. *Energy and Buildings*, 166, 35–47. DOI: <https://doi.org/10.1016/j.enbuild.2018.01.033>
- Matter, J. M., & Kelemen, P. B.** (2009). Permanent storage of carbon dioxide in geological reservoirs by mineral carbonation. *Nature Geoscience*, 2(12), 837–841. DOI: <https://doi.org/10.1038/ngeo683>
- MHCLG.** (2020). *English Housing Survey data on stock profile*. Ministry of Housing, Communities & Local Government (MHCLG). <https://www.gov.uk/government/statistical-data-sets/stock-profile>
- Moncaster, A. M., Anderson, J., & Mulligan, H.** (2021). *Supporting the development of quality data: Availability, quality and use of construction product LCA data for Ireland, Italy and Croatia. A report for the Irish, Italian and Croatian Green Building Councils*. [https://www.igbc.ie/wp-content/uploads/2021/05/LIFE-Levels-CAR-Report\\_revA\\_29April-2021\\_clean.pdf](https://www.igbc.ie/wp-content/uploads/2021/05/LIFE-Levels-CAR-Report_revA_29April-2021_clean.pdf)
- Moncaster, A. M., Hinds, D., Cruickshank, H., Guthrie, P. M., Crishna, N., Baker, K., Beckmann, K., & Jowitt, P. W.** (2010). A key issue: Knowledge exchange between academia and industry. *Proceedings of the Institute of Civil Engineers—Engineering Sustainability*, 163(3), 167–174. DOI: <https://doi.org/10.1680/ensu.2010.163.3.167>
- Monteiro, I., Branco, F. A., Brito, J. de, & Neves, R.** (2012). Statistical analysis of the carbonation coefficient in open air concrete structures. *Construction and Building Materials*, 29, 263–269. DOI: <https://doi.org/10.1016/j.conbuildmat.2011.10.028>
- MPA.** (2012). *Zero carbon performance: Cost-effective concrete and masonry homes*. Mineral Products Association (MPA). <https://www.concretecentre.com/Resources/Publications/Zero-Carbon-Performance-cost-effective-concrete.aspx>
- MPA.** (2015a). *Ahead of the Game magazine*. Mineral Products Association (MPA). <https://www.concretecentre.com/Resources/Publications/This-is-Concrete-Ahead-of-the-Game.aspx>
- MPA.** (2015b). *Visual concrete: Guidance on specification of formed concrete finishes*. Mineral Products Association (MPA). <https://www.concretecentre.com/Publications-Software/Publications/Visual-Concrete.aspx>
- MPA.** (2016). *Whole life carbon and buildings: Concrete solutions for reducing embodied and operational CO<sub>2</sub>*. Mineral Products Association (MPA). <https://www.concretecentre.com/Publications-Software/Publications/Whole-life-Carbon-and-Buildings.aspx>
- MPA.** (2019). *Thermal mass explained*. Mineral Products Association (MPA). <https://www.concretecentre.com/Resources/Publications/Thermal-Mass-Explained.aspx>

