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RESEARCH

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

Jane Anderson[1] and Alice Moncaster[2]

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.

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1.2 Embodied carbon of buildings

The environmental impacts of buildings are commonly divided into two types: embodied and operational (Ibn-Mohammed *et al.* 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 (**Figure 1**). 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 *et al.* 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 *et al.* 2019). In most of the case studies analysed, the product stage was found to have the highest impact (**Figure 2**). 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 *et al.* 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 *et al.* 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 *et al.* 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.

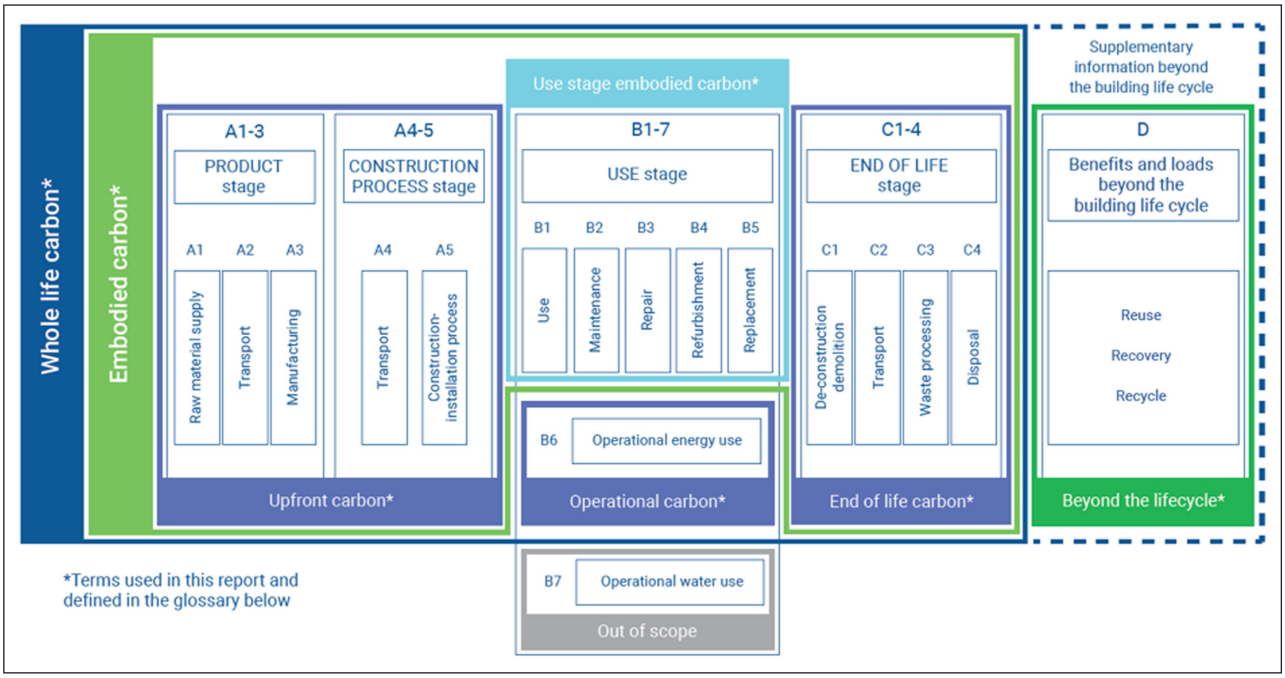

Figure 1: System boundaries definitions in relation to the life-cycle stages of a building. Reproduced with permission from WGBC (2019: 3) and based on EN 15978 (CEN 2011).

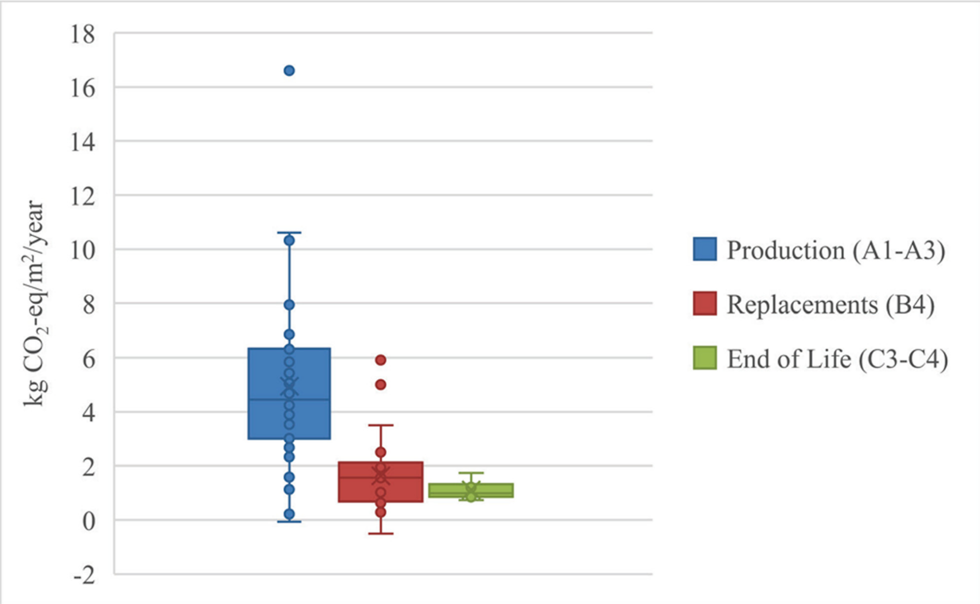

Figure 2: Variations in embodied greenhouse gases from different life-cycle stages representing product stage A1–A3 (56 cases), replacements B4 (42 cases) and end-of-life C3 and C4 (nine cases). Reproduced from Moncaster *et al.* (2019: fig. 2).

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 CO_2 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 *et al.* (2018).

Other researchers have conducted research into different mix designs for low carbon concrete (*e.g.* 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 *et al.* 2019). Shanks *et al.* (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 **Table 1**. 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 https://doi.org/10.21954/ou.rd.12200873.v1/.

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_2e). For construction products, this is known in the UK as 'embodied carbon' (ECO_2e).

Table 1: Numbers of Environmental Product Declarations (EPD) (and products separately declared within the EPD) by programme and product group.

EPD programmes	Cementitious material	Aggregates	Specialist aggregate	Admixtures	Ready-mix concrete
EN 15804+A1 EPD					
ATILH (France)	10				
Bau EPD	0				
BCS Okogarantie	1				
BRE EN 15804 EPD	4	4			13
Cembureau	3				
DAPcons	2				
EPD Australasia	4 (2)				114 (2)
EPD Danmark	0				
EPD Ireland	0				
EPD Italia	5 (2)				2
EPD Norge	18 (17)	16 (4)			30
FDES/inies	0	4			3
Global EPD	7				
IBU	26		3	13	10
International EPD	18 (11)	14 (3)	5 (3)	3 (1)	40 (11)
ITB	1				
MRPI	3				
RT EPD	0		1		
SUGB	0	5 (1)			
UL Environment	0				
Cemsuisse	4				
ISO 21930:2007 EPD					
ASTM	4	48 (3)			6 (1)
CSA	2				
NRMCA	6 (3)	2 (1)			1583 (18)
NSF	0				244 (73)
Total	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.

Figure 3 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. **Figure 4** 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 (*e.g.* Barcelo *et al.* 2014). The IPCC, OECD & IEA (1996) states the amount of CO_2 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 CO_2 (44 g) = 0.507 kg CO_2 per kg clinker. For each cement reporting the clinker content, the CO_2 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). **Figure 5** shows the CO_2e (CO_2 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.

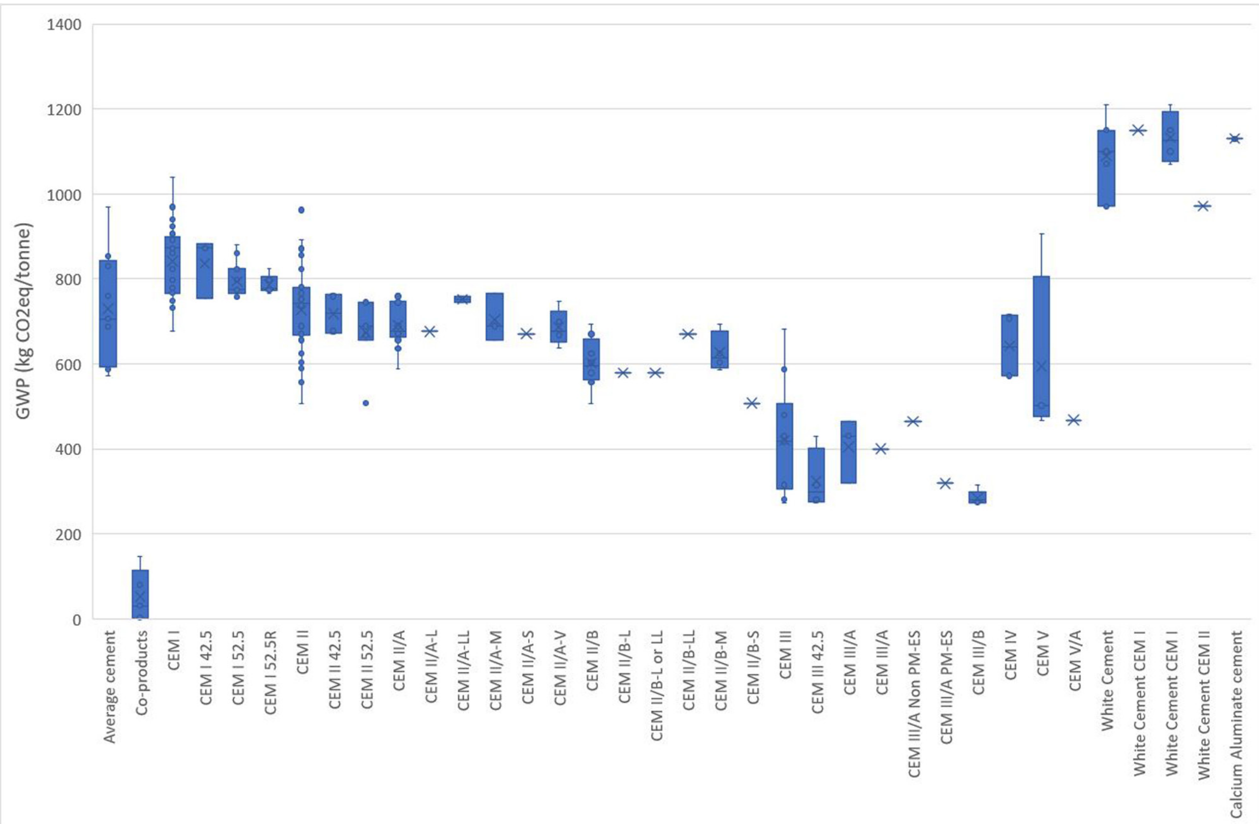

Figure 3: Global warming potential (GWP) range for cementitious Environmental Product Declarations (EPD) by type.

