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ORIGINAL ARTICLE

Factors affecting the carbon footprint of reinforced concrete structures

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Abstract With the need to decarbonise global cement and concrete production, much emphasis has been placed on the use of supplementary cementitious materials, such as ground granulated blast furnace slag. However, while such blends can significantly reduce the carbon footprint of cements, other options are also available to decarbonise concrete structures. For example, changing the dimensions of structural elements or concrete strengths can affect both the volume of structural concrete and its carbon footprint. This study has examined the effects of changing concrete strength, span and binder type on the carbon footprint of a hypothetical two-storey concrete structure. Furthermore, durability requirements can impose additional demands, such as higher-grade concrete or greater cover depths, affecting the structure's carbon footprint. Thus, these structures were designed to resist a non-aggressive (XC1) and a mildly aggressive (XS1) environment. Higher-strength concrete, despite allowing dematerialisation, increased the carbon footprint of the structures, as did longer beam spans. The use of a 50% GGBS CEM III/A-S cement offered significant carbon reduction potential, with greater carbon reduction in a mildly aggressive environment. GGBS is a limited resource, so while it can always reduce concrete's carbon footprint, its use should be focused where it can also offer durability benefits.

Keywords Reinforced concrete · Carbon footprint · GGBS · Durability · Sustainability · Design

1 Introduction

Global cement production is approximately 4 billion tonnes per annum (USGS) [1] and is predicted to reach 8.2 billion tonnes globally by 2030, contributing about 8% of global CO_2 emissions [2]. Cement is almost exclusively used in the manufacture of concrete, making up between 10 and 25% by mass of the finished product. Growing awareness of climate change is driving efforts to decarbonise both cement and concrete production, and a number of decarbonisation roadmaps have now been published [3].

Cement consists of clinker—the raw output from cement plants—combined with various additives such as gypsum, limestone powder or supplementary cementitious materials (SCMs). With clinker accounting for approximately 90% of concrete's carbon footprint [4] reducing concrete's clinker content is paramount. Many SCMs such as ground granulated blast furnace slag (GGBS) from iron production, pulverized fuel ash (PFA) from electricity generation and silica fume (SF) from ferrosilicon production, are often industrial by-products.

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By convention, they have lower carbon dioxide emission factors, as the emissions associated with their production are almost entirely assigned to the primary product i.e. iron, electricity or ferrosilicon. For example, the production of 1 tonne of Portland cement clinker releases about 0.9 tonnes of carbon dioxide, while the emissions associated with GGBS production are much lower, ranging from about 0.05 to 0.14 [5].

Rahla et al. [6] examined how various SCMs can reduce the environmental impact of concrete. Comparing different replacement levels of GGBS, PFA and SF, they showed how GGBS (ideally at 40–50% replacement) showed the greatest environmental benefit across multiple indicators including global warming potential (GWP, i.e. equivalent CO_2 emissions). Many other studies have demonstrated the environmental benefits of GGBS [7–10], mostly focusing on GWP. Furthermore, GGBS facilitates high clinker replacement, and so substituting up to 80% of cement with GGBS can cut concrete's CO_2 emissions by 70% [7, 11].

Furthermore, GGBS can significantly enhance the durability of concrete and prolong its lifespan [6]. For example, 67% cement replacement with GGBS led to a five-fold improvement in chloride resistance [12]. This is due to the refined pore structure of slag cements, plus increased chloride binding either adsorbed onto C–S–H or bound within aluminate phases such as Friedel's salt [13]. Such improvements have also been seen upon exposure of slag cements to combined sulphate-chloride solutions [14]. However, GGBS does not always have the same effect on carbonation resistance. While GGBS can lead to pore refinement, there is also consumption of portlandite, which can reduce buffering against carbonation. Gruyaert et al. [15] showed that pore refinement was gradual and the benefits were not realised until samples had been cured for many months. Their 50% GGBS blends carbonated extensively when they had been cured for only 1 month prior to exposure, while carbonation was more gradual after curing for 3 or 6 months, and almost non-existent when cured for 18 months.

However, only about 300–400 million tonnes of suitable GGBS is produced per year [16], i.e. about 10–12% of global clinker production. Demand for GGBS, driven by the environmental and technical benefits to concrete it confers, is likely lead to shortages and price rises [17]. Furthermore, increased steel recycling is further limiting supply of GGBS, and the development of technologies for direct reduction of iron will further restrict supply [18, 19]. Therefore, means of reducing concrete's carbon footprint that can be used in parallel to clinker replacement are needed.

In general terms, for a given "family" of concrete with similar aggregates, workability, cement type etc., the clinker content, and hence carbon footprint, of concrete increases with strength [4]. Habert and Roussel [20] explained this by considering the Feret relationship, whereby strength is proportional to the square root of the cement content. Thus, with cement being the predominant contributor to concrete's carbon footprint, concrete's carbon footprint is proportional to the square root of the compressive strength. This prompted Purnell and Black to consider carbon footprint per unit strength, as did Damineli et al. [21] who elegantly referred to this as the carbon dioxide intensity index (c_i). In both studies there was a decrease in c_i with increasing strength, with an optimum at approximately 60 MPa.

Nonetheless, it is possible to maintain concrete strength while adjusting cement content by a factor of three [21, 22], leading to a reduction in nominal greenhouse gas (GHG) emissions [23]. Workability, binder type, the use of chemical admixtures, plus aggregate size and shape all influence the carbon footprint of concrete; choosing the right concrete family often has more influence than choosing the right strength.

Purnell [24] investigated this by comparing the carbon footprint of beams and columns as a function of concrete strength, stressing the importance of comparing materials based on a functional unit of structural performance e.g. per moment capacity per unit length for beams. Purnell [25] also reported that varying grades of steel rebar have a minimal impact on the carbon footprint of reinforced concrete. This contrasts with Gan et al. [26], who suggested a positive carbon impact of optimising steel rebars in high-rise buildings.

Work on the carbon footprint of structures as a function of concrete strength is limited. Fantilli et al. [27] looked at multi-storey structures of 13, 30 or 60 floors, designed using C25, C40, C60 and C80 concrete. The 13-storey building showed an increase in carbon footprint with increasing concrete strength.

The 30-storey building showed a maximum carbon footprint when using C40 concrete, slightly higher than both the C25 and C60 grades, while the C80 concrete gave the lowest impact. For the 60-storey structure, the carbon footprint decreased with increasing strength. The differences between the three buildings were due to the limitations on minimum dimensions placed by Eurocode 2. For the 13-storey structure the minimum dimensions were already met by the lowest concrete strength, so any increase in grade simply increased the carbon footprint without any structural benefit.

Habert and Roussel [20] also considered the trade-off with increasing concrete strength between the increased carbon footprint per unit volume versus the potential volume reduction. They did, however, only consider a “quasi-dimensional approach” which neglected the complications added by design codes (e.g. minimum cement contents to preserve durability) or other architectural requirements such as thermal or fire aspects. For slabs and columns they suggested reduced emissions with increasing strength, while overall emissions for beams were not altered significantly by changing concrete strength.

Gan et al. [26] assessed numerous carbon mitigation strategies for a 40-storey reinforced concrete tower block, including the use of SCMs, larger aggregate or recycled steel, and changing the concrete grade. The use of SCMs and recycled steel significantly reduced carbon footprints. The use of larger aggregates, as also shown by Purnell and Black [4], also led to a lower carbon footprint.

Moving from a C40 to a C60 concrete led to a 5% drop in overall carbon emissions, with an 18% reduction in concrete volume more than offsetting a 15% increase in carbon footprint per cubic metre of concrete. The was complemented by a 15% reduction in steel volume. Moving from a C40 to C80 concrete led to an overall 18% carbon reduction, again primarily arising from the reduced steel volume.

Further investigations have examined the role of architectural considerations such as spans, orientations, and building height on carbon footprint [26–31]. These studies collectively highlight the potential positive environmental outcomes attainable through efficient building design based on these factors.

Longer spans increase the carbon footprint of columns and lower floors, but lower the carbon footprint of roofs [28]. The optimum span is a function of the building type. This apparently contradicts Purnell [25] who asserted that shorter beams are more carbon-efficient than longer beams, but actually highlights the need to consider broader building optimisation, as well as minimising the footprint of individual elements.

Despite these numerous studies optimising various aspects of structural design and concrete composition with respect to carbon footprint, and despite many people reporting on the environmental and durability benefits of using GGBS, there does not appear to have been any consideration given to how improved durability may also allow greater structural optimisation when using SCMs. This study therefore investigates the effect on the carbon footprint of concrete grade, binder type and spans in multi-storey RC buildings. The role of durability considerations on carbon footprint are also considered.