- MPA. (2020). *Roadmap to beyond net zero*. Mineral Products Association (MPA).
- O'Connor, J. (2004). Survey on actual service lives for North American buildings. *Woodframe Housing Durability and Disaster Issues*. <http://www.softwoodlumber.org/pdfs/SurveyonActualServiceLives.pdf>
- Orr, J., Drewniok, M. P., Walker, I., Ibell, T., Copping, A., & Emmitt, S. (2019). Minimising energy in construction: Practitioners' views on material efficiency. *Resources, Conservation and Recycling*, 140, 125–136. DOI: <https://doi.org/10.1016/j.resconrec.2018.09.015>
- Pappas, C., & Williams, I. (2011). Grey literature: Its emerging importance. *Journal of Hospital Librarianship*, 11(3), 228–234. DOI: <https://doi.org/10.1080/15323269.2011.587100>
- Quééré, C., Andrew, R., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P., Ivar Korsbakken, J., Peters, G., Canadell, J., Arneeth, A., Arora, V., Barbero, L., Bastos, A., Bopp, L., Ciais, P., Chini, L., Ciais, P., Doney, S., ... Zheng, B. (2018). Global carbon budget 2018. *Earth System Science Data*, 10(4), 2141–2194. DOI: <https://doi.org/10.5194/essd-10-2141-2018>
- RAEng & NEPC. (2021). *Decarbonising construction: Building a new net zero industry*. Royal Academy of Engineering (RAEng) & National Engineering Policy Centre (NEPC). <https://t.co/NCLzMgb2V6?amp=1>
- Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., Allwood, J., Dupree, P., Linden, P. F., & Scherman, O. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, 68(1), 333–359. DOI: <https://doi.org/10.1016/j.rser.2016.09.107>
- Rasmussen, F. N., Malmqvist, T., & Birgisdóttir, H. (2020). Drivers, barriers and development needs for LCA in the Nordic building sector—A survey among professionals. *IOP Conference Series: Earth and Environmental Science*, 588(3), 032022. DOI: <https://doi.org/10.1088/1755-1315/588/3/032022>
- Reilly, A., & Kinnane, O. (2017). The impact of thermal mass on building energy consumption. *Applied Energy*, 198, 108–121. DOI: <https://doi.org/10.1016/j.apenergy.2017.04.024>
- RIBA. (2017). *Embodied and whole life carbon assessment for architects*. The Royal Institute of British Architects (RIBA). <https://www.architecture.com/knowledge-and-resources/resources-landing-page/whole-life-carbon-assessment-for-architects>
- RICS. (2015). Methodology to calculate embodied carbon of materials. In *RICS QS & Construction Standards*. The Royal Institution of Chartered Surveyors (RICS). [https://www.igbc.ie/wp-content/uploads/2015/02/RICS-Methodology\\_embodied\\_carbon\\_materials\\_final-1st-edition.pdf](https://www.igbc.ie/wp-content/uploads/2015/02/RICS-Methodology_embodied_carbon_materials_final-1st-edition.pdf)
- RICS. (2017). *RICS professional statement: Whole life carbon assessment for the built environment*. The Royal Institution of Chartered Surveyors (RICS). <https://www.rics.org/globalassets/rics-website/media/news/whole-life-carbon-assessment-for-the-built-environment-november-2017.pdf>
- Rothstein, H., & Hopewell, S. (2009). Grey literature. In *Sage handbook of research synthesis and meta-analysis* (pp. 103–126). Russell Sage Foundation.
- Ruuska, A., & Häkkinen, T. (2014). Material efficiency of building construction. *Buildings*, 4(3). DOI: <https://doi.org/10.3390/buildings4030266>
- Sacchi, R., & Bauer, C. (2020). Should we neglect cement carbonation in life cycle inventory databases? *International Journal of Life Cycle Assessment*, 25(8), 1532–1544. DOI: <https://doi.org/10.1007/s11367-020-01776-y>
- Sáez del Bosque, I. F., Van den Heede, P., De Belie, N., Sánchez de Rojas, M. I., & Medina, C. (2020). Carbonation of concrete with construction and demolition waste based recycled aggregates and cement with recycled content. *Construction and Building Materials*, 234, 117336. DOI: <https://doi.org/10.1016/j.conbuildmat.2019.117336>
- Schlanbusch, R. D., Fufa, S. M., Häkkinen, T., Vares, S., Birgisdóttir, H., & Ylmén, P. (2016). Experiences with LCA in the Nordic building industry—Challenges, needs and solutions. *Energy Procedia*, 96, 82–93. DOI: <https://doi.org/10.1016/j.egypro.2016.09.106>
- Shanks, W., Dunant, C. F., Drewniok, M. P., Lupton, R. C., Serrenho, A., & Allwood, J. M. (2019). How much cement can we do without? Lessons from cement material flows in the UK. *Resources, Conservation and Recycling*, 141, 441–454. DOI: <https://doi.org/10.1016/j.resconrec.2018.11.002>
- Sharston, R., & Murray, S. (2020). The combined effects of thermal mass and insulation on energy performance in concrete office buildings. *Advances in Building Energy Research*, 14(3), 322–337. DOI: <https://doi.org/10.1080/17512549.2018.1547220>
- Simonen, K., Rodriguez, B. X., & De Wolf, C. (2017). Benchmarking the embodied carbon of buildings. *Technology|Architecture + Design*, 1(2), 208–218. DOI: <https://doi.org/10.1080/24751448.2017.1354623>
- Svensk Betong. (2021). *Svensk Betong svar på remiss Fi 2020/02715 Remiss av Boverkets rapport Utveckling av regler om klimatdeklaration av byggnader* [Svensk Betong responds to consultation Fi 2020/02715 Referral of the National Board of Housing, Building and Planning's report Development of rules on climate declaration of buildings]. <https://www.regeringen.se/49befc/contentassets/eee4559302dc4ac5a904c92df5e836de/svensk-betong.pdf>