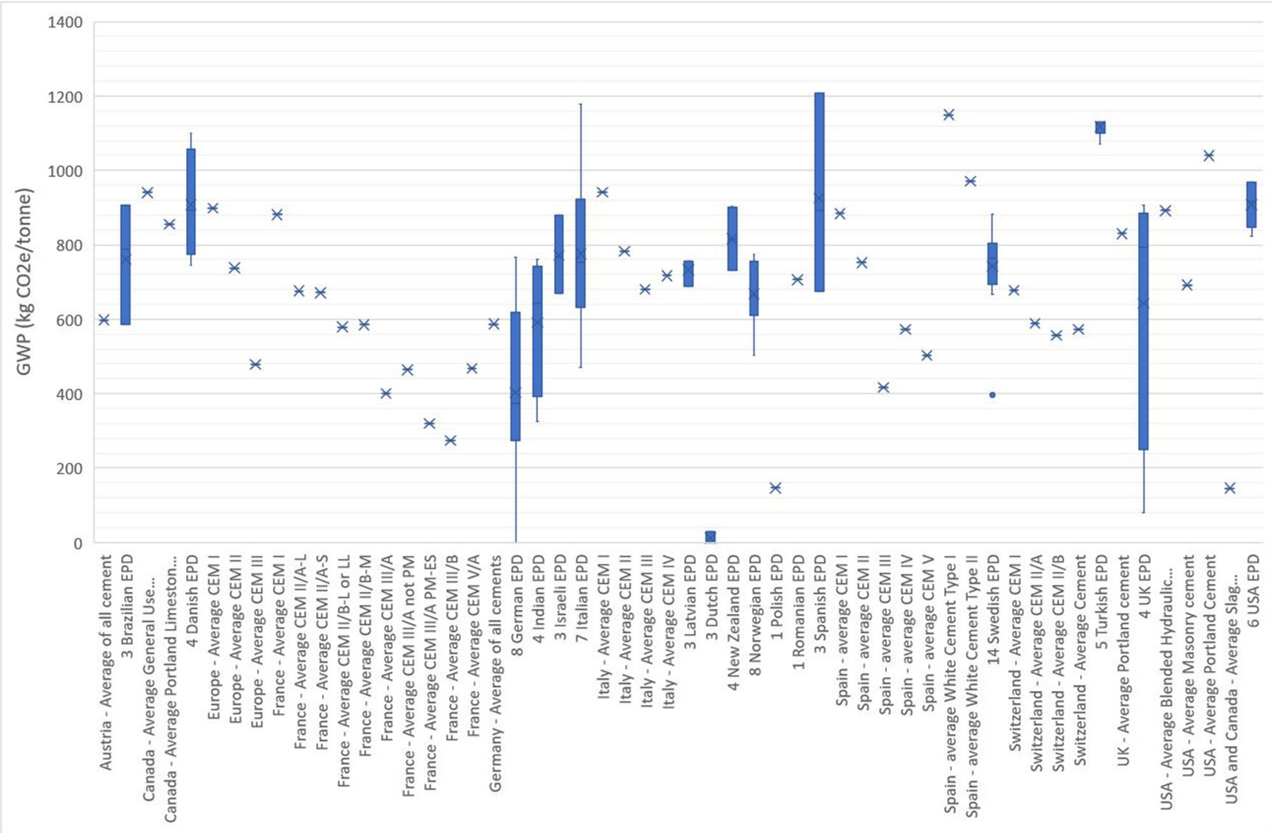

Figure 4: Global warming potential (GWP) for cementitious Environmental Product Declarations (EPD) by country of producer.

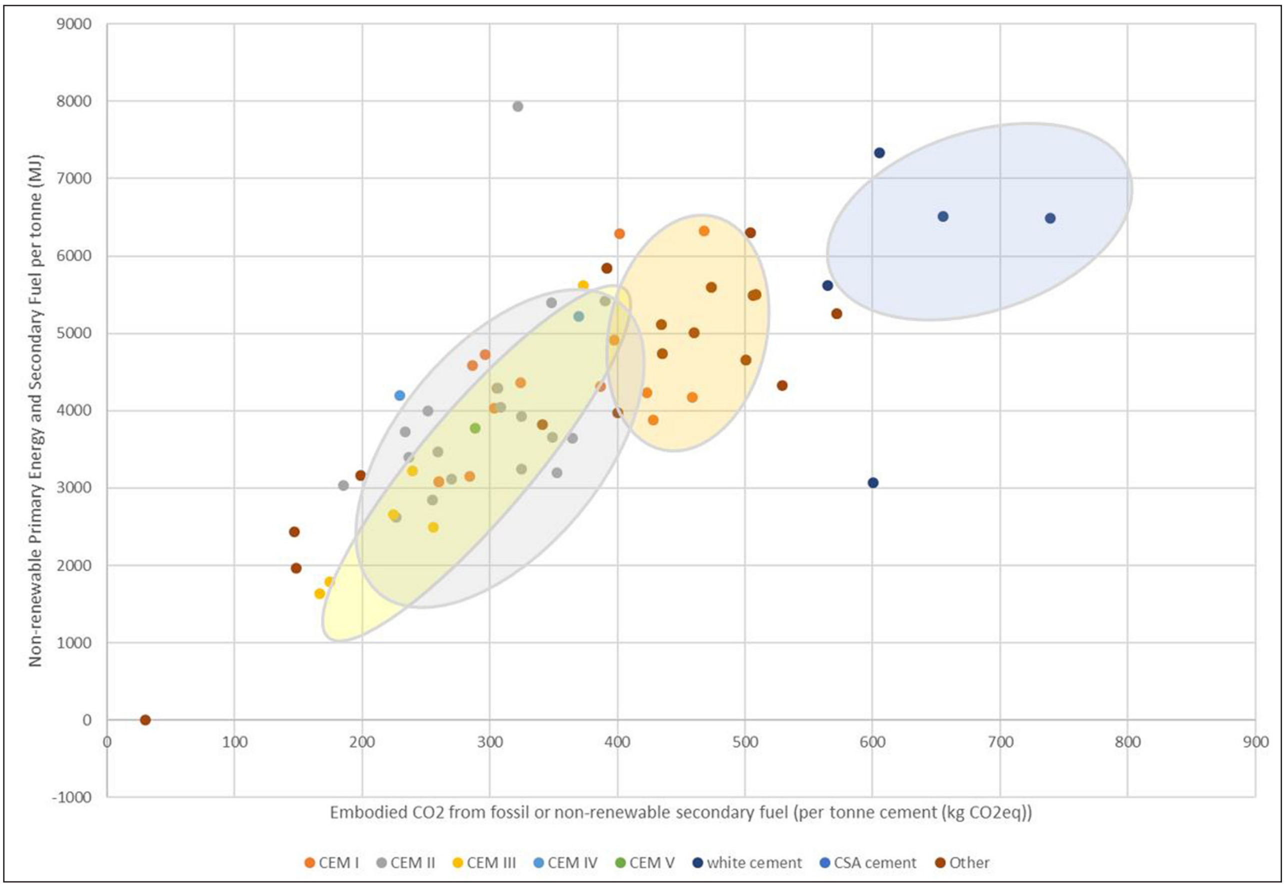

Figure 5: ECO_2e from fuel *versus* use of fossil fuel (abiotic depletion potential—fossil (ADP-F)) and secondary fuel non-renewable (SF-NR).

Figure 6 shows the impact of cement in cementitious EPD by year of EPD registration and clinker content. Scrivener, John, & Gartner (2017) show an increase in supplementary cementitious material (SCM) over time for World Business Council for Sustainable Development Cement Sustainability Initiative (WBCSD CSI) members, which would be matched by a reduction in the clinker content over time. However there is no clear decrease in clinker content for the EPD over time. For the EPD that provide this information, the average clinker content reported is 75%. **Figure 7** shows the broad correlation between increasing clinker content (for those EPD reporting it) and increasing GWP impact (A1–A3) per tonne. For CEM III (ground granulated blast furnace slag (GGBS) >40%) and white cement, GWP correlates closely with clinker content. However for CEM I, II and IV, the results are more widely spaced. For CEM I and II cements, the results are considered in more detail and described below.

3.2 Inconsistencies in the data

As part of the review, several inconsistencies or errors in data within the EPD as originally collected were identified. For example, several EPD were identified which appeared to have either a very high or a very low fossil and SF-NR energy use in relation to their reported GWP, and EPD programmes and/or manufacturers were informed and some errors were corrected and the EPD reissued by the EPD programmes. These errors included reporting primary energy—non-renewable total (PENRT) measured in kJ as MJ and GWP measured in grams as kg CO_2e, both resulting in a factor 1000 error. These types of errors could be avoided by using the charts shown in **Figures 3, 5** and **7**, for example, to identify whether the results are plausible.

Two technical aspects have some relevance for the embodied carbon of cement, and can be treated differently in some EPD: fossil CO_2e emissions from the combustion of waste in the cement kiln, and the allocation of impact to cementitious co-products.