2 Methodology

This study focuses on an analysis of the carbon footprint of a hypothetical two-storey RC office building in different exposure classes. The primary objective was to investigate the dependency of carbon footprint on binder type and concrete strength at the structural level, extending the work of Purnell and Black [32] which was undertaken at the material and/or component level. Twelve structural designs were implemented according to the requirements for a 50-year design life assuming XC1 and XS1 exposure classes according to BS 8500-1.

2.1 Structural layouts

The two-storey reinforced concrete structure had a 36 × 36 m footprint and a 3.3 m column height. This allowed two different beam spans to be considered; 6 m and 9 m (Fig. 1). The buildings were designated for office use, class B according to BS EN1990-1-1 Table A1 (CEN 2005).

To ensure a fair and meaningful comparison, a consistent structural form was used across different spans. The floor systems adopted a one-way solid slab for the 6 m span. Although alternative floor systems, such as two-way solid slabs for 6 m spans or waffle slabs for 9 m spans, may offer improved

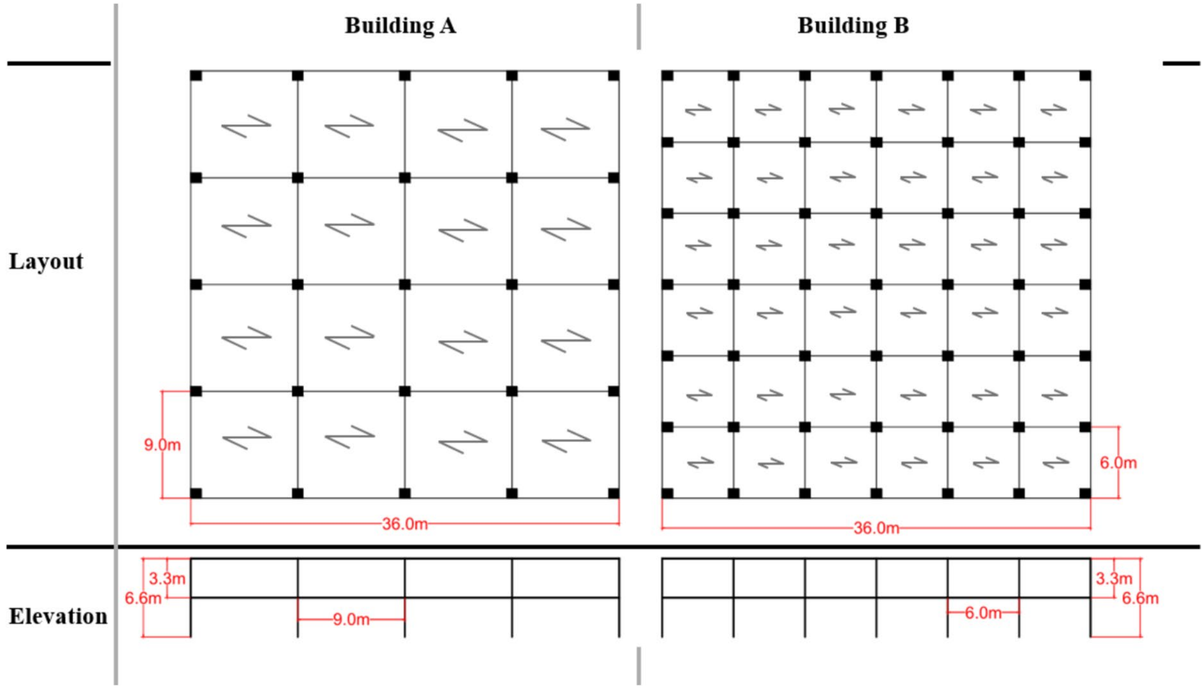

Fig. 1 Plan and elevation views of the 9 m span (**A**) and 6 m span (**B**)—one-way load direction

efficiency, this choice simplified the designs and comparisons between different designs.

All structures were designed with rectangular continuous solid RC beams, with internal and end RC beams designed to withstand hogging and sagging moments, plus the high shear forces near supporting columns. Similarly, rectangular columns were adopted to simplify the design process by ensuring similar second moments of inertia in both directions and enhancing the lateral resistance of the structures. Table 1 summarises the implemented structural member types, shapes, and minimum dimensions as recommended by various guides.

2.2 Structural actions

Actions were determined in accordance with BS EN1990-1-1, with the incorporation of the UK National Annex. Noting that, only vertical actions were considered in the study, assuming category B for all considered structures.

2.3 Summary of the main variables

In addition to beam spans, this study also considered whether the increased carbon footprint of higher strength concrete was compensated by the dematerialisation associated with its use. Both Daminelli et al. [18] and Purnell and Black [4] showed an increase

Table 1 Summary of the implemented structural member systems with the provision of the minimum dimensions

	Structural member type	Minimum dimensions (mm)		References
Floor slab	One-way solid slab	Thickness = 125		Cobb [33]
Beam	Rectangular continuous solid	Interior	125 or 1.3 x span/30	Cobb [33]
		End	125 or 1.3 x span/26	
Column	Rectangular solid	Cross-section = 225 × 225		IStructE [34]

in carbon footprint per unit strength with decreasing strength from 50 MPa. The study compares the use of CEM I and of CEM III/A-S, in particular with reference to minimum cover depths stipulated by exposure classes in BS8500-1:2006. Two exposure classes were considered; XC1 and XS1. The former represents a non-aggressive environment, while XS1 represents a structure at moderate risk of airborne marine chlorides. Table 2 summarises and justifies the variables considered in this study.

These variables gave 24 structural designs, as listed in Table 3. To streamline the number of variables an internal structural frame was considered for each scenario. This decision was based on the understanding that such frames effectively transmit higher loads to their supporting foundations. The

Table 2 Main variables of the study

	Variable parameter			Commentary/Justification
Concrete grade	C30	C40	C50	Examine whether dematerialization outweighed increased carbon footprint per unit volume
Binder type	CEM-I		CEM-III/A-S (50 % GGBS)	Determine whether low-carbon cements translate to low-carbon concrete
Span	6 m		9 m	Longer spans require fewer columns, but deeper beams
Exposure class	XC1		XS1	Durability requirements specify minimum cover depths, which vary with binder type. Low-carbon CEM III/A-S cements can also offer reduced cover depths

Table 3 The various scenarios analysed in this study, and their associated nomenclature

No	Building code	Column spans (m)	Concrete grade	Binder type	Exposure class
1	6C301XC	6	C30	CEM-I	XC1
2	6C303XC	6	C30	CEM-IIIA	XC1
3	6C301XS	6	C30	CEM-I	XS1
4	6C303XS	6	C30	CEM-IIIA	XS1
5	6C401XC	6	C40	CEM-I	XC1
6	6C403XC	6	C40	CEM-IIIA	XC1
7	6C401XS	6	C40	CEM-I	XS1
8	6C403XS	6	C40	CEM-IIIA	XS1
9	6C501XC	6	C50	CEM-I	XC1
10	6C503XC	6	C50	CEM-IIIA	XC1
11	6C501XS	6	C50	CEM-I	XS1
12	6C503XS	6	C50	CEM-IIIA	XS1
13	9C301XC	9	C30	CEM-I	XC1
14	9C303XC	9	C30	CEM-IIIA	XC1
15	9C301XS	9	C30	CEM-I	XS1
16	9C303XS	9	C30	CEM-IIIA	XS1
17	9C401XC	9	C40	CEM-I	XC1
18	9C403XC	9	C40	CEM-IIIA	XC1
19	9C401XS	9	C40	CEM-I	XS1
20	9C403XS	9	C40	CEM-IIIA	XS1
21	9C501XC	9	C50	CEM-I	XC1
22	9C503XC	9	C50	CEM-IIIA	XC1
23	9C501XS	9	C50	CEM-I	XS1
24	9C503XS	9	C50	CEM-IIIA	XS1

Table 4 Concrete mix design assumptions

Mix design variable	Value
Strength	30 MPa, 40 MPa, and 50 MPa
Cement Strength Class	52.5
Workability	60–180 mm
Aggregate rel. density	2.7
Aggregate type	Uncrushed
Binder	CEM-I and CEM-IIIA (50 per cent GGBS)
Max aggregate size	20 mm
Margin ($\pm 1.64 \times$ SD)	6.6

dimensions of structural units were kept constant in each scenario, with no optimisation of slabs, beams or columns based on their location within a structure. This was adopted for a 'buildability' perspective. By minimising variations in section sizes, the construction of these structures can be executed more seamlessly.