- Thomsen, A., & van der Flier, K.** (2011). Understanding obsolescence: A conceptual model for buildings. *Building Research & Information*, 39(4), 352–362. DOI: <https://doi.org/10.1080/09613218.2011.576328>
- UKGBC.** (2021). *Net zero whole life carbon roadmap: A pathway to net zero for the UK built environment*. UK Green Building Council (UKGBC). <https://www.ukgbc.org/ukgbc-work/net-zero-whole-life-roadmap-for-the-built-environment/>
- UNEP.** (2021). *2021 Global status report for buildings and construction*. United Nations Environment Programme (UNEP). <https://www.unep.org/resources/report/2021-global-status-report-buildings-and-construction>
- USGS.** (2020). *Mineral commodity summaries*. United States Geographical Survey (USGS). <https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf>
- Warszawski, L., Kriegler, E., Lenton, T. M., Gaffney, O., Jacob, D., Klingensfeld, D., & Rockström, J.** (2021). All options, not silver bullets, needed to limit global warming to 1.5°C: A scenario appraisal. *Environmental Research Letters*, 16(6), 064037. DOI: <https://doi.org/10.1088/1748-9326/abfeec>
- WGBC.** (2019). *Bringing embodied carbon upfront: Coordinated action for the building and construction sector to tackle embodied carbon*. World Green Building Council (WGBC). <https://www.worldgbc.org/bringing-embodied-carbon-upfront-report-webform>
- World Bank.** (2020). *Urban population (% of total population)*. <https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS?end=2018&start=2014&view=chart>
- 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.** (2016). Substantial global carbon uptake by cement carbonation. *Nature Geoscience*, 9, 880–883. DOI: <https://doi.org/10.1038/ngeo2840>
- Zheng, X. W., Li, H. N., & Gardoni, P.** (2021). Life-cycle probabilistic seismic risk assessment of high-rise buildings considering carbonation induced deterioration. *Engineering Structures*, 231, 111752. DOI: <https://doi.org/10.1016/j.engstruct.2020.111752>
- Zhou, W., Moncaster, A., Reiner, D. M., & Guthrie, P.** (2019). Estimating lifetimes and stock turnover dynamics of urban residential buildings in China. *Sustainability (Switzerland)*, 11(13), 3720. DOI: <https://doi.org/10.3390/su11133720>
- Zhou, W., Moncaster, A. M., O'Neill, E., Reiner, D., Wang, X., & Guthrie, P.** (2022). Estimating past and future annual embodied energy of the urban residential building stock in China. *Energy Policy*, 165, 112932. DOI: <https://doi.org/10.1016/j.enpol.2022.112932>

#### TO CITE THIS ARTICLE:

Moncaster, A., Malmqvist, T., Forman, T., Pomponi, F., & Anderson, J. (2022). Embodied carbon of concrete in buildings, Part 2: are the messages accurate? *Buildings and Cities*, 3(1), pp. 334–355. DOI: <https://doi.org/10.5334/bc.199>

**Submitted:** 21 January 2022

**Accepted:** 04 May 2022

**Published:** 25 May 2022

#### COPYRIGHT:

© 2022 The Author(s). This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (CC-BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited. See <http://creativecommons.org/licenses/by/4.0/>.

*Buildings and Cities* is a peer-reviewed open access journal published by Ubiquity Press.