3.2.1 Inconsistences in the combustion of waste in the cement kiln

The use of secondary fuels and waste to produce energy is common in cement kilns with over 80% of EPD reporting some use of secondary fuel. EPD reported the use of non-renewable secondary fuel as up to 68% of total energy use and renewable secondary fuel as up to 26%. The average use of secondary fuel overall is 20% (weighting each product equally). **Figures 9** and **10** (discussed below) show the reported use of renewable and non-renewable secondary fuels in the production of CEM I and II EPD. The distinction between a waste and a secondary fuel is defined in EN 15804, based on the Waste Framework Directive (European Parliament and Council 2008). Only the impacts from the use secondary fuels need to be considered in a cement EPD; the impacts from the use of waste are considered using the 'polluter pays'

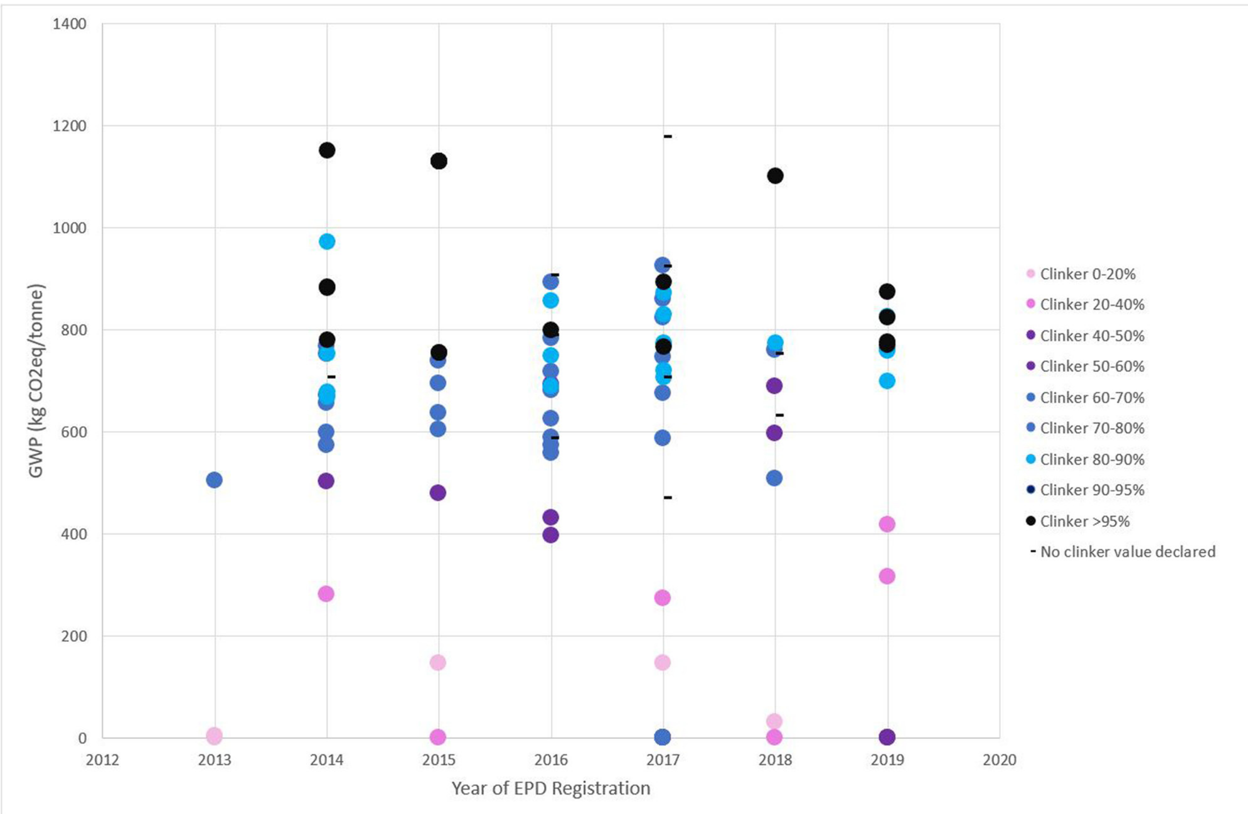

Figure 6: Global warming potential (GWP) from cementitious Environmental Product Declarations (EPD) by year and clinker content.

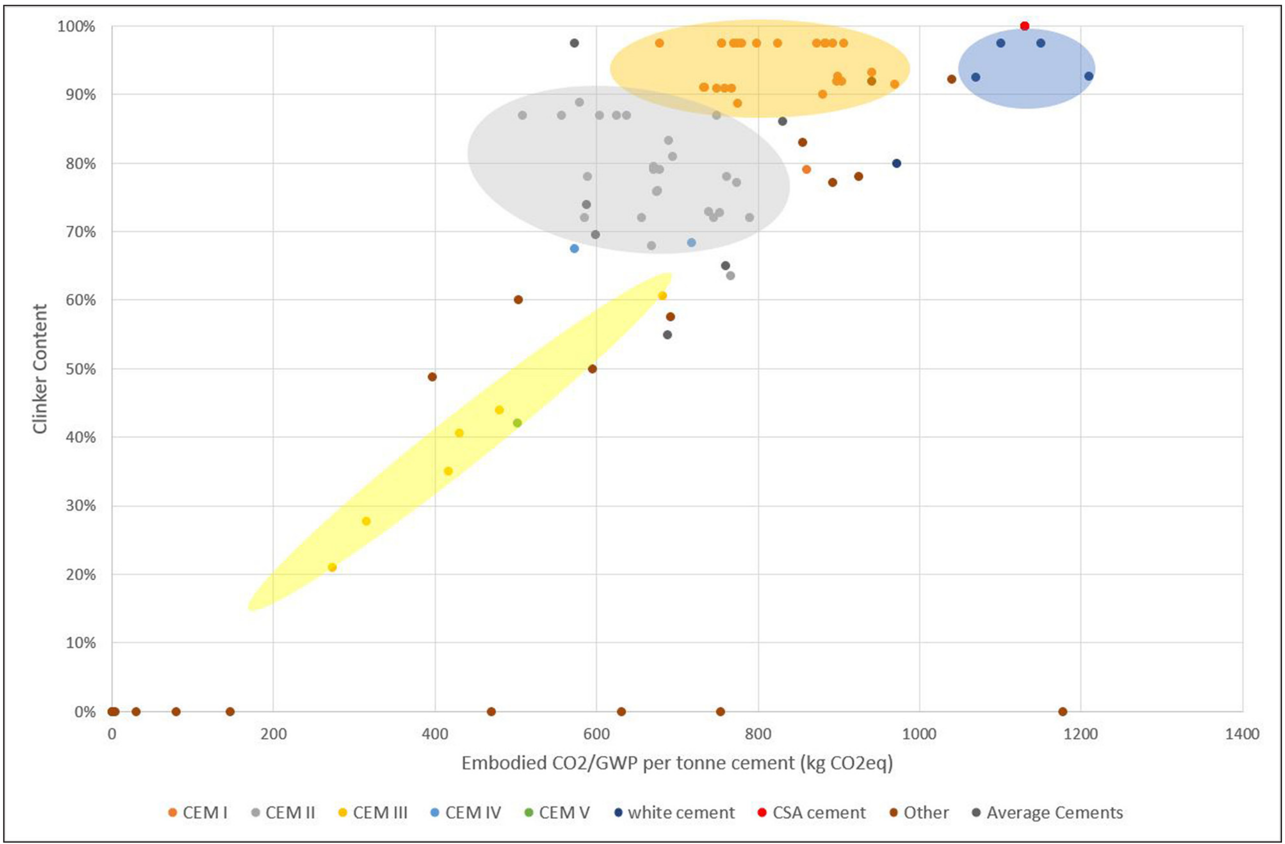

Figure 7: Global warming potential (GWP) and clinker content for all cementitious Environmental Product Declarations (EPD).

principle and are assigned to the industry producing the waste. The difficulty is that the same material may be a waste in one jurisdiction and a secondary fuel in another. EN 15804, CEN/TR 16970 (CEN 2016) and EN 16908 (CEN 2017) state that the use of all secondary fuels should be included in the system boundary and the impacts reported in the EPD. EN 16908 additionally states:

> As a conservative approach, if wastes are used for energy or material recovery and do not have the same waste status in all regions, for transparency reasons two figures may be specified in the communication of the LCA [life cycle assessment] results in module A1 to A3:
>
> – the environmental impacts caused by the emissions including processing, incineration and co-incineration of waste (gross figure); and
> – the environmental impacts caused excluding the incineration of waste (net figure) see Annex D.

It also states in Annex D (which is informative) that for use of wastes:

> Do not declare the impacts from waste processing, *e.g.* co-incineration of waste. Declare the use imported of energy from the waste within 'use of secondary fuel' as a more appropriate indicator does not currently exist. It is recommended to note this below [the indicator results] table.

However, reviewing the EPD, there is a wide variety of practice shown in **Table 2**, though for many EPD it is not at all clear how this aspect has been considered.

The Swiss average cement EPD considers all alternative fuels used are wastes and does not report the emissions from their use, but it does detail that they comprise 487 MJ from renewable sources and 1090 MJ from non-renewable sources per tonne cement as additional information. The French average CEM I EPD states that the use and CO_2e emissions from what are considered wastes in France are not included in the EPD. However although the use of secondary fuels is reported, the EPD does not include the CO_2e emissions from the use of secondary fuels in the reported GWP, but it provides the GWP including these emissions as additional information.

The amount of CO_2e associated with the use of waste in these EPD which explicitly report it ranges from 37 to 122 kg CO_2e/tonne cement (or from 4% to 16% of the total GWP with CO_2e from waste included), with an average of 77 kg CO_2e per tonne (or 7% of the total CO_2e including CO_2e from waste).

Table 2: Treatment of the use of waste and secondary fuels and the resulting CO_2e emissions in cementitious Environmental Product Declarations (EPD).

EPD	Treatment of waste incinerated in the kiln	Treatment of secondary fuel	Treatment of CO_2e from NR waste	Treatment of CO_2e from secondary fuel NR
Austrian average cement EPD 13 Cementa Sweden EPD 3 Sia Cemex Latvia EPD 3 Cembureau EPD	Not explained	Reported as use of a secondary fuel	Included in GWP, but provided as additional information	Assumed included in GWP
German Average Cement EPD Holcim Germany EPD	Not explained	Reported as use of a secondary fuel	Excluded from GWP, but provided as additional information	Assumed included in GWP
French Average CEM I EPD	Not reported	Reported as use of a secondary fuel	Excluded from GWP and not provided	Not included in GWP, but reported as additional information
Swiss Average Cement EPD	Considers all alternative fuels are wastes. Reports amount as additional information		Excluded from GWP and not provided	
Other cementitious EPD	Not explained			

Note: GWP, global warming potential; NR, non-renewable.