2.4 Determination of carbon footprint

Carbon footprints were based on the mass of concrete (cement, water, aggregate, superplasticizer) and steel used in each design multiplied by a fixed value for the carbon intensity of each material (see Table 6). Theoretical mix designs were calculated according to the BRE Design of Normal Concrete Mixes [35], consistent with earlier work [4]. To ensure consistency, this study adopted consistent cement strength, workability and aggregate type, changing only the characteristic concrete compressive strength and the binder type, as detailed in Table 4. The steel reinforcement rebars were considered separately. Tables 5 and 6 show the assumed concrete mix designs and the carbon intensity of the various reinforced concrete components respectively. It should be noted that embodied carbon values for the constituents are variable according to the source consulted and thus contested to some degree. The effect of this on the interpretation of the results is discussed in Sect 3.3.

Carbon emissions associated with transportation, formwork, and construction operations were

Table 5 Concrete mix designs

Component/Mix	C30 CEM I	C30 CEM IIIA	C40 CEM I	C40 CEM IIIA	C50 CEM I	C50 CEM IIIA
CEM I (kg/m^3)	341.0	170.5	424.0	212.0	499.0	249.5
GGBS (kg/m^3)	0.0	170.5	0.0	212.0	0.0	249.5
Coarse aggregate (kg/m^3)	1157.0	1157.0	1141.0	1141.0	1113.0	1113.0
Fine aggregate(kg/m^3)	701.0	701.0	636.0	636.0	586.0	586.0
Water (kg/m^3)	180.0	180.0	180.0	180.0	180.0	180.0
Superplasticiser (ltr/m^3)	3.4	3.4	4.2	4.2	5.0	5.0
Carbon footprint (kgCO_2e/m^3)	299	166	369	204	434	240

Table 6 Carbon intensities of the reinforced concrete components

Component	Carbon intensity (kgCO_2e/tonne) *(kgCO_2e/litre)	References
CEM I	860.0	Burridge [3, 36]
GGBS	79.6	Burridge [3, 36]
CEM III/A-S	469.8	Inferred from above
Coarse aggregate	3.2	Jones [37]
Fine aggregate	2.3	Jones [37]
Water	0.56	Jones [37]
Superplasticiser	5.2*	Flower and Sanjayan [7]
Steel rebars	412	Burridge [3, 36]

excluded as they represent 2–3% of total emissions from reinforced concrete structures [38], and were also assumed to be relatively consistent across all 24 designs.

3 Results

3.1 Volume of concrete

Figure 2 shows the total concrete volume for each superstructure, while Figs. 3, 4 and 5 show the volume of each set of structural elements. Slabs dominate the total volume in all designs, accounting for 80–86% of the total. Increasing column spans from 6 to 9 m increased the concrete volume on average by 52%, in line with previous findings [28]. This is due entirely to the need for deeper beams (Fig. 4), and slabs (Fig. 3) to ensure deflection limitation in compliance with BS EN 1992-1-1. For example, transitioning from 6C301XC to 9C301XC adds 425 mm to beam depths and 112 mm to slab depths, agreeing with previous studies (Robertson 2005; Marí et al. 2010). Despite only a modest increase in depth, slab volumes dominate over other structural units to such an extent that this increase in depth significantly increases the concrete volume.

Total column volumes however decreased by between 3 and 42% with longer spans (Fig. 5). So, while individual columns had larger sections, the reduced column count more than offset this.

The total concrete volume in each structure was also dependent on concrete strength, agreeing with earlier work Purnell [24], Gan et al. [26], Habert et al. [20]. The volume of concrete fell with increasing strength, regardless of span, exposure class or binder type. Table 7 presents total percentage reductions, plus percentage reductions according to each class of structural element.

While total concrete volumes fell with increasing concrete strength, there were some significant differences within the trends. The volume reduction

