Embodied carbon of concrete in buildings: Part 1 - analysis of published EPD

How to cite:
Anderson, Jane and Moncaster, Alice (2020). Embodied carbon of concrete in buildings: Part 1 - analysis of published EPD. Buildings and Cities, 1(1) pp. 198–217.

© 2020 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.59

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.
1.2 Embodied carbon of buildings

The environmental impacts of buildings are commonly divided into two types: embodied and operational (Ibn-Mohammed 2013). These can be further defined through reference to European Standards EN 15978 and EN 15804 in 2012 (CEN 2011, 2019), which produced clear descriptions of the life-cycle stage impacts of a construction product, building or project (CEN 2011). Embodied impacts of buildings include those from material production and transport, construction activities, maintenance and replacement of components, demolition, and transport and processing of demolition waste, and are described in substages A1–A5, B1–B5 and C1–C4 in EN 15978. The operational impacts (also known as ‘regulated impacts’ in the UK) come from heating, lighting and cooling, as well as from operational water use, and are described by substages B6 and B7.

Embodied impacts have historically been considered to be insignificant compared with operational impacts, and regulation has therefore tended to focus on the latter (Szalay 2007). Since the publication of the standards, both research into and industry concern with the embodied impacts of buildings have grown rapidly (WGBC 2019). However the complexities of and variations in the data, along with remaining inconsistencies in spatial and temporal boundaries, have meant that conclusions remain nebulous (Moncaster 2018).

Consensus is nevertheless emerging on some aspects. A recent output from the International Energy Agency (IEA) project Annex 57 reviewed and analysed the data from over 80 individual life-cycle assessments of buildings (Moncaster 2019). In most of the case studies analysed, the product stage was found to have the highest impact (IEA 2019). Cements and metals were shown to be the highest impact materials, and the sub- and super-structure found to be the highest impact building elements. This confirmed findings elsewhere (Häkkinen 2015; Kreiner, Passer, & Wallbaum 2015).

There is increasing evidence that for rapidly developing countries the embodied impacts of buildings also form a substantial proportion of their total energy use. The energy used in construction and demolition materials and processes in China in 2014, for example, was 16% of the total energy consumed in the country, and a comparable proportion with the annual operational energy used in all existing buildings in China in the same year (Zhou 2019). Averaging over all developed and developing countries, the construction of buildings is responsible for 11% of global greenhouse gas emissions (IEA & UNEP 2018: 11).

Globally the majority of the sub- and super-structures of both residential and non-residential new buildings are also constructed of concrete; it is unsurprising therefore that cement, the main constituent of concrete in terms of emissions, is alone responsible for 7% of global greenhouse gas emissions (IEA 2018).

1.3 Previous research on the embodied carbon of cement and concrete

One of the key challenges for calculating embodied impacts from buildings is the choice of carbon coefficient for materials at the early design stage before they have been fully specified (Moncaster 2018). For concrete, the potential variations are almost infinite, dependent on the type and proportions of cement and aggregates, the addition of admixtures and plasticisers, and on the specific manufacturers’ plants, processes and fuels.
There have been different approaches to dealing with this challenge. Ashby (2016), for example, offers a useful single value for the carbon footprint of concrete. An alternative approach is given in an early paper by Flower and Sanjayan (2007), who offer CO₂ emissions for several different theoretical mixes. These are based on primary data for aggregates collected from quarries, combined with secondary data for cement (Heidrich, Hinczak, & Ryan 2005); the paper is specifically focused on the Australian data and context. Purnell and colleagues followed a similar ‘bottom-up’ approach, summing the embodied carbon impacts of the individual constituents of a large number of theoretical mixes of concrete (Purnell and Black 2012), and then of different beams and columns (Purnell 2013). However the accuracy of the results is limited by the underlying data used, which derived from three UK sources: Hammond and Jones (2008), which has since been radically updated (Jones 2019), and two others produced by Scottish Water and trade body the Cementitious Slag Makers Association, which are no longer available. The Australian data from Flower and Sanjayan (2007) were also used. As well as their region-specific nature, all four sources were published before any approved EPD methodology, and so are based on data points themselves developed with considerable variation.

A review by Pomponi and Moncaster (2018) found that this variation has led to a wide range of energy and carbon coefficients being assumed by academic researchers, in developing case studies of buildings. It has also led to considerable uncertainty for designers as to which is the appropriate value to use for the embodied carbon of concrete at the early design stage of a building, and the potential for extremely differing answers, as demonstrated by Moncaster (2018).