None of the other EPD studied provides any explicit information on the reporting of use or CO_2e emissions from waste so it is not clear how it has been considered.

3.2.2 Inconsistencies in the allocation of the impact to cementitious co-products

Cementitious products also include cement substitutes. Fly ash (also known as pulverised fuel ash (PFA) and GGBS are two of the main co-products used in cement production which are waste products from other industries (coal-fired power stations and steel production, respectively). EN 16908 states:

> According to EN 15804, allocation according to economic values shall be applied where the difference in the amount of revenue earned by the original producer[1] for each of the co-products is high (greater than 25%). This is the case for co-products used in cement and building limes. Contributions to the overall revenue of the order of 1% or less are regarded as very low. Where this is the case, impacts from the process may be neglected.

Both EN 16908 and CEN/TR 16970 state:

> … this cut off rule for neglecting allocation is intended to allow manufacturers to put all emissions onto the main product where it considers allocation too much effort for minor co-products. However, if a low value co-product is being used as an input into a production process, allocation rules are used to understand the impact connected to that product.

EN 16908 also states that for slag, fly ash and aluminium oxide-containing sources arising from aluminium and alumina production, the contribution of the co-product to the overall revenue of steel production, electricity production and aluminium/alumina production on average in Europe is very low (<1%).

Most cementitious EPD state that they use an economic allocation according to EN 15804. The text in EN 16908 would suggest that even when the economic value of the co-product is very low, then allocation rules should be used to understand the impact connected to that product. However many EPD, particularly those addressing the impact of individual cementitious co-products, in fact make no allocation. For example, the three Milieu Relevante Product Informatie (MRPI) EPD do not allocate any emissions from steel or electricity production to their co-products, and the ASTM EPD for slag cement (GGBS) considers 'Blast furnace slag (BFS) is a waste material of pig iron production and as such is categorised as a "recovered waste material"' and allocates no impacts from steel production. The Cembureau EPD states that economic allocation is applied according to EN 15804, but states:

> [the] contribution to the overall revenue of steel or electricity production is very low (<1%). Environmental impacts from the joint process on the coproduct are neglected in the cement LCA [life cycle assessment].

Generally, this would appear to be the way that the standard has been interpreted for most co-products within cement EPD, though most EPD only state that economic allocation according to EN 15804 has been used.

Van den Heede and De Belie (2012) explain that neglecting allocation when the economic value of fly ash or slag is low omits significant impacts—they calculated an impact of 196 kg CO_2/tonne for fly ash at 1% economic allocation and 130 kg CO_2/tonne for blast furnace slag at 2.3% economic allocation using values calculated by Chen *et al.* (2010). It would be useful if cement EPD could be clearer about the detailed approach to allocation used, rather than implying economic allocation has been used when in fact no allocation has been used.

3.3 Choice of database for cement EPD

Several different databases were used to generate the cement EPD studied, including various versions of ecoinvent (ecoinvent 2020), GaBi (sphera 2020), United States Life Cycle Inventory (USLCI) (National Renewable Energy Laboratory (NREL) 2012) and Athena (Athena Sustainable Materials Institute 2020), together with some which have EPD for key input materials. Where the source database has been specified, this information, together with the cement class, was used to analyse the embodied carbon (**Figure 8**). This shows that within each class (CEM I, II and II/A) the EPD using various versions of GaBi (shown in orange) have a range of embodied carbon impacts within the range of the EPD which use various versions of ecoinvent (shown in blue). The effect of database choice does not therefore seem to be significant for cement EPD.

4. Cement classes

4.1 CEM I

CEM I cements are ordinary Portland cements (OPC) with no more than 5% additional material. OPC itself is normally 0–5% gypsum and 95–100% clinker. **Figure 9** shows the impact of the 24 CEM I EPD, which also provides the clinker content and a breakdown of the primary and secondary energy used. EPD report PENRT, which is the total primary energy from fossil and nuclear sources. ADP-F reports the total primary energy from fossil sources. This allows the PE-NUC to be calculated: the amount of primary energy from nuclear sources, which is assumed to have very low carbon emissions. PERT is the primary energy from renewable sources: this will only be associated with carbon emissions from the fossil processing and transport of renewable fuel and energy. Biogenic carbon emissions from the use of biomass fuels will be balanced by the uptake in the growing phase. EN 15804 reports the use of both renewable and non-renewable secondary fuels. Of these, only non-renewable secondary fuels will be associated with carbon emissions from combustion. The EPD may also report the gross emissions, including the use of waste from non-renewable sources disposed of within the kilns.

Figure 9 also shows the impacts of various CEM I cements in order of their embodied carbon. The IPCC *et al.* (1996) states the amount of CO_2 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 CO_2 (44 g) = 0.507 kg CO_2 per kg clinker. The percentage

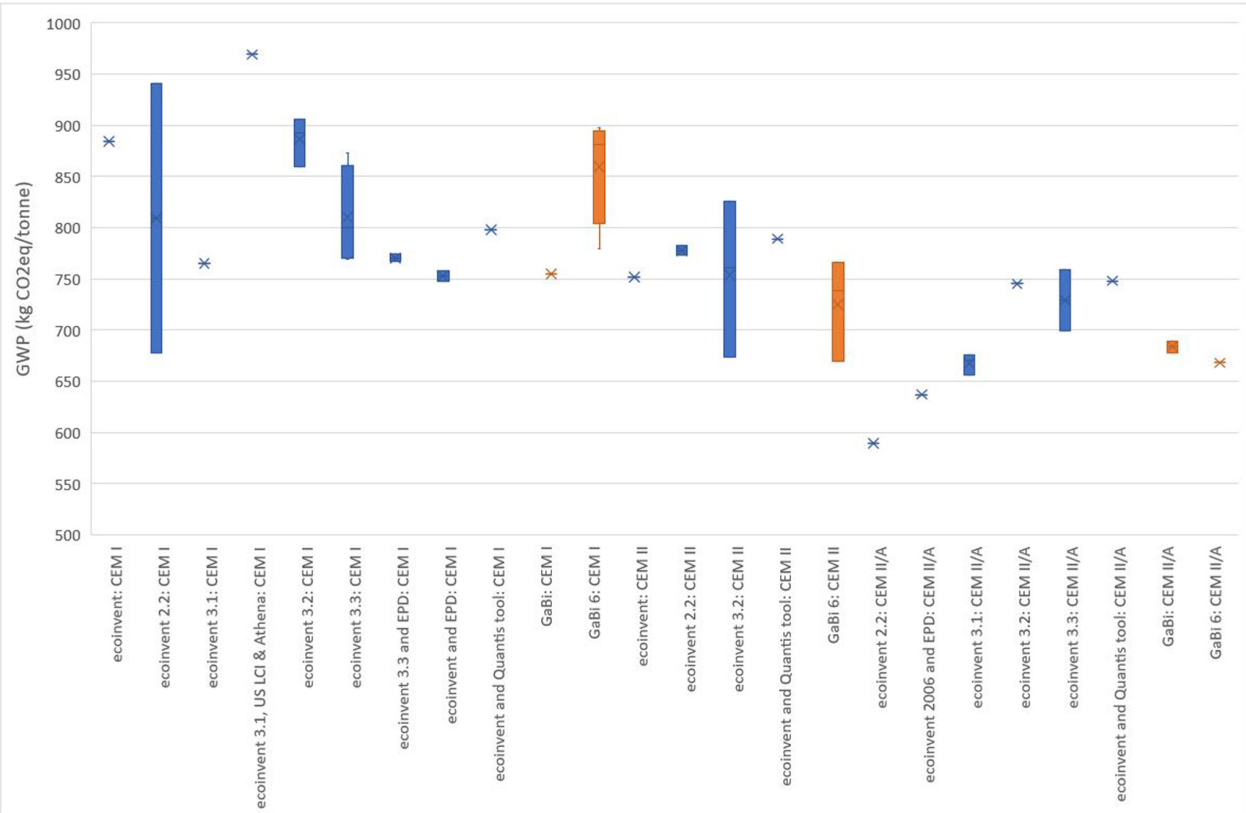

Figure 8: Embodied carbon for CEM I, II and II/A cements by source database.