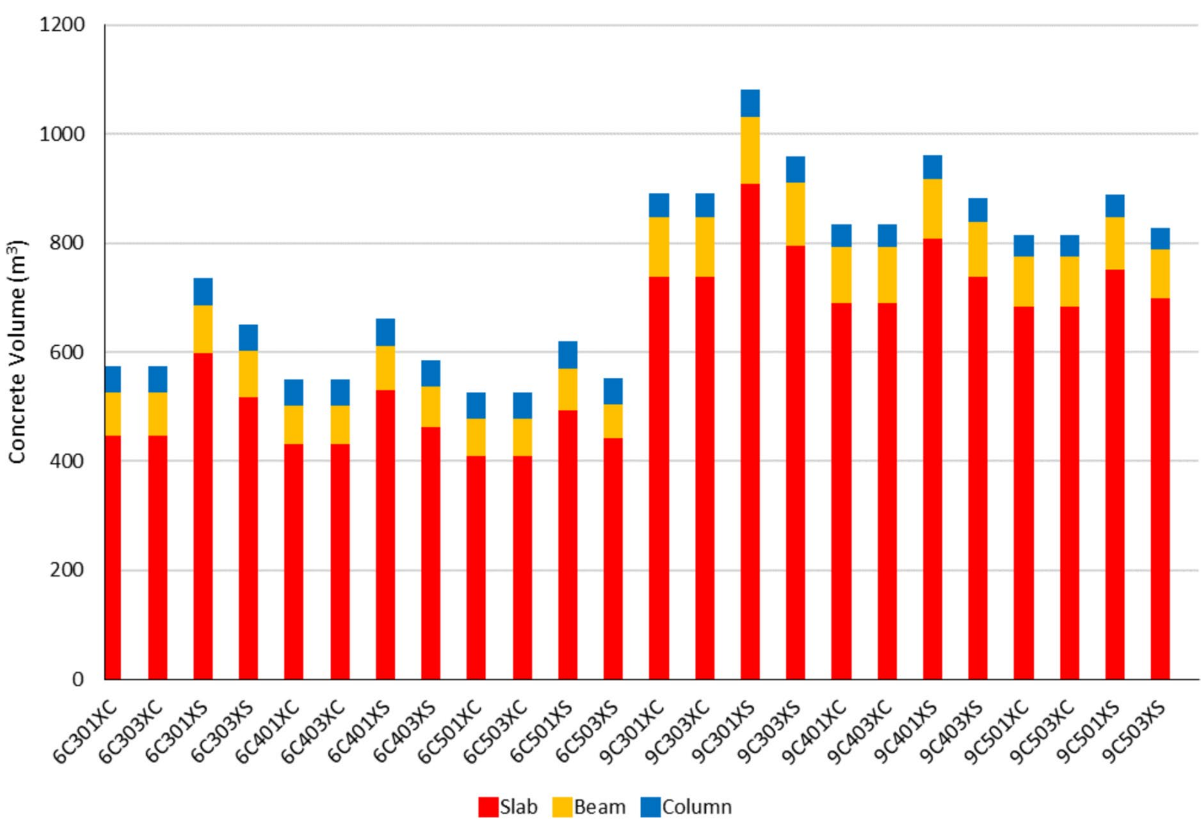

Fig. 2 Total concrete volume for each structure

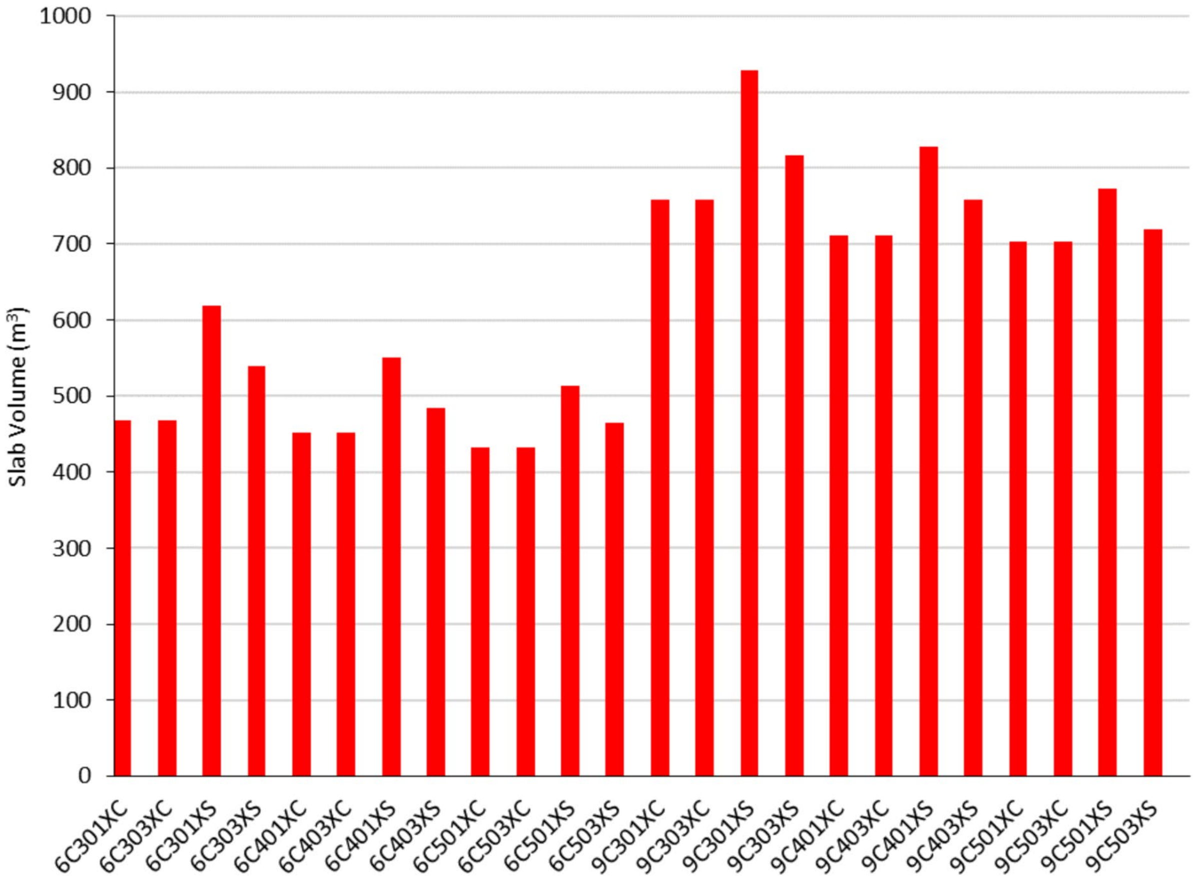

Fig. 3 Total volume of concrete required for slabs in each structure

was greater when increasing the concrete strength from C30 to C40 than from C40 to C50. This was due to minimum cover limits often being reached or approached for C40 concrete, such that further strength increases didn't allow for significant reductions in cover. Furthermore, fire safety rules (CEN 2004a) also restrict cover depths, such that column volumes were the same for all 6 m span designs exposed to XC1 conditions. For 6 m spans, the lower loads on each column ensure that the minimum code requirements for durability and fire safety are met, rendering concrete strength's impact on column dimensions negligible. In contrast, 9 m spans impose higher loads on each column, requiring larger cross-sectional areas to comply with code limits. Consequently, increasing the concrete strength permits a reduction in column dimensions until the minimum limits for fire safety and durability are achieved. Hence, higher concrete gradesled to remarkable decreases in column volumes, in agreement with previous research [20]. These findings also highlight how external design requirements, such as fire and safety considerations, impact on carbon footprints.

Volume decreases were typically greater in the structures exposed to XS1 exposure classes. Structural longevity requires increased cover, increased binder content or reduced permeability, be that achieved via reduced water/binder ratios or using composite binders. Thus, for a given binder type, increased strength (obtained by lowering the w/b ratio) allowed reduced cover depths. This aligns with studies indicating high-strength concrete's lower chloride ion permeability [20].

Switching from CEM I to CEM III/A-S had no impact on concrete volume in XC1 environments (Fig. 2), but did offer significant volume reductions in XS1 environments. This is due to the improved

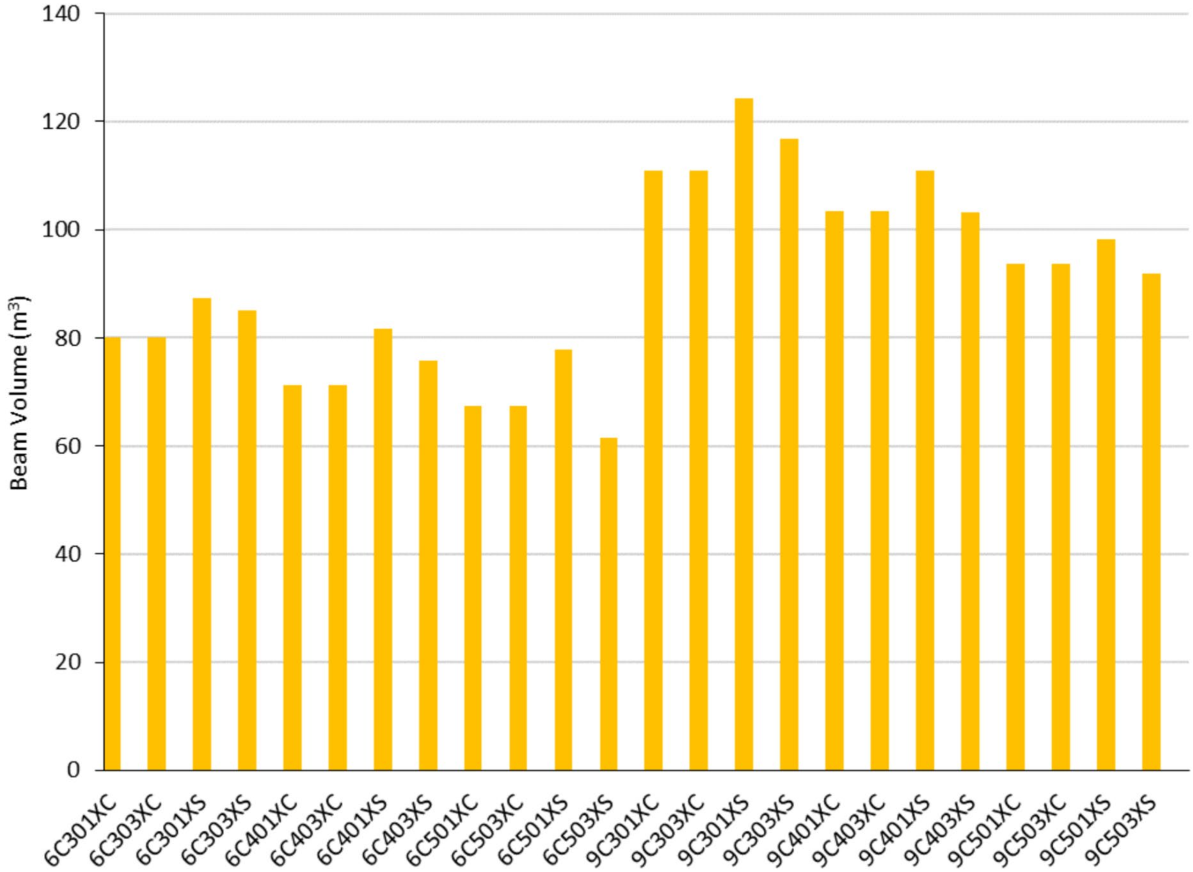

Fig. 4 Total volume of concrete required for beams in each structure

chloride resistance imparted by slag cements [11], thanks to reduced capillary porosity and enhanced chloride binding [13, 39], allowing reduced cover depths. Table 8 summarises the volume reductions associated with changing binder type.

The increased durability of slag cements reduced nominal cover depths for C30, C40, and C50 concrete by 25 mm, 20 mm, and 15 mm, respectively. Therefore, as the concrete grade increases, the overall concrete volume reduction becomes less pronounced. The smaller volume reductions in the longer spans can be attributed to design constraints where control of deflection necessitates deeper beams. Slabs experienced greatest reductions in concrete volume. This is due to their overall greater volume and the greater proportion of the total volume that is cover concrete. Meanwhile, the volume reduction for columns was limited due to the need to maintain fire resistance, as specified by BS EN 1992-1-2. The columns were predominantly designed with low actions, reflecting the nature of the considered low-rise structures with only two storeys. As a result, the section sizes of the columns were already close to the minimum allowable dimensions.