Other researchers have conducted research into different mix designs for low carbon concrete (Kim, Tae, & Roh 2013, Bostanci, Limbachiya, & Kew 2018), and into novel replacements for cements such as alkali activated fly ash/slag (Abdalqader, Jin, & Al-Tabbaa 2016) and phosphorous slag (Yang 2019). Shanks (2019) expand the issue to consider more broadly: ‘How much cement can we do without?’

Since EN 15804 set out an agreed methodology for EPDs for construction materials (CEN 2019), there have been over 500 registered EPD for cements, ready-mix concretes, precast concrete products and mortars. Several countries have developed national databases of EPD and generic material data, and other databases are either free or available to purchase through subscription. However no previous publication has collated, reviewed or analysed these data.

### 1.4 Structure of the paper

This paper collates and analyses the published and verified EPD for cementitious materials, aggregates, admixtures and ready-mix concrete products, demonstrating the full up-to-date range of carbon impacts of this material, to the same accuracy as the primary data used.

The paper is structured as follows. A short methodology section follows, after which the paper considers the range of EPD for cementitious products with a discussion on two important remaining inconsistencies in data. Section 4 analyses the ranges of carbon impacts for the different standard classes of cement, followed by section 5 on the impacts of aggregates and additives, and section 6 on the impacts of different ready-mix concretes. A short concluding section is offered as section 7.
2. Methodology

Construction Product EPD Programmes were accessed in August 2019, and all published EPD for cementitious materials, aggregates, admixtures and ready-mix concrete products were downloaded. A further check was undertaken in November 2019 to download any further EPD published in the interim. The EPD programmes accessed were members of ECO Platform (2019) or have product category rules (PCR) listed in the North American PCR Catalog (Sustainable Minds 2019). Several additional verified EPD were also included that have been published through trade associations. The sources of EPD for each type of product are listed in [link]. All EPD were to EN 15804:2012+A1:2013, ISO 21930:2017 or ISO 14025:2010, and have been independently verified according to ISO 14025:2010. For a list of references to all EPD used in this analysis, see the open access website [link].

Note that EPDs for cement usually only quote the global warming potential (GWP) for the ‘cradle to gate’ modules A1–A3, including impacts from extraction, transport and manufacturing until the product is ready to leave the factory gate. Modules A4 and A5 (transport to site and construction), B1–B7 (use phase), C1–C4 (end of life) and D are generally omitted since cement is normally only used in other construction products. The GWP indicator measures the CO$_2$ and other greenhouse gases so it gives a measure in carbon dioxide equivalents (CO$_2$e). For construction products, this is known in the UK as ‘embodied carbon’ (ECO$_2$e).

Numbers of Environmental Product Declarations (EPD) (and products separately declared within the EPD) by programme and product group.

| Programme | ATILH (France) | Bau EPD | BCS Okogarantie | BRE EN 15804 EPD | Cembureau | DAPcons | EPD Australasia | EPD Danmark | EPD Ireland | EPD Italia | EPD Norge | FDES/inies | Global EPD | IBU | International EPD | ITB | MRPI | RT EPD | SUGB | UL Environment | Cemsuisse | ASTM | CSA | NRMCA | NSF | NSF | 118 (102) | 93 (20) | 9 (7) | 16 (14) | 2045 (163) |
|-----------|----------------|---------|----------------|-----------------|------------|---------|----------------|-------------|-------------|-----------|-----------|-----------|-----------|------|----------------|-----|------|---------|------|----------------|--------|------|------|-------|------|-------|--------|-------|-------|----------|----------|
3. Cementitious products

3.1 Overview of EPD for cementitious products

A total of 102 EPD for 118 cementitious products were evaluated, covering cements, cementitious co-products such as fly ash, and cementitious products such as ground limestone. Most EPD cover a single product, and over 80% of EPD use EN 15804:2012+A1:2013. Most EPD provide information on clinker content and the use of secondary fuels, and just over half provide some detail on the constituents of the cement, though many provide a range rather than precise figures.

shows the range of embodied carbon (taken as the GWP impact for modules A1–A3) for each type of cement. The impact of cement is highest for white cements, followed by CEM I cements, with impact reducing as the amount of clinker reduces in CEM II (with CEM II/A having more impact than CEM II/B because of the higher clinker content), then CEM III. CEM IV (pozzolanic cements) have a similar impact to CEM II/B. Co-products such as fly ash have the lowest impact.

Manufacturers and/or trade associations in 21 countries have produced EPD for cementitious materials. shows the embodied carbon for the EPD from each country. It shows both national average or generic EPD as separate data points (some of these are for the average cement, others for particular products such as CEM I), and the range of manufacturer-specific EPD for a country, which can cover different types of cementitious materials, so it should not be seen as being representative of the range of national production. For example, the three Dutch EPD are all for cementitious by-products, hence their low impact. Conversely, the Turkish EPD are all for white cement or calcium alumino-sulphate cements, hence their high impacts.