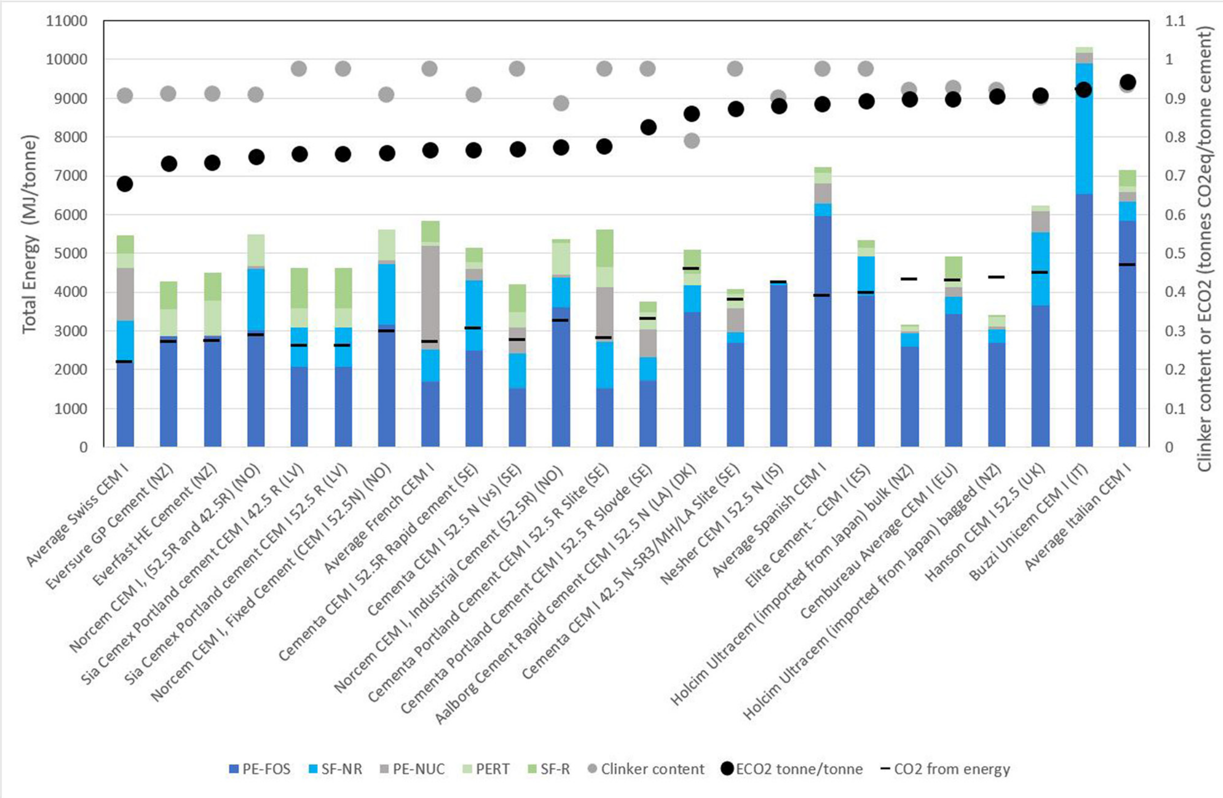

Figure 9: CEM I Environmental Product Declaration (EPD): Energy consumption, ECO_2e and clinker content.

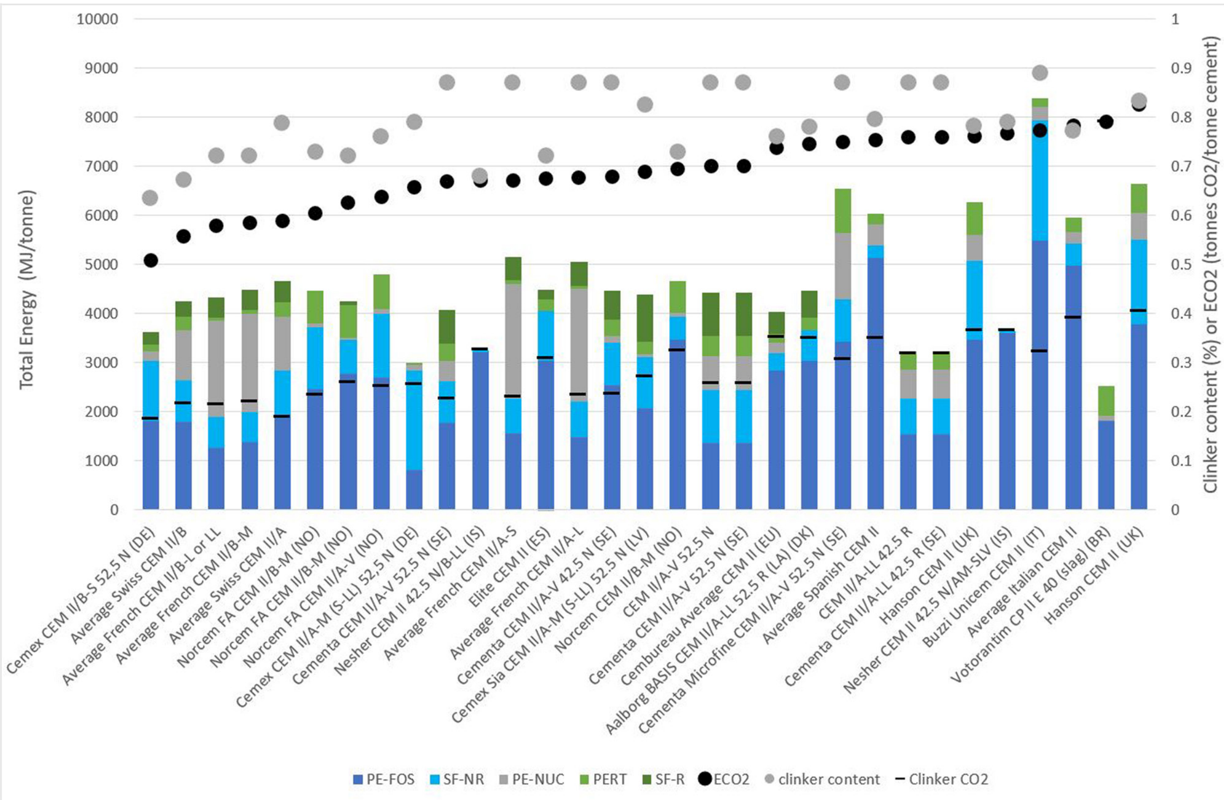

Figure 10: CEM II Environmental Product Declaration (EPD): Energy, ECO_2e and clinker content.

of clinker for each cement is shown by the grey dot; the total CO_2e emission by the black dot; and the black line shows the expected CO_2e emission from use of energy (having deducted the CO_2 from calcination from the total). This results in emission factors from the use of fossil fuel and non-renewable secondary fuel of between 62 and 147 g CO_2/MJ primary energy. It should be noted that both the Swiss and French CEM I's do not include any CO_2e emissions from the use of non-renewable secondary fuel in the reported GWP result.

Across the range of CEM I EPD, the embodied carbon ranges from 732 to 941 kg CO_2e/tonne cement. There appears to be no clear link between strength of cement (42.5 or 52.5 N), energy use, clinker content and embodied carbon.

It might be expected that only manufacturers whose production is better than average will produce EPD, and Cembureau (the European trade association for cement manufacturers) produced a representative EPD for average European CEM I in 2015 based on data from national cement bodies—this has a CO_2e emission of 898 kg CO_2e/tonne, which only four EPD exceed. One is a bagged Japanese CEM I shipped to New Zealand; a CEM I from Hanson in the UK; an Italian manufacture-specific CEM I cement that appears to use very much more energy than any of the other CEM I cements; and the average Italian CEM I cement. The Swiss average cement has an impact of 678 kg CO_2e/tonne, but this excludes any CO_2e emitted by the 1090 MJ non-renewable secondary fuel which it uses per tonne. The average French CEM I has an impact of 764 kg CO_2e, again excluding use of non-renewable secondary fuel; the Spanish average CEM I EPD has an impact of 884 kg CO_2e/tonne.

4.2 CEM II

CEM II cements are made with a minimum of 65% OPC with other materials such as fly ash, ground limestone or GGBS.

Figure 10 (like **Figure 9**) shows that CEM II have lower embodied carbon than CEM I (508–789 kg CO_2e/tonne cement), which would be expected because of their lower clinker content. As before, the French and Swiss CEM II EPD do not include CO_2e emissions from the use of non-renewable secondary fuel. As before, there is no particular correlation between clinker content, energy use or strength and embodied carbon across the range of CEM II EPD.

4.3 CEM III

CEM III cements are made with OPC and between 40% and 90% GGBS. They show a very clear correlation between clinker content and CO_2e emissions, and also between fuel and CO_2e emissions (**Figures 5** and **7**).

4.4 CEM IV and V

CEM IV are pozzolanic cements, comprising Portland cement and a higher proportion of pozzolana than in a CEM II cement. Pozzolana can be natural, such as volcanic ash, or artificial, such as fly ash. CEM V are composite cements comprising Portland cement and combinations of blast furnace slag and pozzolana. There are only small numbers of EPD for these cements, so it is difficult to draw conclusions, although the range of impact for both CEM IV and V EPD seems close to CEM II than CEM III cements.

5. Admixtures and aggregates

5.1 Admixtures

EPD for admixtures are provided per kg of admixture, and this may not reflect differences in the functional performance of each admixture, *e.g.* the shrinkage-reducing admixtures includes both liquid- and powder-based products. There are six EPD each for the European and German trade associations in the Institut Bau und Umwelt (IBU) EPD programme, one manufacturer-specific EPD for hardening admixtures in the IBU programme and one manufacturer-specific EPD for three shrinkage-reducing admixture products in the Italian EPD programme. The German and European trade association results are very similar, but the manufacturer-specific data introduce a much greater range of values (**Figure 11**).

5.2 Normal aggregates

Normal aggregates are from crushed stone, recycled aggregate or sand and gravel. A total of 20 EPD covering 93 normal aggregate products provide data per tonne for the average output of a quarry or quarries or for a specific aggregate, often based on the degree of processing. **Figure 12** shows the GWP for different types of aggregate. Where an EPD has been provided for, for example, 'crushed rock—mobile plant', it has been assigned to both the group 'crushed rock' and the group 'crushed rock—mobile plant'. Although there are differences between the aggregates, almost all have a GWP between 2 and 7 kg CO_2e/tonne. One French EPD covering 'end-of-life treatment' has been included which provides the impact of treating 1 tonne of demolition waste with a view to preparing recycled aggregate—in effect this reports the impacts of module C3 in the previous life of the building after demolition in order to reach the end-of-waste state so that the material can be used as fill or as recycled aggregate with additional processing.

Where aggregate EPD cover a specific size or range of sizes of aggregate, then this is also considered in **Figure 13**, which shows that there is some evidence that the impact of aggregate decreases the larger the maximum size of the aggregate, presumably because more energy is used to crush aggregate to smaller sizes.

5.3 Specialist aggregates

Seven EPD cover nine specialist aggregates: five for lightweight aggregate made from either clay (two), aerated autoclaved concrete or glass (two) assessed on a per m^3 basis, and four aggregates made from incinerator bottom ash assessed per tonne. As described in **Table 3**, all these specialist aggregates have considerably more impact than normal aggregates on a per tonne and per m^3 basis.