3.2 Carbon footprint of structures

Figure 6 shows the carbon footprint of each of the 24 structural designs. There are significant variations between the different designs, with total embodied carbon ranging from 106.6 tCO_2 to 397.7 tCO_2. The majority of the emissions are due to the concrete, with the emissions associated with the steel ranging from ~ 13.5 tCO_2 (6 m span, C30 concrete) to ~ 17.1 tCO_2 (9 m span, C50 concrete), i.e. 10–25% of total emissions. Note that steel areas for each concrete grade within the various elements were kept almost uniform. The incorporation of steel shear rebars,

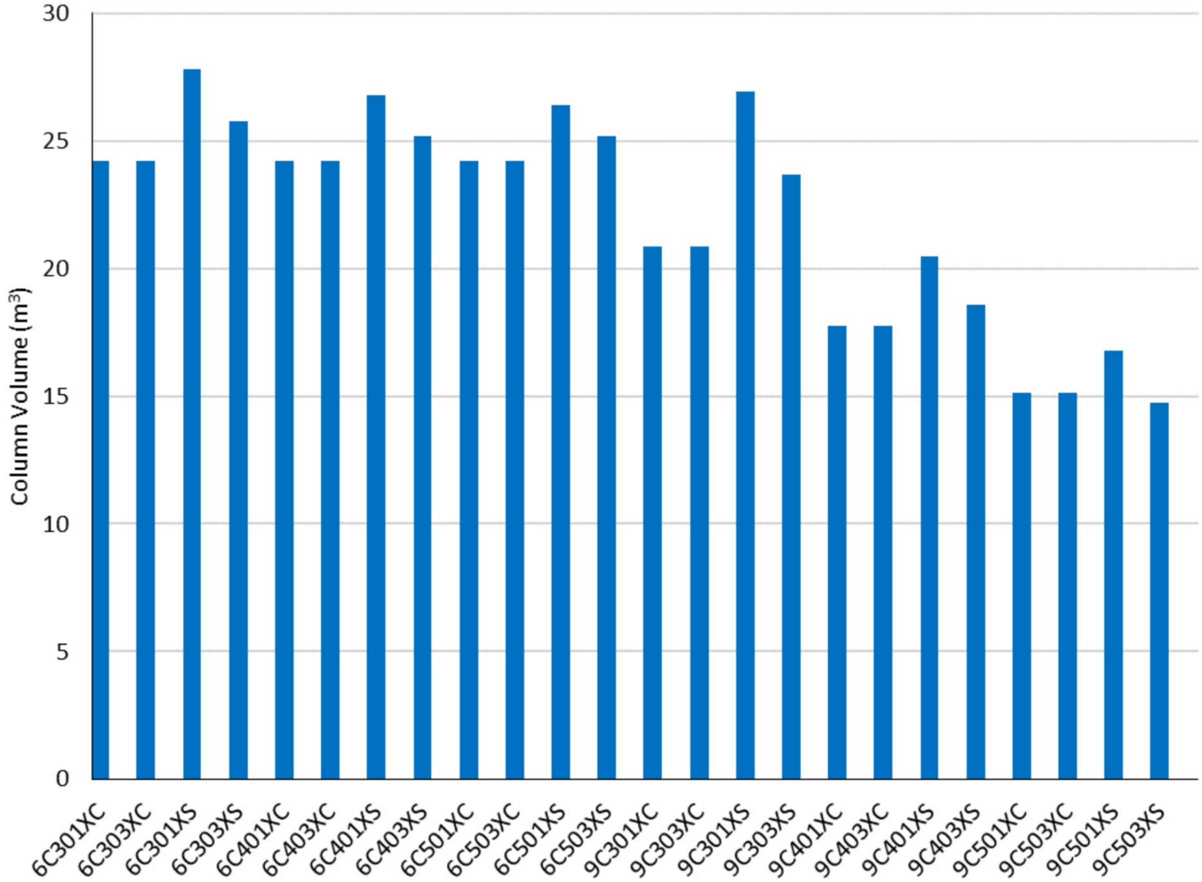

Fig. 5 Total volume of concrete required for columns in each structure

Table 7 Total volume reduction associated with increased concrete strength

Exposure class	From	To	Volume reduction (%)							
			6 m Span				9 m Span			
			Slab	Beam	Column	Total	Slab	Beam	Column	Total
XC1	C30 C1	C40 C1	3.4	11.1	0.0	4.3	6.2	6.9	15.1	6.9
	C30 C1	C50 C1	7.9	15.9	0.0	8.7	7.3	15.7	27.9	8.8
	C40 C1	C50 C1	4.7	5.4	0.0	4.6	1.1	9.5	15.0	2.1
	C30 CIIIA	C40 CIIIA	3.4	11.1	0.0	4.3	6.2	6.9	15.1	6.9
	C30 CIIIA	C50 CIIIA	7.9	15.9	0.0	8.7	7.3	15.7	27.9	8.8
	C40 CIIIA	C50 CIIIA	4.7	5.4	0.0	4.6	1.1	9.5	15.0	2.1
XS1	C30 C1	C40 C1	11.3	6.6	3.8	10.4	11.0	10.9	24.2	11.3
	C30 C1	C50 C1	17.41	11.08	5.14	16.2	17.04	21.21	38.02	18.0
	C40 C1	C50 C1	6.9	4.8	1.5	6.5	6.8	11.6	18.3	7.6
	C30 CIIIA	C40 CIIIA	10.51	11.05	2.38	10.3	7.22	11.72	21.87	8.1
	C30 CIIIA	C50 CIIIA	14.18	28.00	2.38	15.5	12.04	21.53	38.12	13.8
	C40 CIIIA	C50 CIIIA	4.10	19.05	0.00	5.9	5.19	17.19	20.80	6.2

Table 8 Total volume reduction when replacing CEM-I with CEM-III/A-S for different concrete grades and XS1 exposure classes

Concrete grade	From	To	6 m Spans			9 m Spans		
			Volume difference (m^3)			Volume difference (m^3)		
	Structural elements		Slab	Beam	Column	Slab	Beam	Column
C30	C30 CI	C30 CIIIA	80.4	2.2	2.0	112.8	7.4	3.2
C40	C40 CI	C40 CIIIA	67.4	5.8	1.6	70.0	7.5	1.9
C50	C50 CI	C50 CIIIA	49.3	16.1	1.2	53.1	6.2	2.0

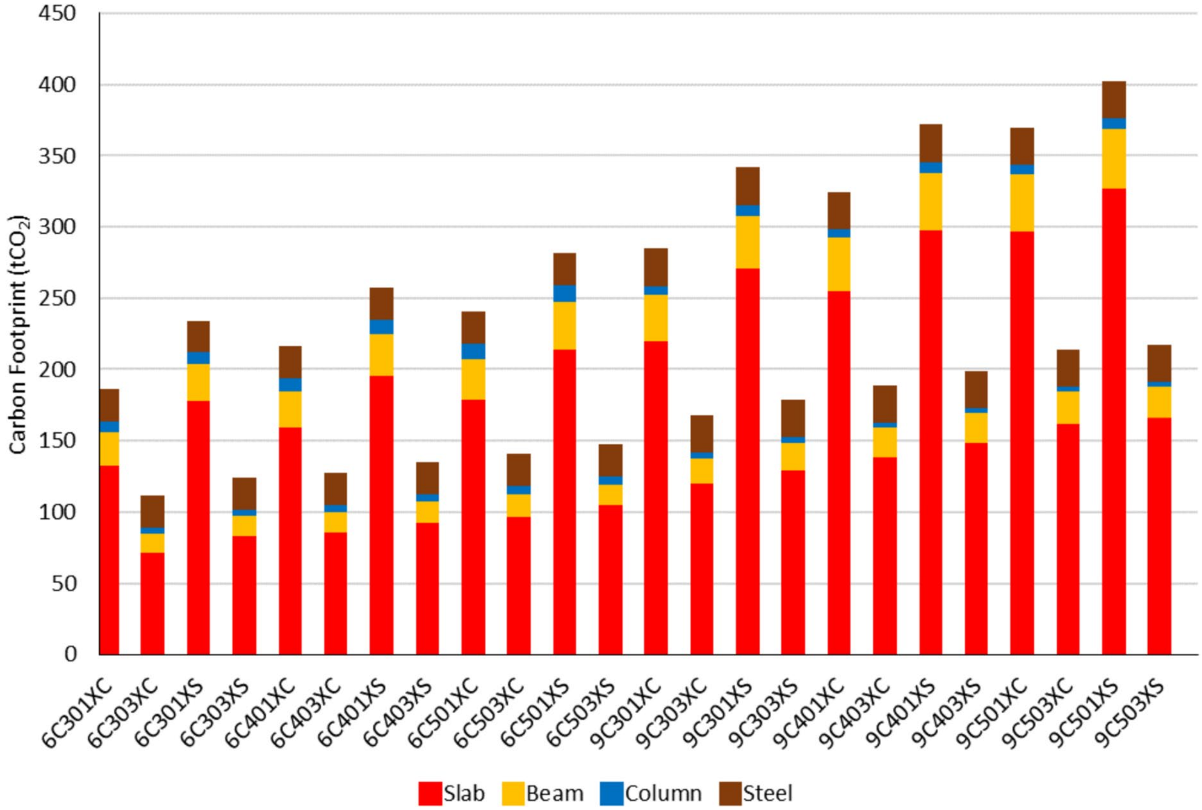

Fig. 6 The carbon emissions of each structural design due concrete, and contributions from steel rebars

commonly referred to as links, had a marginal influence, contributing 0.2 to 0.8 tCO_2 to the overall footprint (i.e. < 1%), but for consistency a value of 0.8 tCO_2 was used. Slabs were designed without transverse reinforcement rebars due to their inherent shear resistance.