The embodied carbon associated with cement comes from two sources: the emissions from the use of fuels and process emissions from the calcination of limestone (Barcelo 2014). The IPCC, OECD & IEA (1996) states the amount of CO₂ from calcination can be calculated using the assumed limestone fraction of clinker (64.6%) and the relative molecular masses of calcium oxide (56 g) and CO₂ (44 g) = 0.507 kg CO₂ per kg clinker. For each cement reporting the clinker content, the CO₂ from calcination could be calculated and deducted from the reported GWP indicator, giving the amount of GWP assumed to come from fossil fuel use and from use of non-renewable secondary fuels, and in some cases the disposal of waste in the cement kiln (see below). shows the CO₂ (CO₂ equivalent) reported in the EPD less the amount calculated to be released from calcination as above. This has then been compared with the use of fossil fuels, reported using the indicator abiotic depletion potential—fossil (ADP-F) and the use of secondary fuels—non-renewable (SF-NR). It shows a clear correlation, and there are obvious regions of the graph where different types of cement are located. However several EPD show anomalous results, suggesting a discrepancy in modelling or reporting, which is discussed below.
Global warming potential (GWP) for cementitious Environmental Product Declarations (EPD) by country of producer.
RESEARCH

Embodied carbon of concrete in buildings, Part 1: analysis of published EPD

Jane Anderson¹ and Alice Moncaster²

Abstract
Cement is responsible for 7% of global greenhouse gas emissions, and is predicted to grow with increasing development. The majority is used in concrete, globally the most common material in buildings. Reducing emissions from the use of cement and concrete in buildings is therefore critical in order to limit global warming. However there remain multiple gaps in knowledge about the extent of these emissions. This paper is the first output of a project that aims to understand better the embodied impacts from the use of concrete in buildings, in order to inform and advise policy-makers and industry practitioners, and to provide clear evidence for the path forwards. In order to do so, the project collates, analyses and critiques evidence from multiple sources, reported over three papers. This first paper focuses on the basic data on materials impacts. Over the last few years, several hundred individual Environmental Product Declarations (EPD) have been published for cements, aggregates and concrete mixes, but no publication offers a comparison or overview. Therefore understanding the range and opportunities for the reduction of impacts from concrete remains very limited. This paper provides the first detailed analysis of the EPD for concrete and its constituents.

Practice relevance
The graphs developed in this paper can be used by designers and manufacturers to understand and reduce the impacts from cement and concrete. Designers will have a better idea of an appropriate coefficient to use at the early design stage before more details are known. As the design progresses, they will be able to use the graphs presented to choose a lower impact cement or concrete with the same performance, as well as to check the likely validity of any EPD. The graphs also provide an incentive to manufacturers to reduce impacts, since they will now be able to compare their products with others. Finally, for those involved in producing EPD, the paper demonstrates the necessity of more detailed rules for consistency, and in the meantime the necessity of full transparency in EPD reports.

Keywords: buildings; cement; concrete; construction materials; embodied carbon; Environmental Product Declaration (EPD); infrastructure

1. Introduction
1.1 Aim and structure of the paper
This paper is the first output from a study into the embodied impacts from the use of concrete in buildings. The study aims to inform and advise policy-makers, industry leaders, designers and specifiers through the collation, analysis and critique of evidence from multiple sources. It will be published in three parts. Parts 2 and 3 will look at the effects of industry practices in the use of concrete in buildings, and at the academic evidence for the impact of boundary choice and methodology on the quoted results for embodied impacts.

This first paper, Part 1, looks at current material-specific data, providing the first global review and analysis of the several hundred available verified Environmental Product Declarations (EPD) that have been published for different cements, aggregates, admixtures and ready-mix concretes. General and bespoke concrete mixes are not reviewed, as these do not have associated EPD. However they can be calculated from the data provided for the constituent parts as needed. While the wider project, and the other two papers, focus specifically on the use of concrete in buildings, this paper is therefore also applicable to cement and concrete used in non-building applications.

Each paper draws an independent conclusion and makes recommendations based on the evidence presented.

¹ School of Engineering and Innovation, Open University, Milton Keynes, UK. ORCID: 0000-0002-9161-6913
² School of Engineering and Innovation, Open University, Milton Keynes, UK. ORCID: 0000-0002-6092-2686
Corresponding author: Alice Moncaster (alice.moncaster@open.ac.uk)