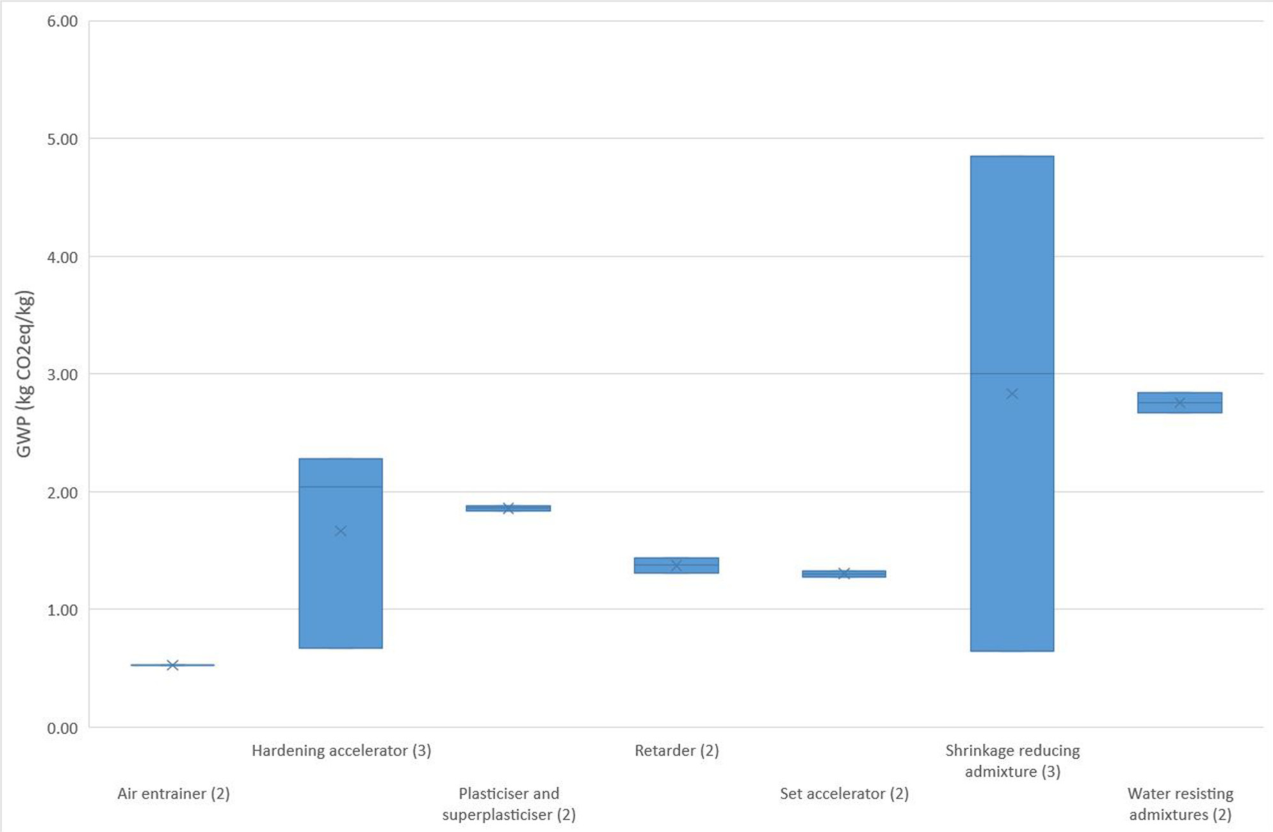

Figure 11: ECO_2 of the admixtures.

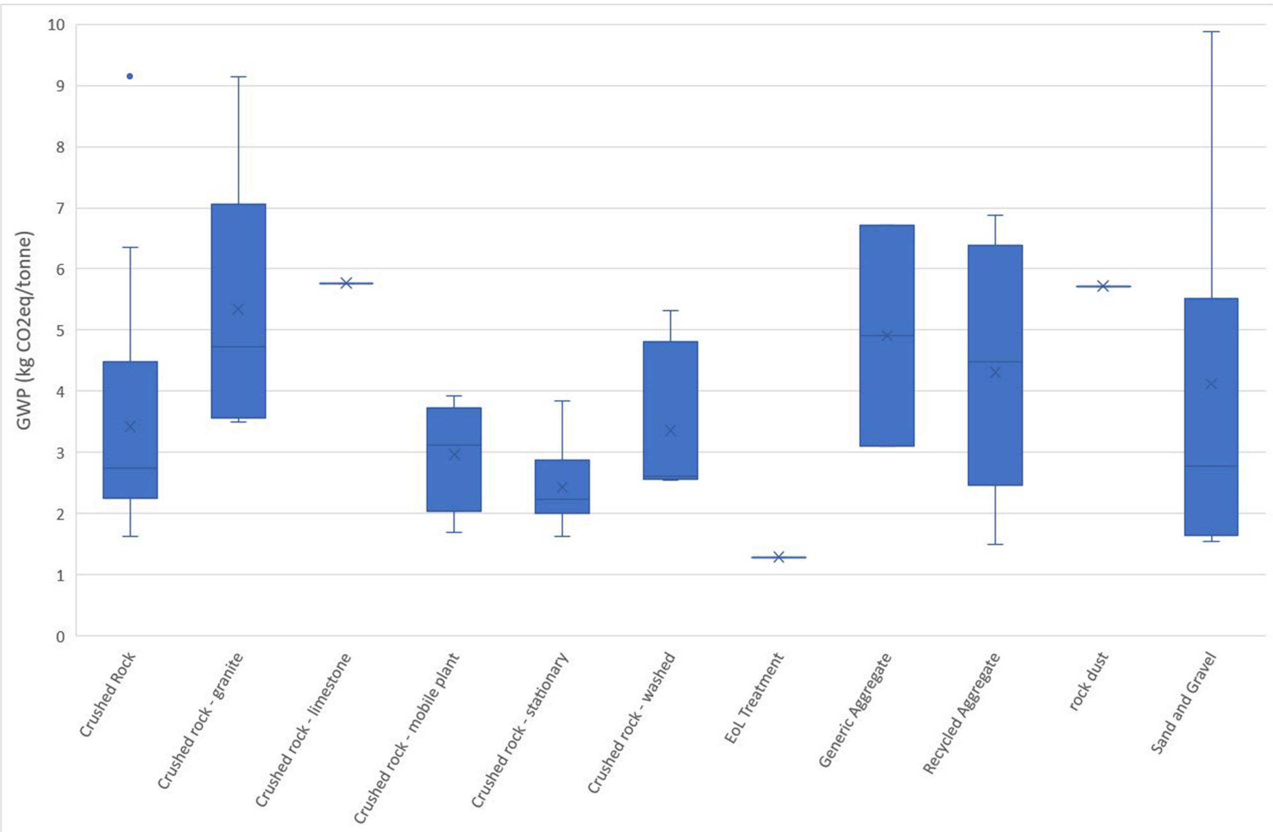

Figure 12: Global warming potential (GWP) of normal aggregate by type.

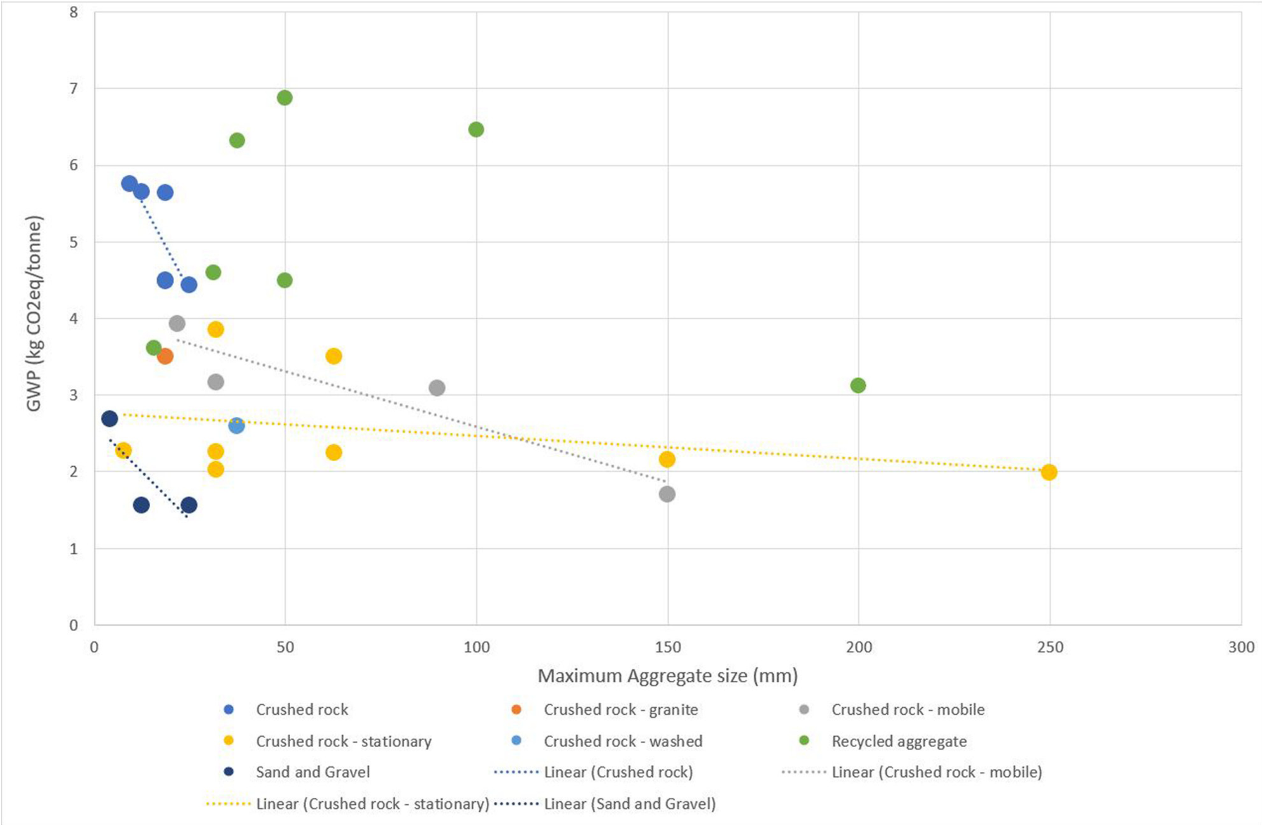

Figure 13: Global warming potential (GWP) by maximum size of aggregate and type.