Figures 7, 8 and 9 show the contributions from the concrete for each of the structural element types. Since the embodied carbon is a function of the concrete mass, the emissions associated with the slabs dominate. While all of the factors are interlinked, for the sake of clarity, the effects of binder type, column spacing, concrete strength and exposure class are presented in turn below.

3.2.1 *Impact of binder type*

Switching from a CEM I to a CEM III/A-S binder always significantly reduced carbon footprints, agreeing with earlier studies Alwash et al. [48]. This is unsurprising given their relative carbon intensities (Table 6), with the slag cement offering a reduction

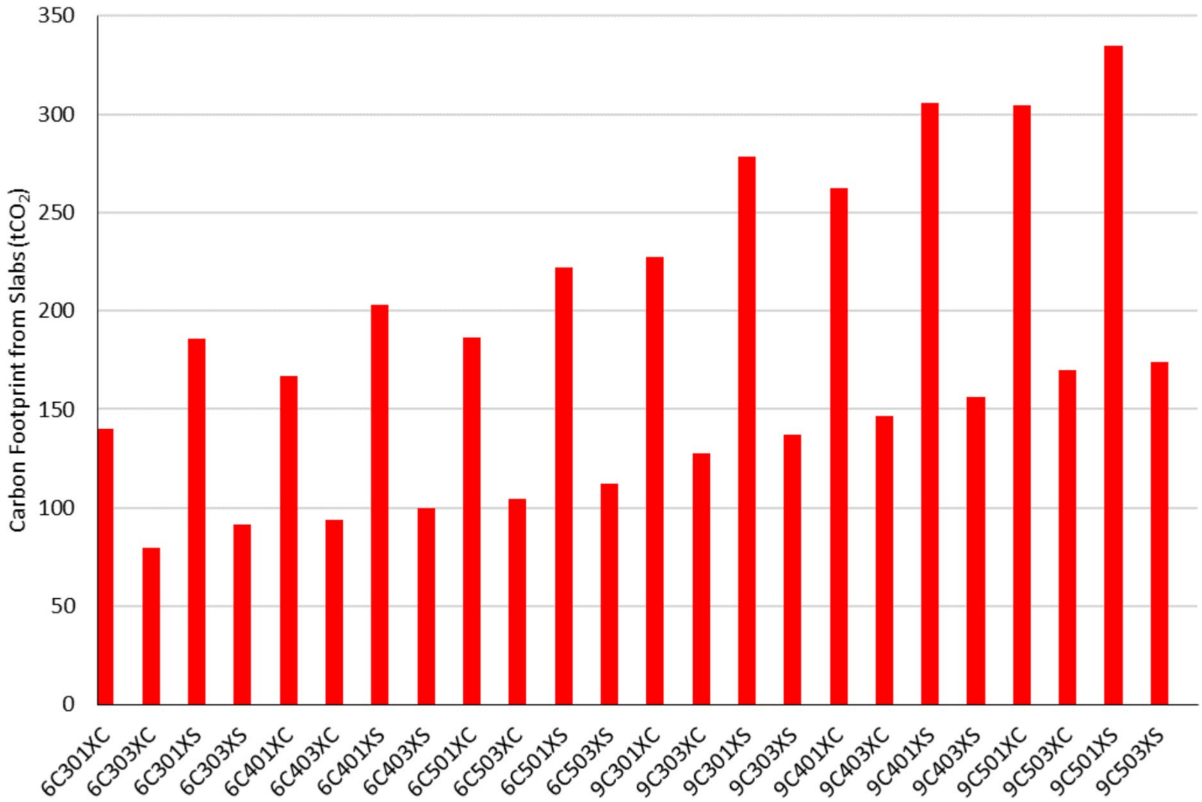

Fig. 7 Carbon emissions associated with the concrete slabs for each structure

in carbon intensity of 45.4%. Thus, the reduction in carbon footprint upon adopting CEM III/A-S cement was 44–45% for all of the structures designed for XC1 exposure. However, with slag cements offering reduced capillary porosity and increased chloride binding, and so allowing reduced cover depths, the reduction was 48–51% for the structures designed to resist chlorides (Table 9). Cover depth is not a concern in non-aggressive environments, and so the dimensions of each structural element are defined by the concrete's structural performance. In aggressive environments, minimum cover depth becomes a possible concern, increasing the dimensions of CEM I concrete structural elements. With no equivalent increase in dimensions when using slag, this enables slag cement to offer a reduction in carbon footprint over and above that associated with the lower eCO_2 of the binder. That a volume reduction is achieved when using GGBS in aggressive environments, coupled with its limited global availability relative to global cement production [16], suggests that GGBS use should be reserved for use where it offers the greatest improvement in durability, such as in chloride-rich environments.

3.2.2 *Impact of increasing column spacing*

Increasing the column spacing increased the overall carbon footprint. This was due to significantly increased concrete volumes for the slabs and beams to account for deflections. This broadly supports the work developed by Purnell [24], who showed that increased beam spans result in a higher carbon footprint per unit gain in strength. However, there was a decrease in concrete volumes for the columns, with the increased column dimensions being more than offset by the reduced number of columns.

3.2.3 *Impact of concrete grade*

Increasing the concrete grade led to a slight reduction in concrete volume, with the reduction being

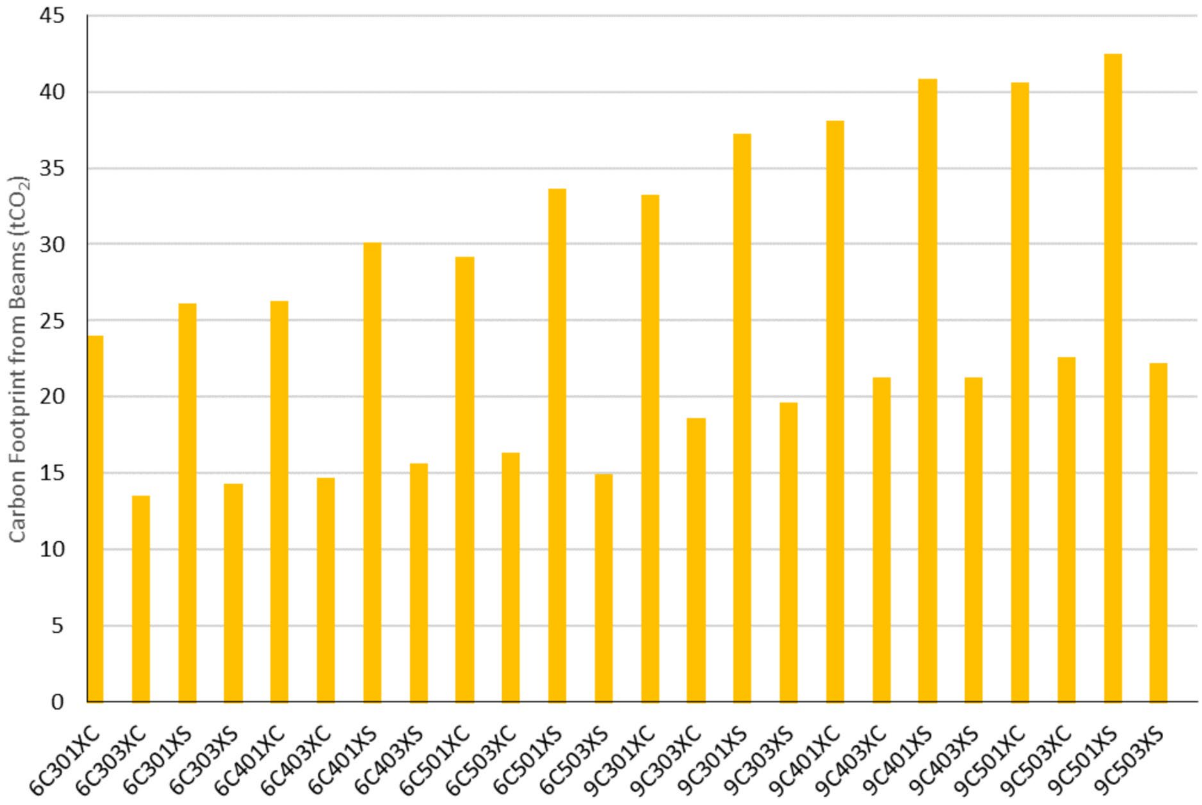

Fig. 8 Carbon emissions associated with the concrete beams for each structure

slightly greater in an aggressive (XS1) environment. However, as shown in Table 5 and in Purnell and Black [4], increasing concrete's strength leads to an increase in paste volume, and so an increase in carbon footprint per unit volume. Consequently, despite the reduction in concrete volume, higher concrete strength consistently increased carbon footprints, regardless of column spacing or binder type (Table 10). This contradicts the findings of both Purnell and Black [4] and Damineli et al. [21] who suggested a decrease in carbon dioxide intensity index (carbon footprint per unit volume per unit strength) with increasing strength. However, as both of these studies only looked at hypothetical concrete cubes, this serves to highlight the importance of considering carbon reduction at the structural level, not just the material level. The lower carbon footprint associated with lower-strength concrete is in line with previous findings [20, 31].

Table 11 shows changes in carbon footprint by structural element as a function of concrete strength, and reveals that the overall trends hide some finer details. Slabs always showed an increase in carbon footprint with increasing concrete strength. This is due to minimum cover depth requirements limiting the reduction in concrete volume. The carbon footprint of columns however often decreased with increasing strength, particularly for the structures with 9 m spans. Table 11 also shows that exposure class had a significant effect, and this is discussed below.

3.2.4 Impact of exposure class

Improved durability requires increased cover depths or improved concrete quality, i.e. lower permeability brought about by a lower water/binder ratio, or a shift from pure Portland cement to a composite cement [40]. Consequently, the concrete structures designed for exposure to chlorides (XS1) had greater carbon footprints than those designed for just moderate carbonation risk (XC1) (Fig. 6). Keeping all other factors

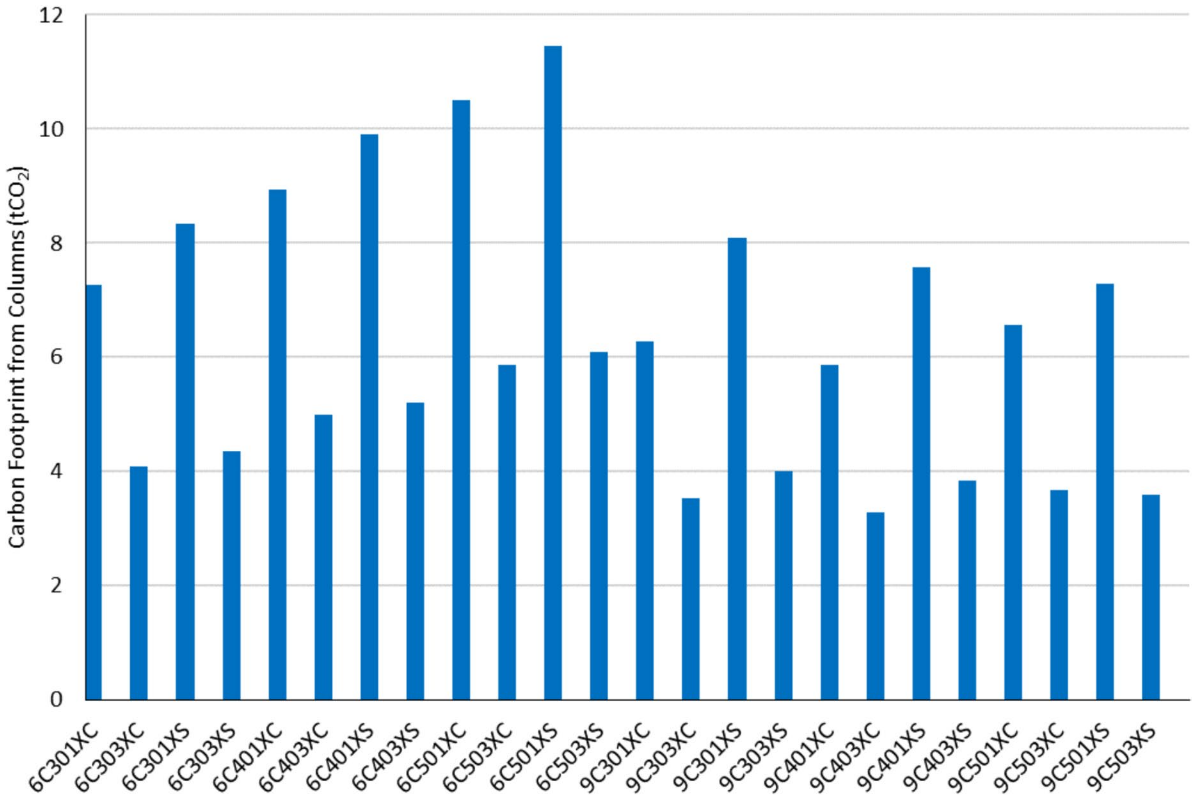

Fig. 9 Carbon emissions associated with the concrete columns for each structure

Table 9 Reduction in carbon footprint upon switching from CEM I to CEM III/A-S for each structural element and exposure class

Exposure class	From	To	Embodied carbon emission reduction (%)					
			6 m Span			9 m Span		
	Structural elements		Slab	Beam	Column	Slab	Beam	Column
XC1	C30 CI	C30 CIIIA	44.5	44.5	44.5	44.5	44.5	44.5
	C40 CI	C40 CIIIA	44.7	44.7	44.7	44.7	44.7	44.7
	C50 CI	C50 CIIIA	44.7	44.7	44.7	44.7	48.2	44.7
XS1	C30 CI	C30 CIIIA	51.8	45.9	48.6	51.3	47.8	51.2
	C40 CI	C40 CIIIA	51.6	48.7	48.1	49.4	48.5	50.0
	C50 CI	C50 CIIIA	50.1	56.4	47.3	48.6	48.2	51.5

the same, the move from an XC1 to an XS1 environment increased the carbon footprint of concrete by between 32 and 57 tCO_2 when using CEM I concrete, and between 7 and 13 tCO_2 when using CEM III/A-S. The greater increase when using CEM I was due to the binder's higher carbon intensity and the improved resistance to chlorides offered by CEM III/A-S binders [13, 41] enabling lower cover depths and thus lower concrete volumes. For example, Table A4 in BS8500-1:2015 specifies a minimum cover depth of 65 mm for a C30 CEM I concrete. This drops to 40 mm when using CEM III/A-S.

The increase in carbon footprint associated with a more aggressive environment decreased with increasing concrete strength. Again, this can be explained by cover depth requirements as stipulated in Table A4 of

Table 10 Embodied carbon increases with increasing concrete strength

Exposure class	From	To	Embodied carbon emission increase (%)	
			6 m Span	9 m Span
XC1	C30 C1	C40 C1	18.07	15.10
	C30 C1	C50 C1	32.53	32.37
	C40 C1	C50 C1	12.25	15.01
	C30 CIIIA	C40 CIIIA	17.58	14.62
	C30 CIIIA	C50 CIIIA	32.01	31.85
	C40 CIIIA	C50 CIIIA	12.28	15.04
XS1	C30 C1	C40 C1	10.58	9.46
	C30 C1	C50 C1	21.45	18.96
	C40 C1	C50 C1	10.02	8.68
	C30 CIIIA	C40 CIIIA	10.28	12.90
	C30 CIIIA	C50 CIIIA	22.14	24.57
	C40 CIIIA	C50 CIIIA	10.75	10.34

BS8500-1:2015. For XC1 exposure classes, durability requirements are met with a minimum cover depth of 15 mm + Dc by all concrete grades (C30–C50) for both binders. But moving to an XS1 exposure class introduces minimum cover depths of 45–65 mm for CEM I concretes, depending on strength, and between 30 and 40 mm for slag cement. The additional cover depth imposed by durability requirements falls with increasing strength, (Table 12), with higher strength concretes offering the potential for more slender beams. These findings align with those of Purnell [24] and Hoxha et al. [28], both of whom established a robust proportional connection between the dimensions of structural elements and carbon emissions.