Table 3: Impact of specialist aggregates.

	GWP A1–A3 per m^3	GWP A1–A3 per tonne	Countries
Lightweight aggregate from clay	114–150 kg CO_2e	209–375 kg CO_2e	Finland and Germany
Lightweight aggregate from AAC	216 kg CO_2e	600 kg CO_2e	Germany
Lightweight aggregate from glass	7.5–20 kg CO_2e	43–117 kg CO_2e	Sweden and Germany
Sand matrix from incinerator bottom ash	n.a.	42–85 kg CO_2e	Italy

Note: AAC = aerated autoclaved concrete; GWP = global warming potential.

6. Ready-mix concrete

6.1 All ready-mix concrete

For ready-mix concrete, some EPD only cover a single product with one mix design and strength; others cover several products with different mix designs and/or strengths. The review found 165 separate EPD from 16 countries covering over 2000 ready-mix products. A total of 95 EPD used EN 15804 covering 237 ready-mix products, and 55 EPD used ISO 14025 and the North American Carbon Leadership Forum (CLF) PCR, which aligns with ISO 21930:2007, covering over 1800 ready-mix products. The CLF PCR closely follows EN 15804+A1 so there should be no difference in outcome for GWP/embodied carbon results based on the use of standard.

All the EPD provided data per m^3, and most of the EPD were 'cradle to gate' EPD. For the purposes of this paper, each individual product has been considered as a separate EPD datapoint.

Table 4 shows the number of products from EN 15804+A1 and ISO 14025 EPD. For EN 15804+A1, although they come from one manufacturer-specific EPD, Australia has the largest number of products covered using this standard. Norway, with 30 EPD, has 31 products covered. In North America, ISO 14025 and CLF PCR have been used, although EN 15804+A1 is starting to be used for concrete, with the United States producing the most EPD (67) and covering the most individual ready-mix products (over 1500).

Figure 14 shows how the results are distributed for the different products for each country. France, the UK, Norway and Germany all have a relatively low impact. The French and German EPD are all generic industry average. Only one UK generic EPD has been produced; this is shown as the coloured region within the general UK outline. The highest impacts are seen for EPD from Saudi Arabia, Mexico, Panama and the United States. These high impacts are all from manufacturer-specific EPD. The grey and pink shaded regions show the US and Canadian generic industry average mixes.

Table 4: Products covered by Environmental Product Declarations (EPD) by country, product category rules (PCR) standard and year.

Country and PCR standard	2013	2014	2015	2016	2017	2018	2019	Total
Australia EN 15804+A1							106	**106**
Brazil EN 15804+A1				1				**1**
Canada ISO 14025 & CLF PCR				125				**125**
Chile EN 15804+A1							1	**1**
France EN 15804+A1						3		**3**
Germany EN 15804+A1						6		**6**
India EN 15804+A1							1	**1**
Italy EN 15804+A1					5	1		**6**
Mexico ISO 14025 & CLF PCR						101		**101**
New Zealand EN 15804+A1		8						**8**
Norway EN 15804+A1	2	2	6	4	13	4		**31**
Romania EN 15804+A1		1			18			**19**
Saudi Arabia EN 15804+A1						1	5	**6**
UAE EN 15804+A1							13	**13**
UAE ISO 14025 & CLF PCR					22	21		**43**
UK EN 15804+A1				5	1	10		**16**
USA EN 15804+A1							20	**20**
USA ISO 14025 & CLF PCR	11	354	69	48	377	412	271	**1542**
Total	**13**	**365**	**75**	**182**	**436**	**559**	**415**	**2045**

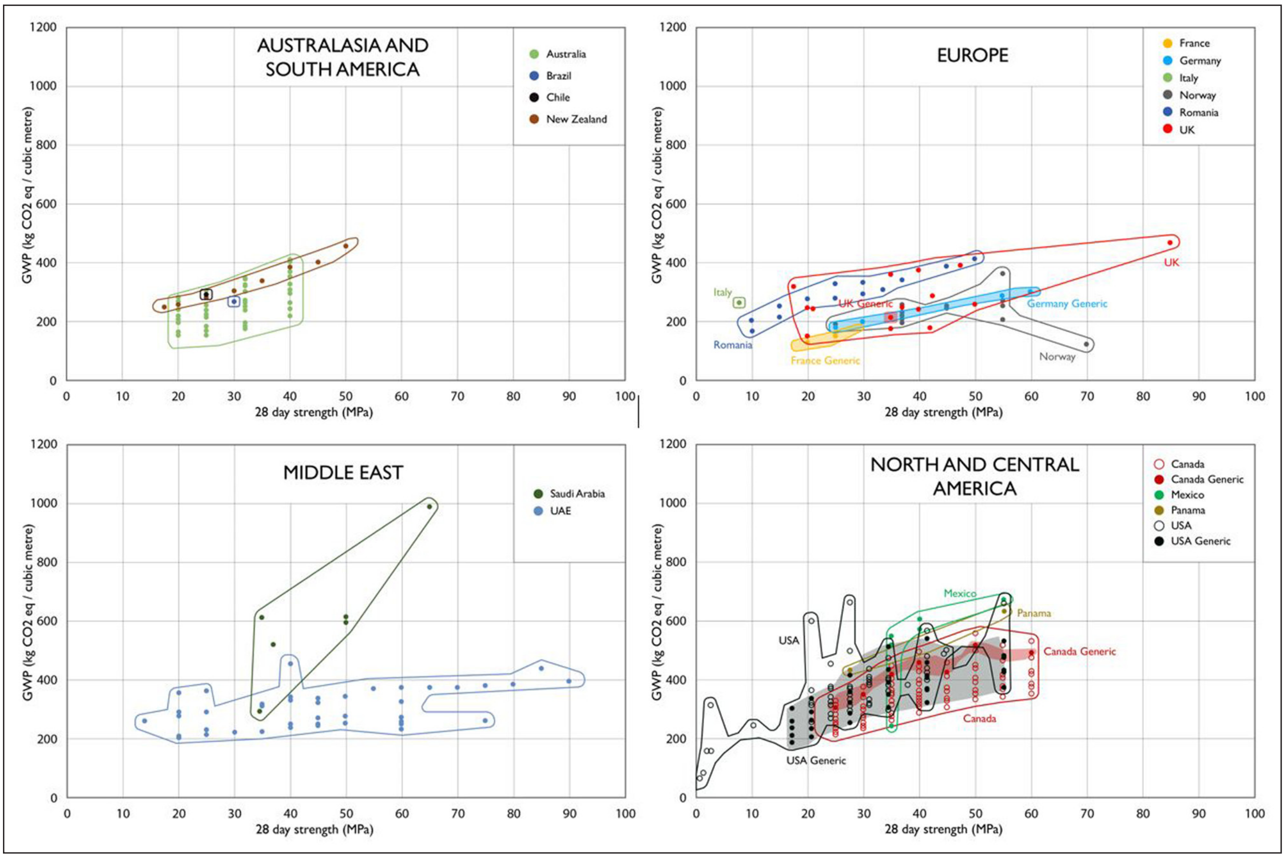

Figure 14: ECO_2e by compressive strength for each country.

Only a few countries (the UK, United Arab Emirates (UAE) and Norway) have produced EPD for concretes with strengths >60 MPa. Conversely, only the United States, Mexico, Italy and Romania have produced EDPs for concretes with strengths of ≤10 MPa.

For most countries, there is a clear trend for increased carbon emissions with increased compressive strength, though some products counter this trend, *e.g.* some high-strength Norwegian[2] and UAE concretes have lower impacts than lower strength concretes from those countries.

The EPD for ready-mix concrete provide a variety of information, mostly for 1 m^3 of concrete, though some of the earlier EPD in North America provide results for 1 cubic yard of concrete (these results have been converted to 1 m^3). Almost all provide a measure of compressive strength, normally the 28-day strength. Some provide the type of cement used, binder intensity and/or percentage of additional cementitious material (ACM) such as fly ash or slag.

Figure 15 shows no particular trend over time for cement impact, but it is clear that there was a strong interest in producing EPD for concrete products in 2016, which coincided with the publication of both the American and Canadian Ready-mix Concrete Association's generic EPD.

National EPD at a national level have been produced in several countries as follows:

- In Canada, up to 18 defined mixes, plus one industry average mix, were each assessed for eight different compressive strengths using Canadian industry-average data, providing results for 125 mixes in a single EPD.
- In the United States, eight defined mix designs were each assessed for six different compressive strengths using US industry-average data, providing results for 48 mixes in a single EPD.
- In Germany, the average mix for five different compressive strengths using German industry-average data was reported in five separate EPD.
- In France, three compressive strengths were modelled using an average mix and French industry-average data, each reported in a separate EPD.
- For the UK, one defined mix design was assessed for one strength using UK industry-average data.
- Dubai Municipality has provided an EPD covering eight productions from eight producers for several defined mixes for 11 different compressive strengths, providing results for 13 mixes in a single EPD; however, this does not cover all producers.