3.2.5 *Consideration of steel reinforcement*

The discussion has, until now, focused on the concrete rather than the rebar. However, the rebar's contribution, while considerably less than that from concrete, was not trivial, contributing 10–25% to the total carbon footprint. The rebars contribute just 1–4% to the carbon footprint of slabs, yet contribute 19–37% to that of beams. This is due to the need for compression rebars to control high-hogging moments near the supports, plus the need to control bonding often necessitating larger steel diameters. But, it should be noted that the overall footprint of the slabs greatly

Table 12 Minimum cover depths (in mm), as specified in Table A4 of BS8500-1:2015, according to exposure class and binder type

Concrete Grade	XC1		XS1	
	CEM I	CEM III/A-S	CEM I	CEM III/A-S
C30	15	15	65	40
C40	15	15	50	30
C50	15	15	45	30

Table 11 Increases in embodied carbon with increasing concrete strength for the different structural elements

Exposure class	From	To	Increase in carbon footprint (%)					
			6 m Span			9 m Span		
	Structural elements		Slab	Beam	Column	Slab	Beam	Column
XC1	C30 C1	C40 C1	19.2	9.7	23.4	15.7	14.9	− 6.6
	C30 C1	C50 C1	33.7	22.1	45.2	34.6	22.3	4.7
	C40 C1	C50 C1	12.1	11.3	17.6	16.3	6.5	12.1
	C30 CIIIA	C40 CIIIA	18.7	9.3	22.9	15.2	14.4	− 7
	C30 CIIIA	C50 CIIIA	33.1	21.6	44.6	34.1	21.8	4.3
	C40 CIIIA	C50 CIIIA	12.1	11.3	17.7	16.3	6.5	12.2
XS1	C30 C1	C40 C1	9.5	15.3	18.9	9.9	9.9	− 6.4
	C30 C1	C50 C1	19.9	29.1	37.7	20.4	14.4	− 10
	C40 C1	C50 C1	9.5	11.9	15.8	9.6	4	− 3.9
	C30 CIIIA	C40 CIIIA	10	9.3	20	14	8.5	− 4
	C30 CIIIA	C50 CIIIA	24.1	4.1	41.1	27.2	13.5	− 10.5
	C40 CIIIA	C50 CIIIA	12.8	− 4.8	17.7	11.5	4.6	− 6.8

exceeds that of the beams. The contribution of steel to the columns' carbon footprint depended on column spacing. For 6 m spans, steel contributes 7–17% of the carbon footprint of the columns, yet contributes 16–33% when 9 m spans are used.

3.3 Sensitivity analysis

The main source of uncertainty is in the carbon intensity factors (Table 6). The values used here are common across many analyses, but they are not "fixed" and alternative values can be found in the literature. While a detailed review of the variability of the factors is beyond the scope of this paper, a preliminary analysis of available industrial data sources suggests that the predominant factors can vary between (in kg CO_2 per kg to 1 s.f.) 0.4–2 for rebar, 0.8–1 for CEM I and 0.04–0.1 for GGBS [36, 42–47]. Performing a "high-low" analysis using this range of factors for the lowest and highest carbon footprint families (6C30[1,3]XC and 9C50[1,3]XS respectively, see Fig. 6) gives the results in Fig. 10.

The total carbon in the "high" scenario is between 49 and 74% higher than that in the low scenario. The fraction of the carbon footprint attributable to the steel also varies between 7 and 35%. While such extreme ranges would not be encountered in practice, this does highlight that small apparent improvements in carbon footprint achieved through design changes have to be weighed in significance against the quality and provenance of the carbon intensity factors used, a point that is very frequently overlooked in analyses of this type. Specific carbon intensity factors for the actual products used in design, derived from transparent environmental product declarations (EPDs), should always be used in preference to generic values derived from sector-wide data sources. It certainly seems reasonable that improvements in carbon footprint derived from design changes that are < 10% are unlikely to be significant and should not be used to enhance the "green" credentials of

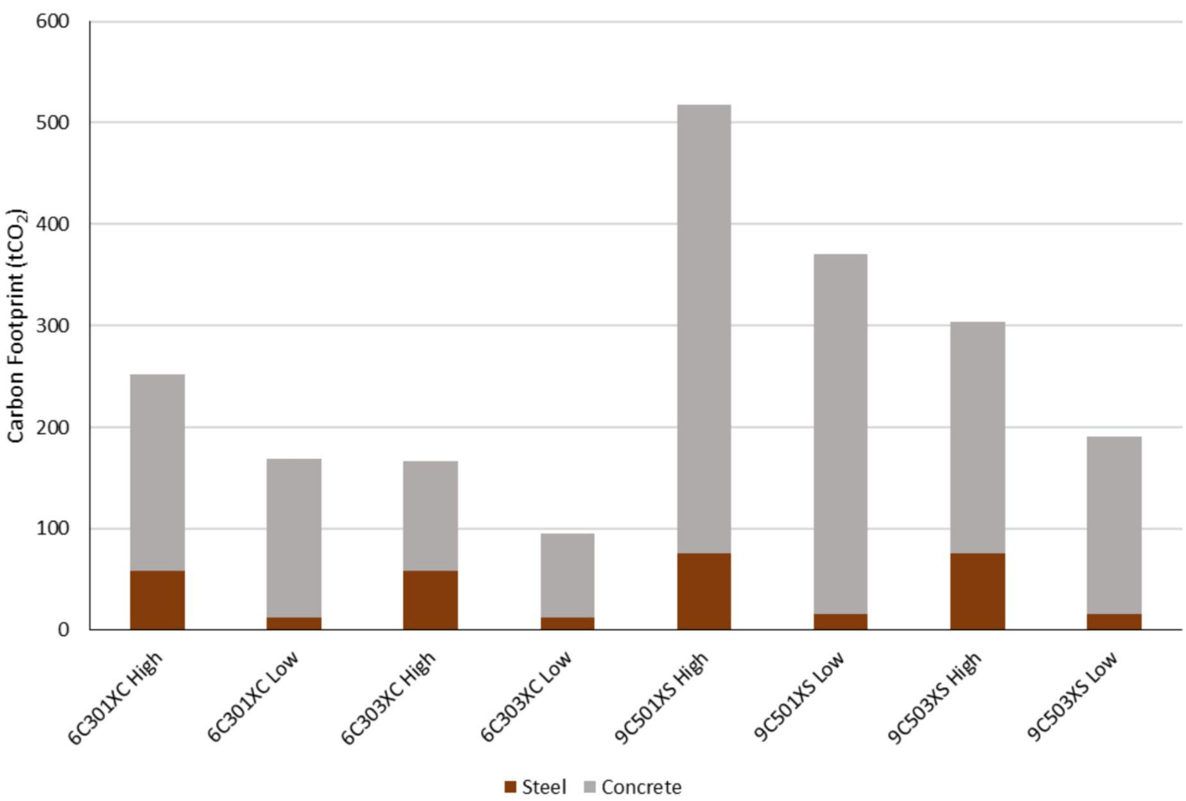

Fig. 10 High-low scenario analysis using a range of carbon intensity factors for rebar, CEM I and GGBS

a given product or process without very rigorous interrogation of the underlying data.

4 Conclusions

This study has investigated the influence of concrete compressive strength and binder type on concrete usage and carbon footprints. To achieve this, two distinct theoretical RC structures were designed with varying spans (6 m and 9 m) exposed to different exposure classes (XC1 and XS1). Both RC structures were designed in accordance with Eurocode standards and the UK National Annex.

There was a greater than threefold difference in carbon footprint depending on the span, concrete strength, binder type and exposure environment. Slabs are the largest contributor to concrete mass and carbon footprint, while the higher steel content gives the beams a higher carbon footprint per unit mass.

Longer spans led to increased carbon footprints of slabs and beams due to having to resist bending. Longer spans also led to broader columns, increasing the carbon footprint of each column, but their reduced number led to a reduction in the carbon footprint of columns as a whole.

Higher concrete strength reduced material consumption but increased the carbon footprint of the structures. This is counter to the concept of carbon dioxide intensity index, but agrees with some previous research, highlighting the role of structural design and safety requirements over material efficiency alone.

The use of a CEM III/A-S binder significantly reduces concrete's carbon footprint, primarily due to the significantly lower carbon intensity of GGBS compared to Portland cement. In aggressive, chloride-rich, environments, composite CEM III/A-S cements offer improved durability, in addition to reductions in carbon footprint. This enables dematerialization compared to CEM I concrete structures due to requirement for less cover concrete. Consequently, using a CEM III/A-S binder in an aggressive environment (in this case XS1) enables reductions in carbon footprint greater than 50%.

Current global production of GGBS is about 400 million tonnes per year, with global cement clinker production 8–12 times greater. Furthermore, the availability of GGBS is set to fall, which is going to put stress on future availability. However, cement replacement remains a common approach to concrete decarbonization. As shown above, in cases where durability is not the primary factor, other approaches, including structural efficiency and concrete mix optimisation, should be preferred to mitigate the carbon footprint.

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