6.2 C30 concrete

A more detailed analysis of the concretes with a 28-day compressive strength of between 28 and 34 MPa was undertaken in order to understand any factors that can be seen to influence impact. This is shown by the six charts in **Figure 16**. However no clear conclusions can be drawn. Possibly this is because there are not enough EPD, or the embodied carbon

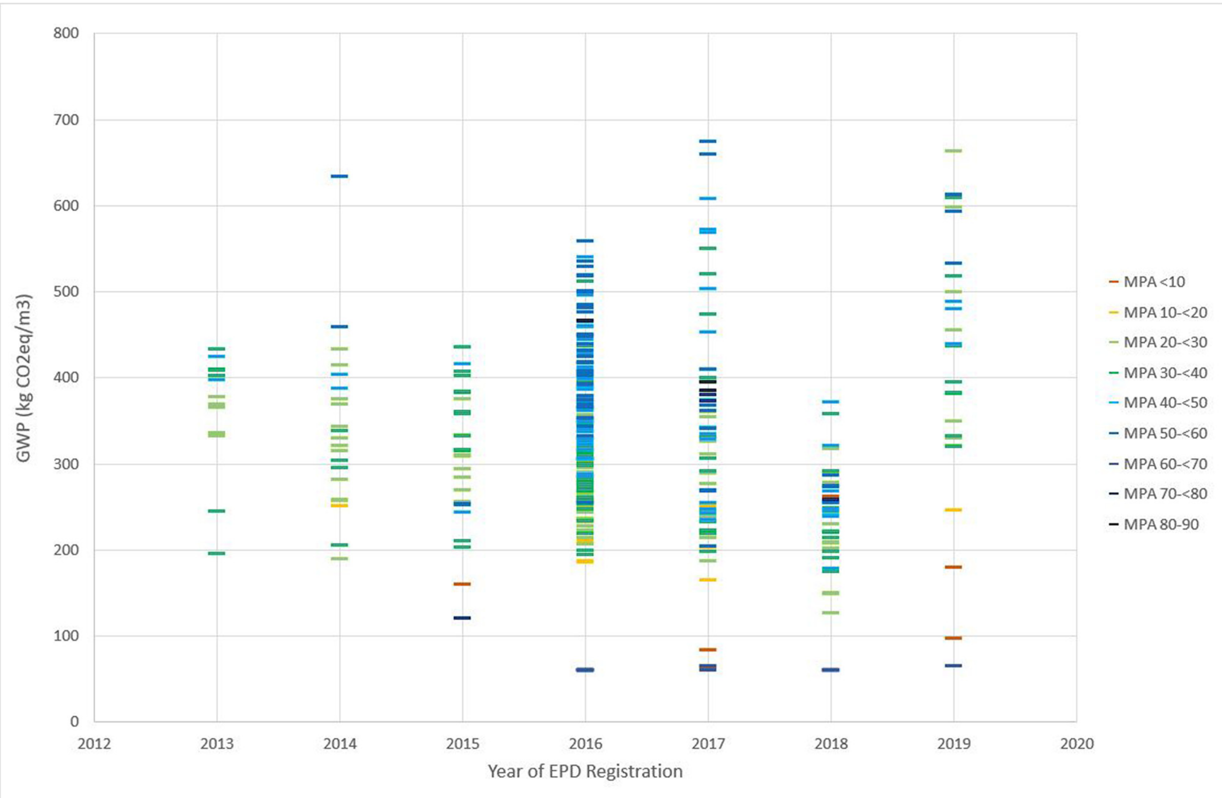

Figure 15: Global warming potential (GWP) impact of ready-mix concretes by 28-day compressive strength and year of registration.

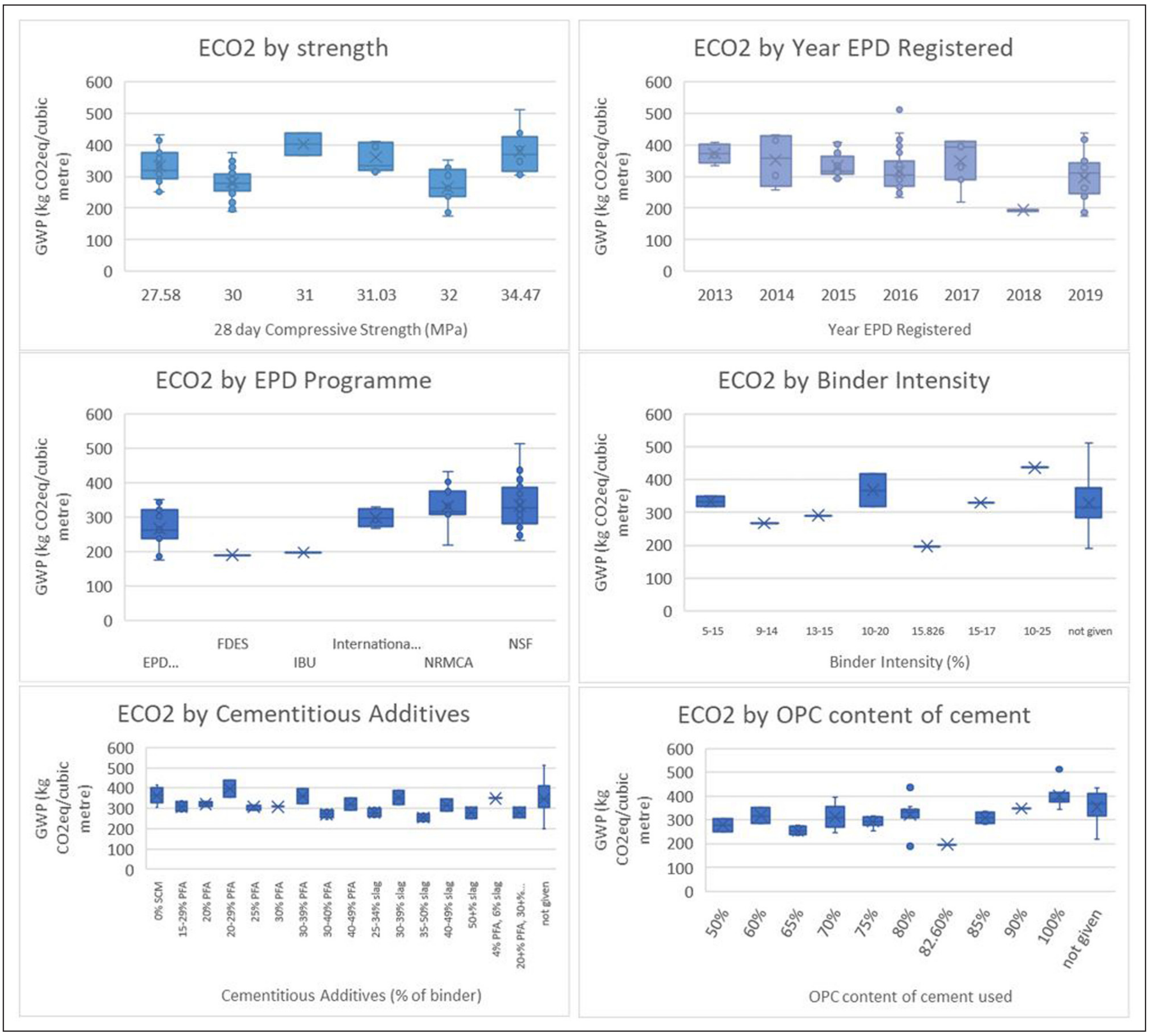

Figure 16: Impacts of concretes with a compressive strength around 30 MPa.

varies in relation to a combination of these factors, *e.g.* both binder content and OPC content together influence the impact of the concrete. Unfortunately, very few EPD reported both binder content and OPC content, so we were unable to consider this possibility.

Within individual EPD that cover a range of different products, or a group of EPD from a single manufacturer, it is possible to see these types of trends. For example, Holcim Australia ready-mix concrete varies with compressive strength and use of G—general blend, F—fly ash blend, B—blast furnace slag blend and T—triple blend (fly ash and blast furnace slag).

6.3 Other life-cycle stages

Very few concrete EPD report life-cycle stages beyond A1–A3. Three manufacturer-specific EPD from the UK provide cradle-to-grave data, as does the UK trade association IBU EPD, the German trade association IBU EPD, the French trade association EPD from inies and the EPD from Australian manufacturer Holcim. EPD from EPD Norge provide A4 (transport to site) data. Owing to the limited data, we have not reviewed these life-cycle stages.

6.4 Verified EPD tools

Many manufacturers can now provide EPD for the range of concretes they produce using EPD tools, which were verified by an EPD programme. For example, there are national tools such as the French BETie EPD tool (Potier 2012), industry association tools such as the CSI EPD Tool developed for WBCSD CSI (Quantis 2016), or that developed for the Norwegian Ready Mixed Concrete Association, FABEKO. There is also an EPD tool developed by BASF for concrete suppliers to assess concretes using its admixtures (BASF 2014) and other manufacturer-specific EPD tools such as that for Tarmac (2016). Although these tools have been used to produce several of the verified and registered EPD included in this systematic review, also many other EPD that have been provided directly for a specific project have not been registered or included in this systematic review.

7. Conclusions

It is clear that the carbon impacts of cement and concrete are very significant. There are now considerable numbers of EPD available for cements, aggregates, admixtures and ready-mix concretes; however, up until the present it has been difficult to compare impacts or to understand the range available.

This paper provides a detailed analysis of the impacts associated with existing EPD, showing the carbon impacts, and revealing that, in many cases, even within a given region and performance specification, there is a considerable range of embodied CO_2. In presenting these data as a series of detailed graphs and charts, the paper offers important information for three stakeholder groups. For building designers, the graphs presented will enable the choice of an appropriate and realistic coefficient for early-stage calculations before the design has been fully specified and at a point where the information can have an impact on major decisions on structural materials. At later design stages it will allow designers and specifiers to compare different products and choose those with lower impacts for the same performance requirements. The plausibility of results for individual EPD produced by manufacturers will also be able to be checked against other results. For manufacturers, the graphs will enable them to compare their products with others and encourage competition to strive to minimise their own impacts.

Since the coefficients presented include multiple cements, aggregates and admixtures that could be used in contexts other than buildings, the information will be similarly useful to stakeholders involved in infrastructure projects.

Finally the paper has highlighted the continued differences in reporting, and the lack of sufficient transparency in many of the EPD reviewed. Therefore for those involved in product category rule (PCR) and EPD programmes, two conclusions and requests are offered: first, more detailed rules should be developed in order to ensure consistency; and second, in the meantime, all EPD produced should offer full transparency about the details.

The carbon impacts of cement and concrete remain complex and highly varied, as this paper demonstrates. However with climate change now starting to affect multiple regions of the world, designers, manufacturers and life cycle assessment (LCA) consultants must reduce these impacts. The analyses presented here will help them to do this.

Notes

[1] For example, in the case of slag, the 'difference in revenue from the co-products' is a comparison of the revenue earned by the steel producer from the sale of slag with that earned from the sale of the main product, steel.

[2] Norwegian concrete with a 28-day compressive strength of 70 MPa is described in the EPD as strength class B45 and resistance class M40.

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Competing interests

The authors have no competing interests to declare.

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